Crack growth monitoring by strain measurements

Masayuki KAMAYA

Institute of Nuclear Safety System (INSS)

Symbio International Workshop 2012
on Advanced Condition Monitors for Nuclear Power and Other Process Systems
(Sep. 3 – 4, 2012 Kyoto)

Outline

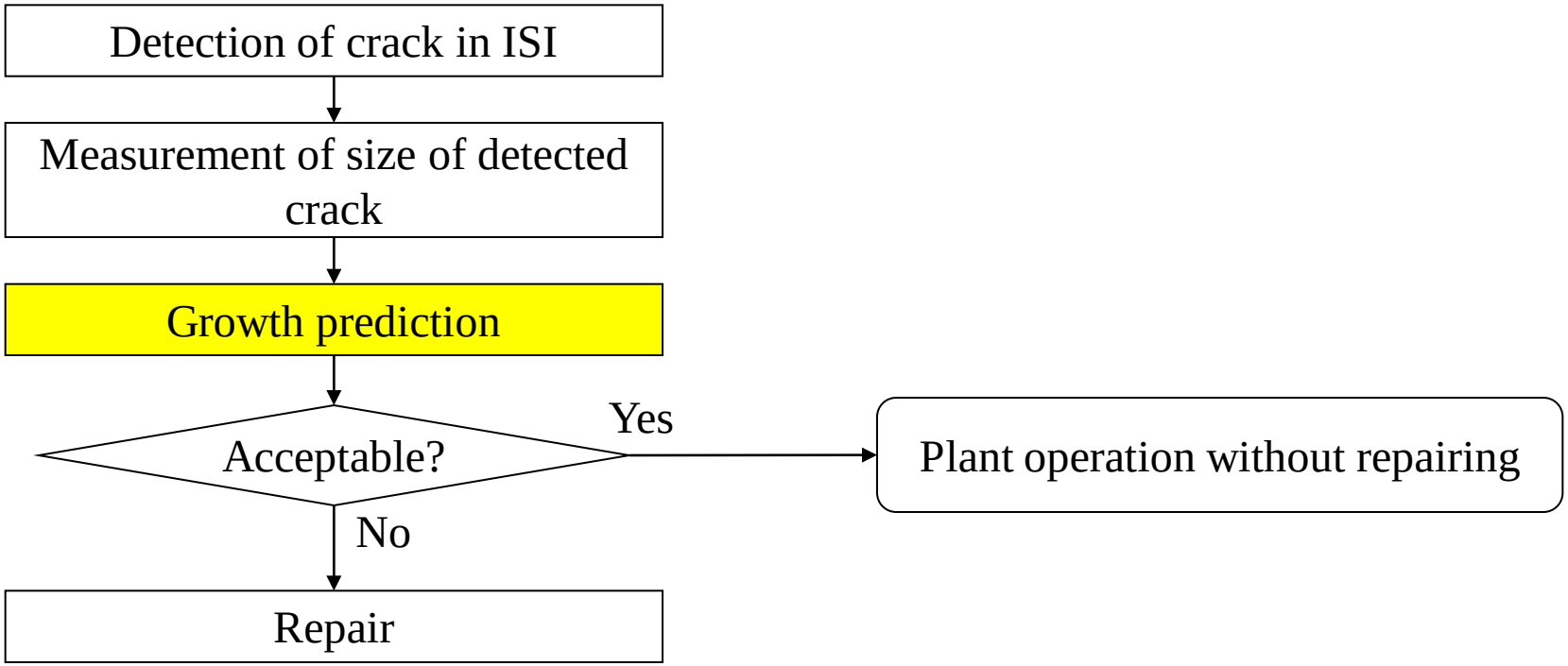
- Introduction
- Basic concept of OS-monitoring method
- Multiple strain measurement technique
- Experimental validation
  - Crack size identification
  - Monitoring of fatigue crack growth

Fitness-for-Service assessment

- Materials used for nuclear power plants
  - Good ductility (excellent fracture resistance)
  - Small crack has little influence on fracture strength

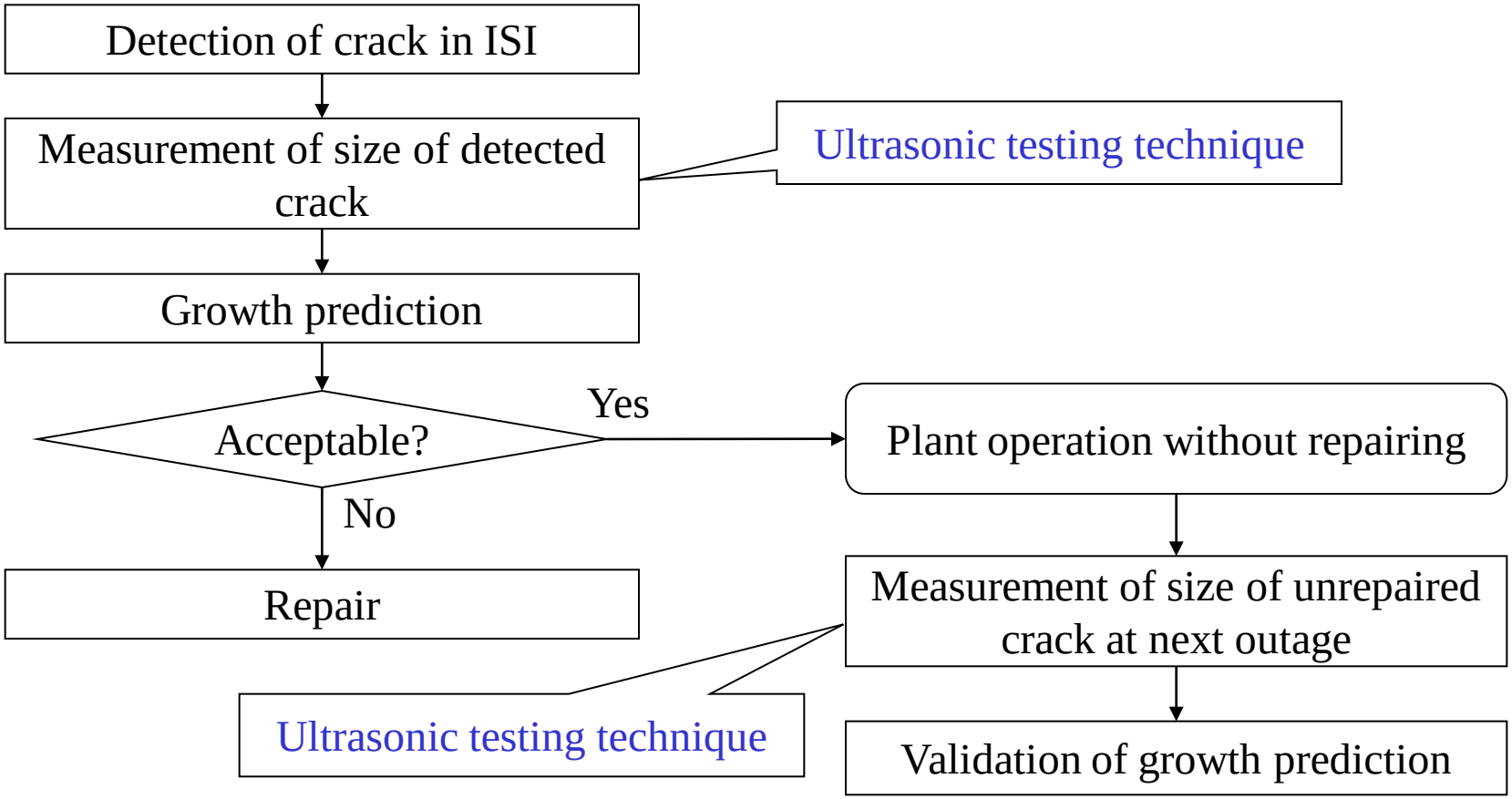
- Cracks detected by NDE should be repaired ?
  - Judgment is made according to fitness-for-service code
    - JSME FFS code
    - ASME BPVC Section XI
    - BS7910
  - Depends on crack size

Crack Growth Prediction for Fitness-for-Service



- Difficulties in growth prediction of stress corrosion cracking (SCC)
  - Conservative experimental data in simulated environment
  - Residual stress (main crack driving force) is difficult to identify

Crack Growth Prediction for Fitness-for-Service



- Accuracy of sizing by ultrasonic testing is not enough
- Alternative technique is required to validate growth prediction
  - Development of growth monitoring technique

Outline

- Introduction
- **Basic concept of OS-monitoring method**
- Multiple strain measurement technique
- Experimental validation
  - Crack size identification
  - Monitoring of fatigue crack growth

Crack Growth Monitoring Technique

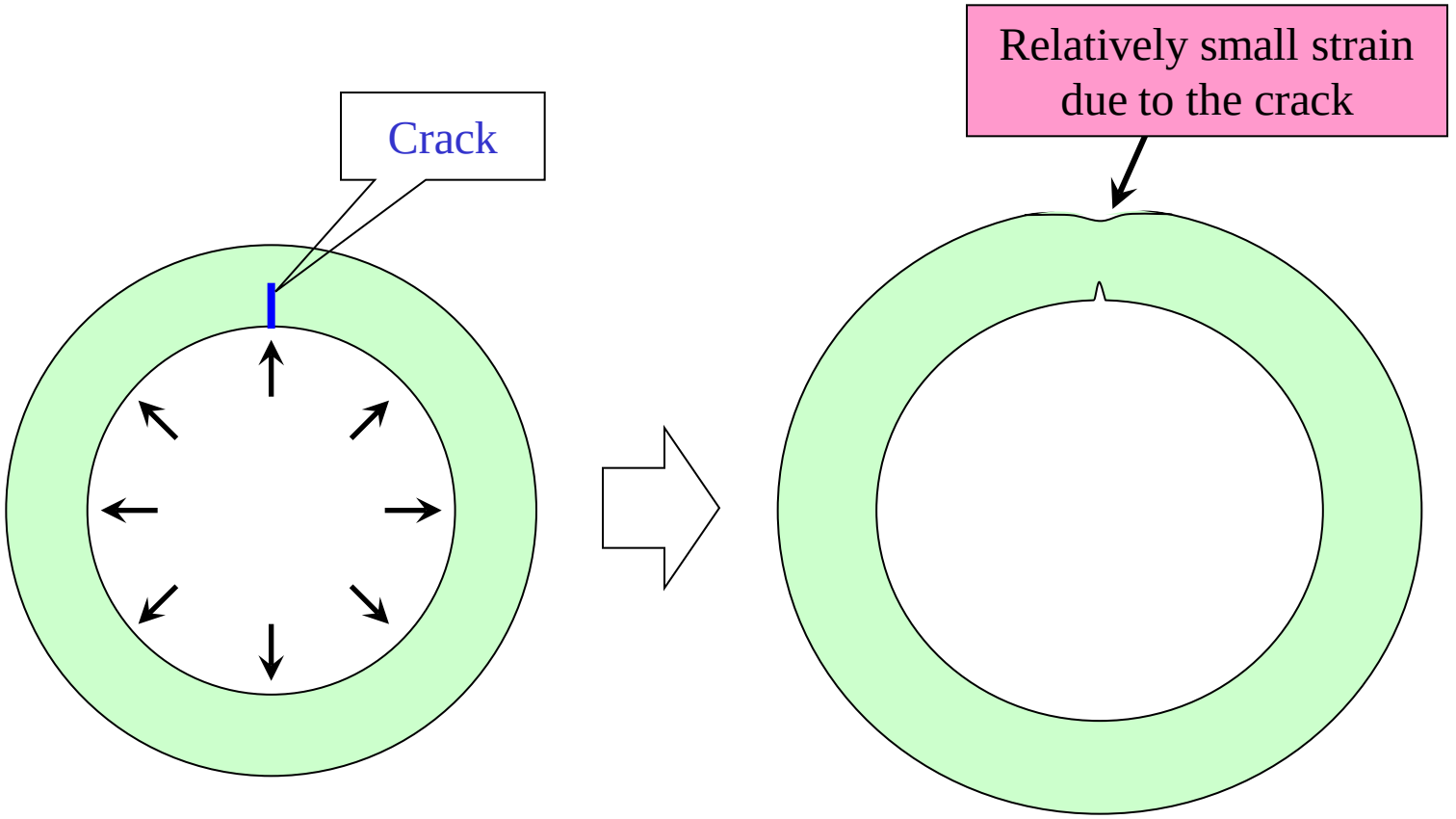
- Target of monitoring
  - Surface crack inside pipe
  - Detected crack
    - Initial size and location are identified

- Method
  - Continuous measurement of strain at external surface of pipe
    - Internal pressure generates elastic strain at pipe surface
    - Change in crack size causes the strain
  - Estimate change in crack size by measured strain

OS (Outside Strain) monitoring method

Deformation due to internal pressure

- Inside crack alters the outside strain caused by internal pressure

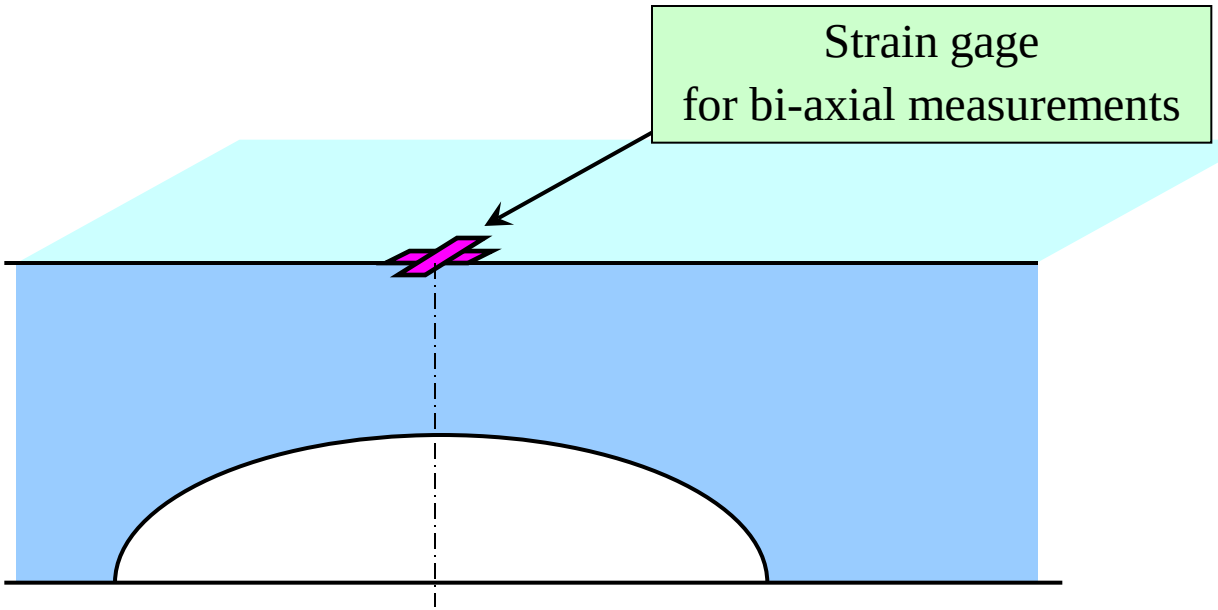


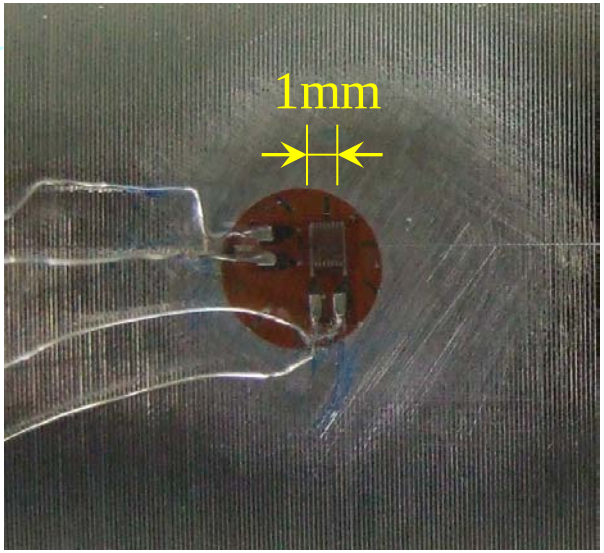
Elastic bulging due to internal pressure

Strain measurement by strain gage

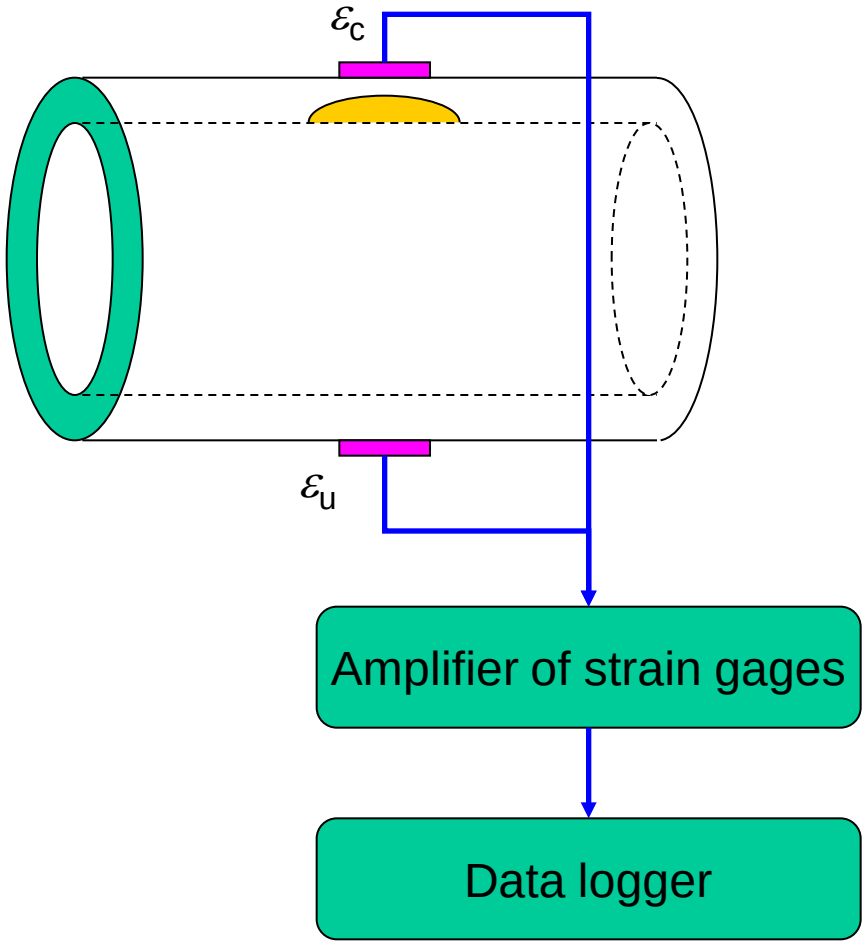
- Strain gage
  - Good sensitivity
    - Resolution is less than several micro strain (με)

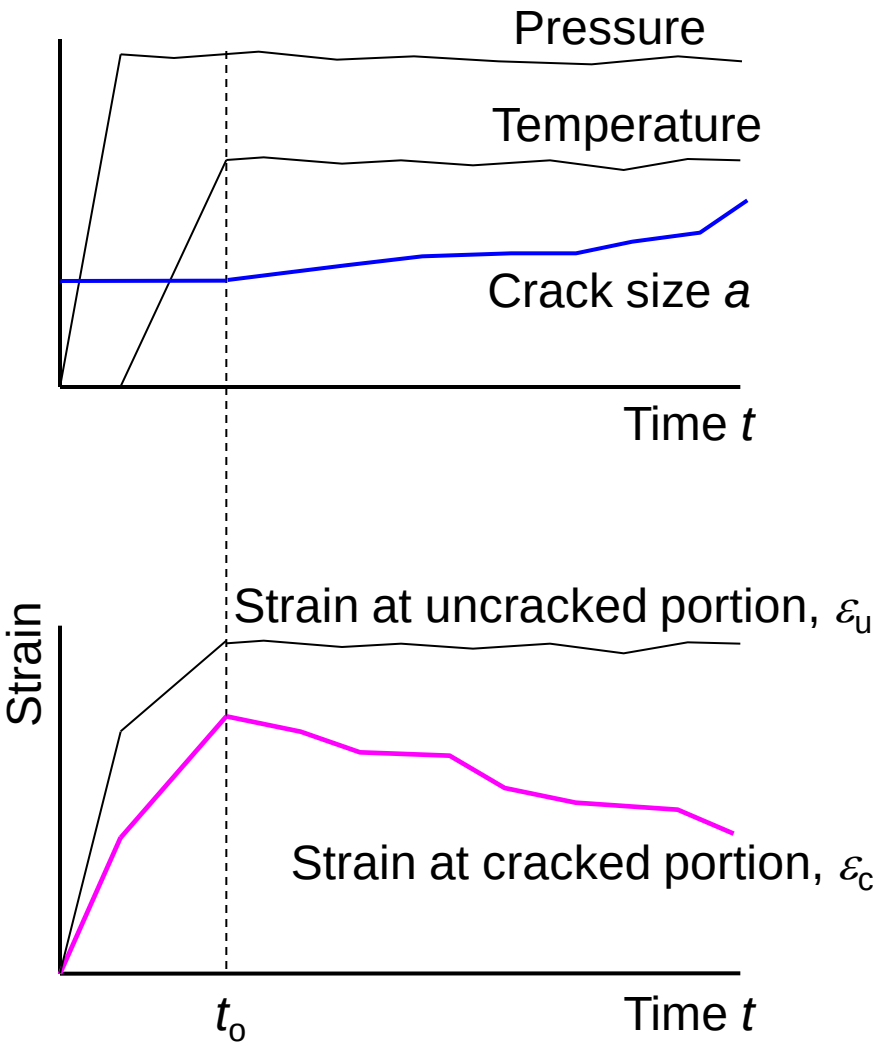
      (Elastic strain due to internal pressure is about 200 με)
  - Attached outside of the pipe





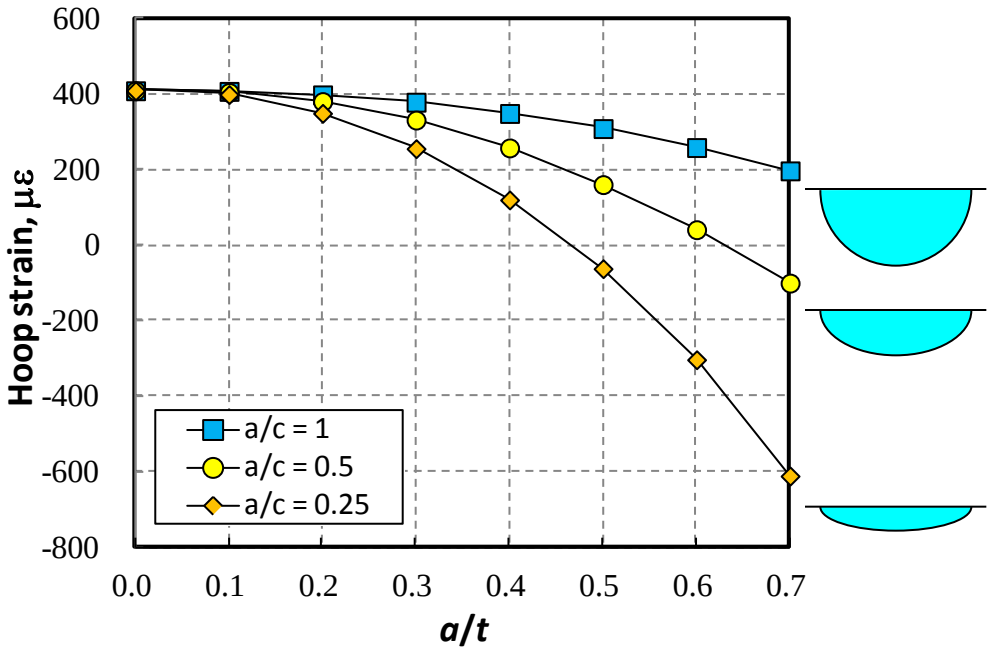
Crack Growth Monitoring System

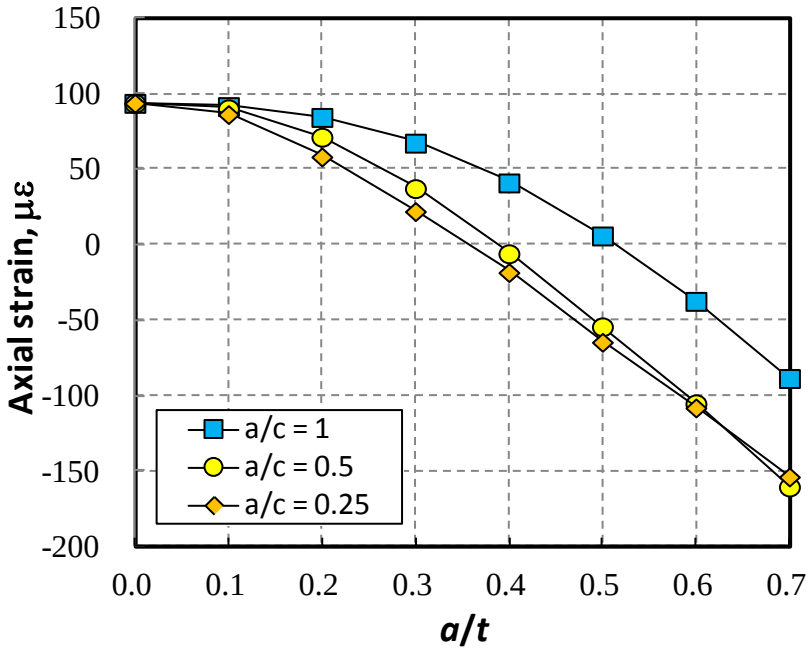




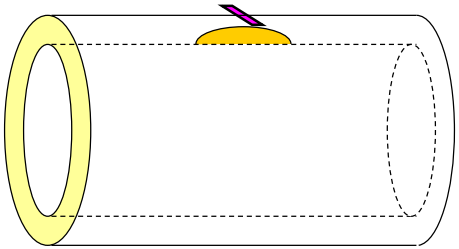
Change in strain vs. crack size

- Finite element analysis results
- Crack shape dependent
- Large crack causes more change in strain

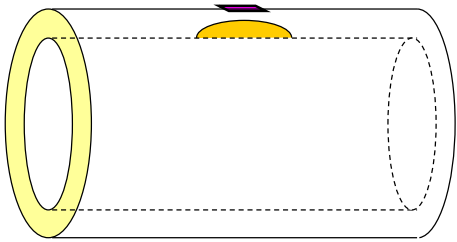




Hoop strain



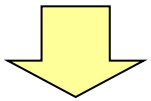
Axial strain



Problems in practical application

- Strain change depends on crack shape
  - Difficult to identify crack grow in the depth or surface direction

- Strain can be zero at some conditions
  - Small strain causes large error



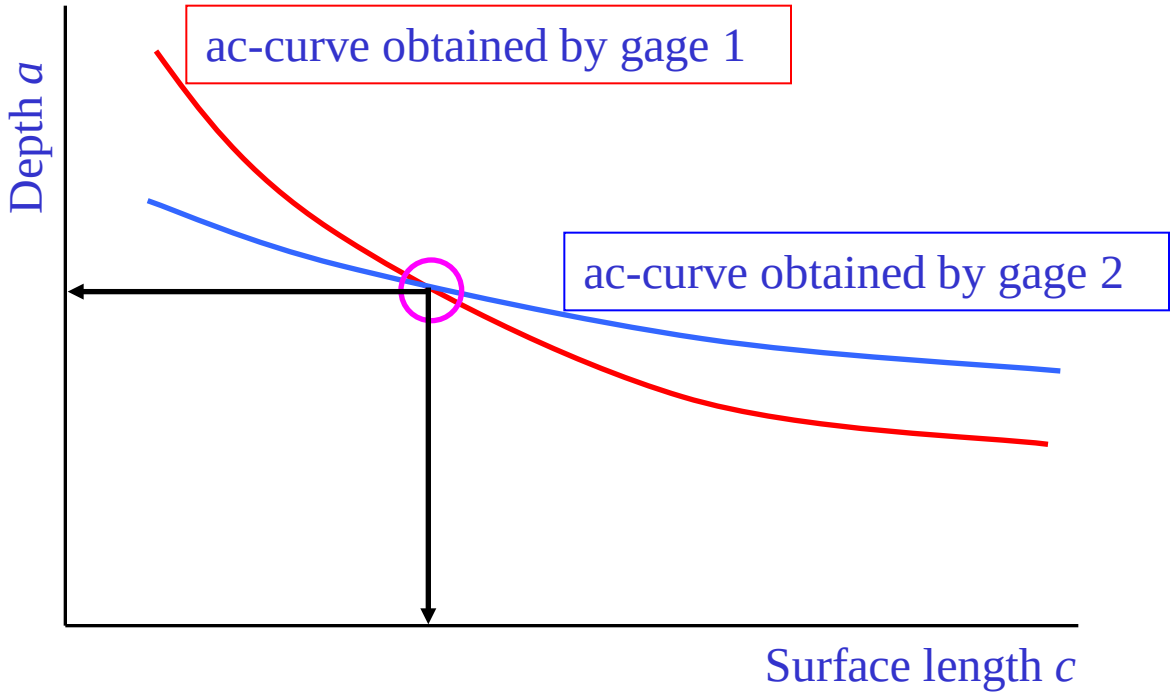
- Development of multiple strain measurement technique

Outline

- Introduction
- Basic concept of OS-monitoring method
- **Multiple strain measurement technique**
- Experimental validation
  - Crack size identification
  - Monitoring of fatigue crack growth

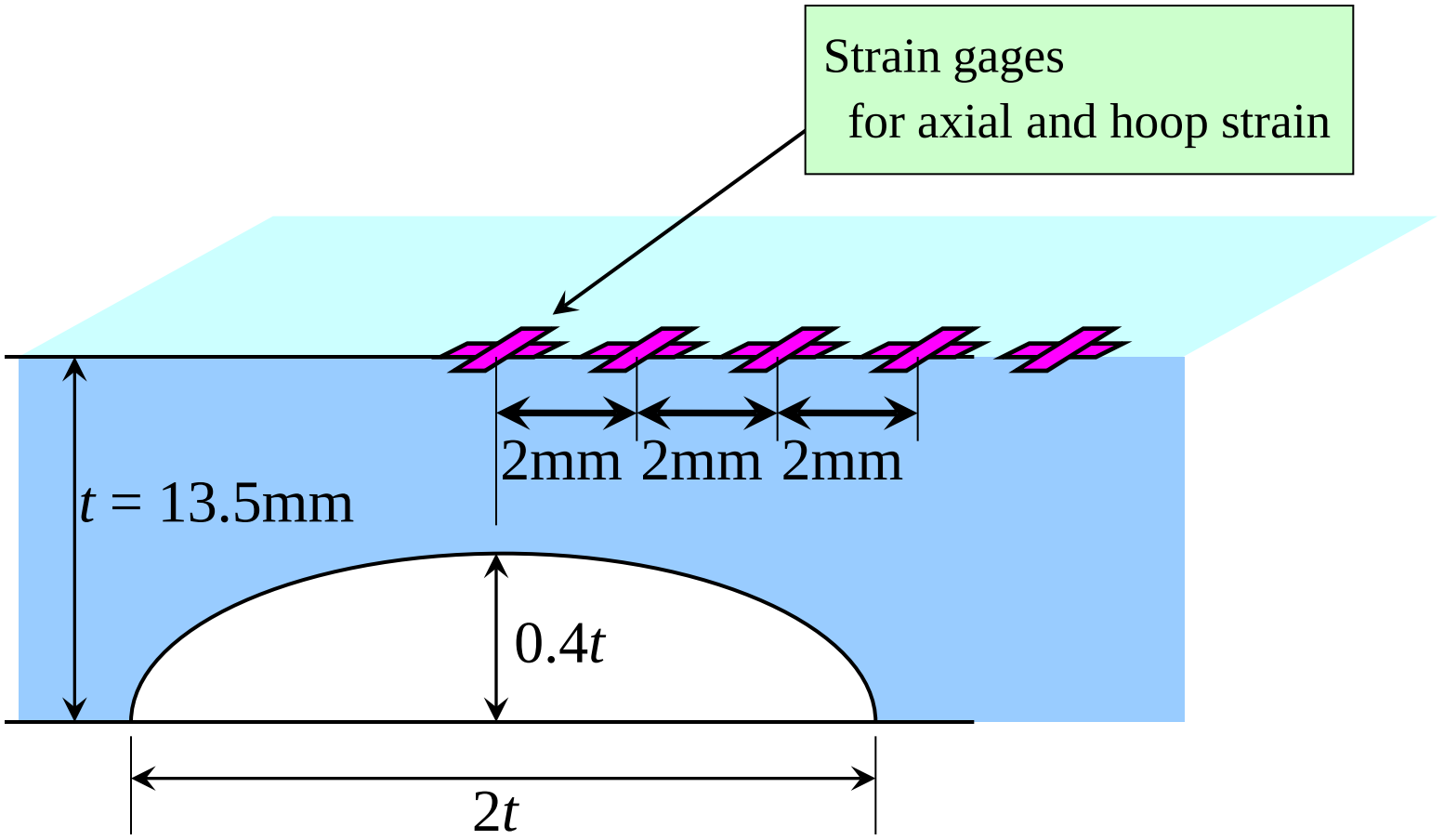
Multiple strain measurement technique

- Combination of depth (a) and surface length ($2c$) is obtained from single strain measurement (referred to as “ac-curve”)
- The crossing point from two strain measurements corresponds to the crack size of the interest



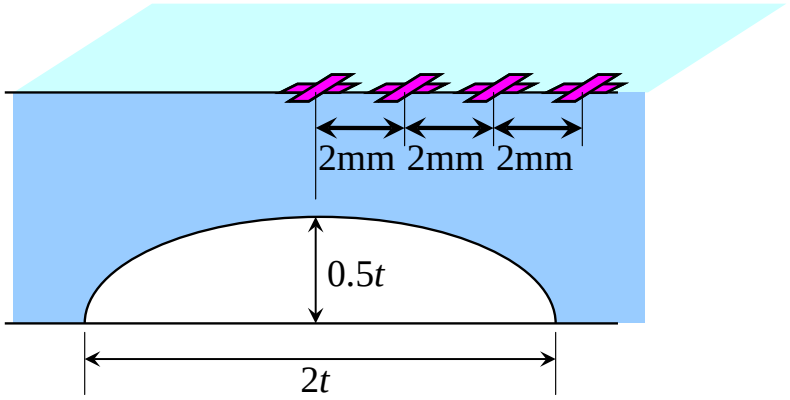
Example of multiple measurement technique (1/2)

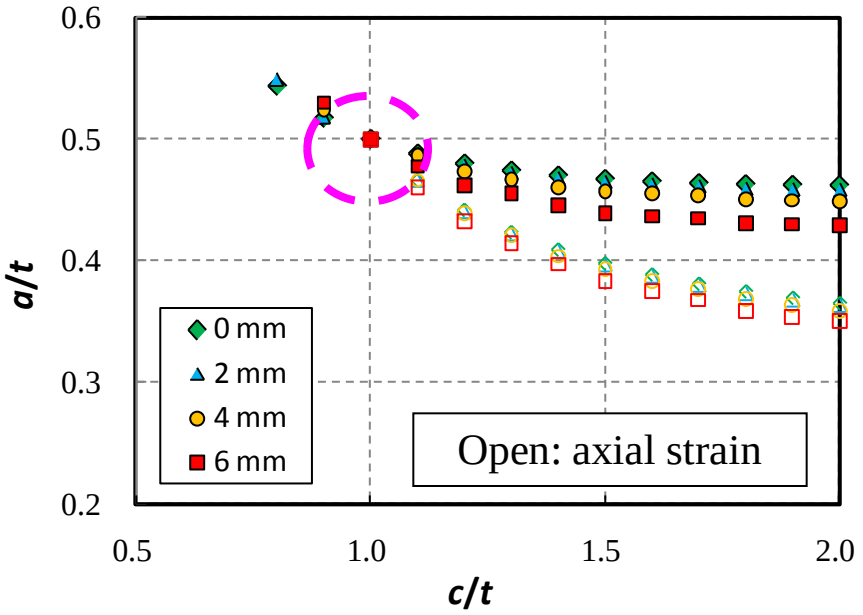
- Circumferential crack（$a = 0.5t$, $2c = 2t$）
- Strain gages were attached every 2 mm from the center



Example of multiple measurement technique (2/2)

- Both depth and surface length was identified
- Accuracy could be improved by taking the average of the estimated sizes



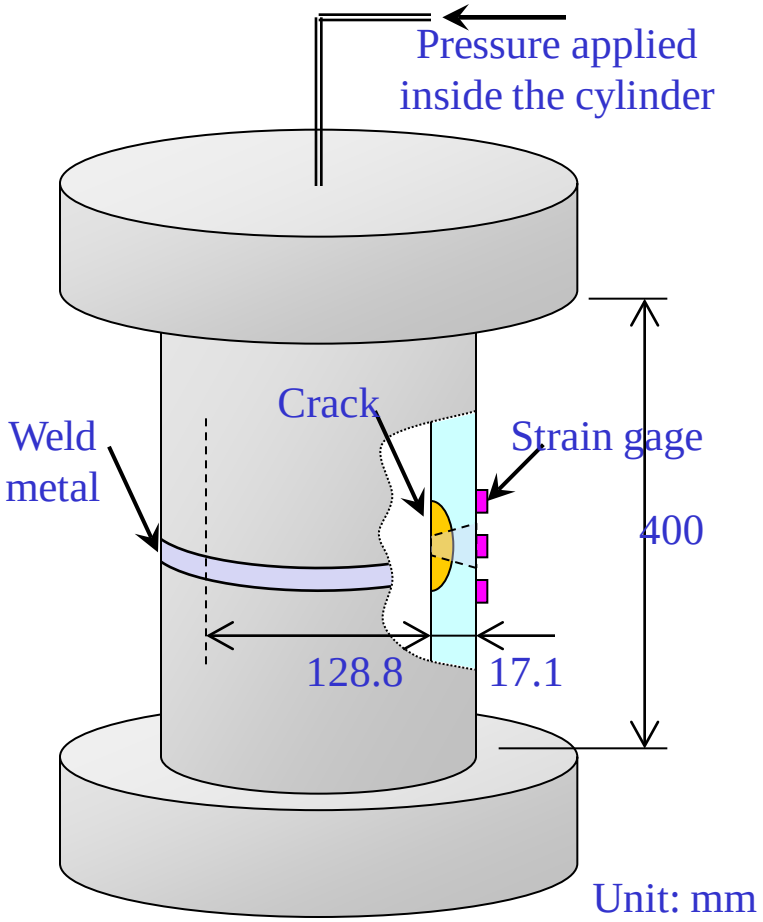


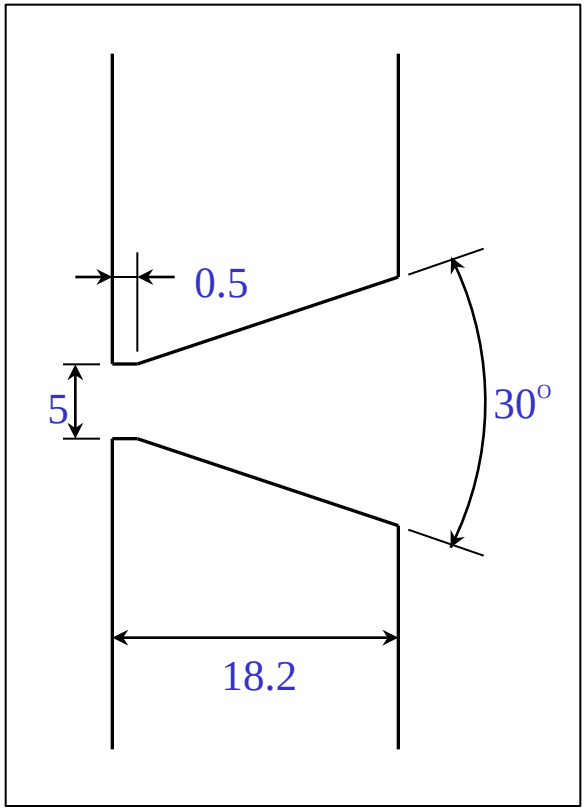
Outline

- Introduction
- Basic concept of OS-monitoring method
- Multiple strain measurement technique
- **Experimental validation**
  - Crack size identification
  - Monitoring of fatigue crack growth

Experimental validation

- Pressurized pipe with an axial crack
- Machined notch was introduced at welding portion
- Fatigue cracking was initiated and propagated by cyclic internal pressure

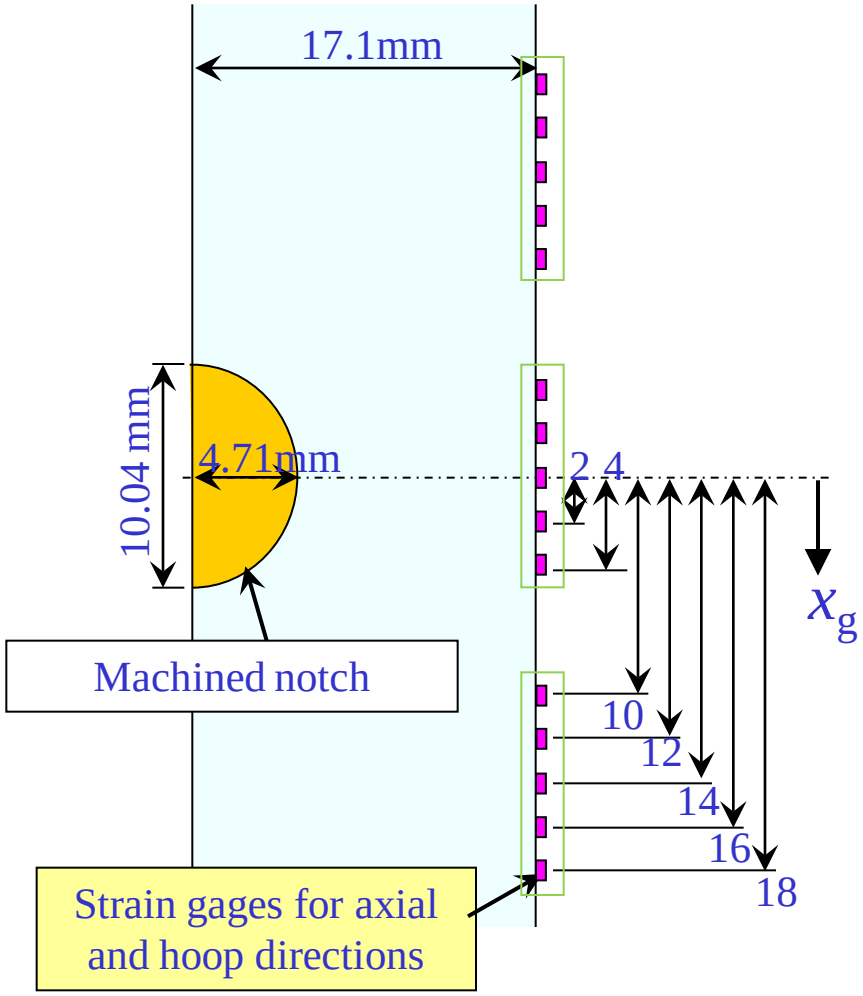


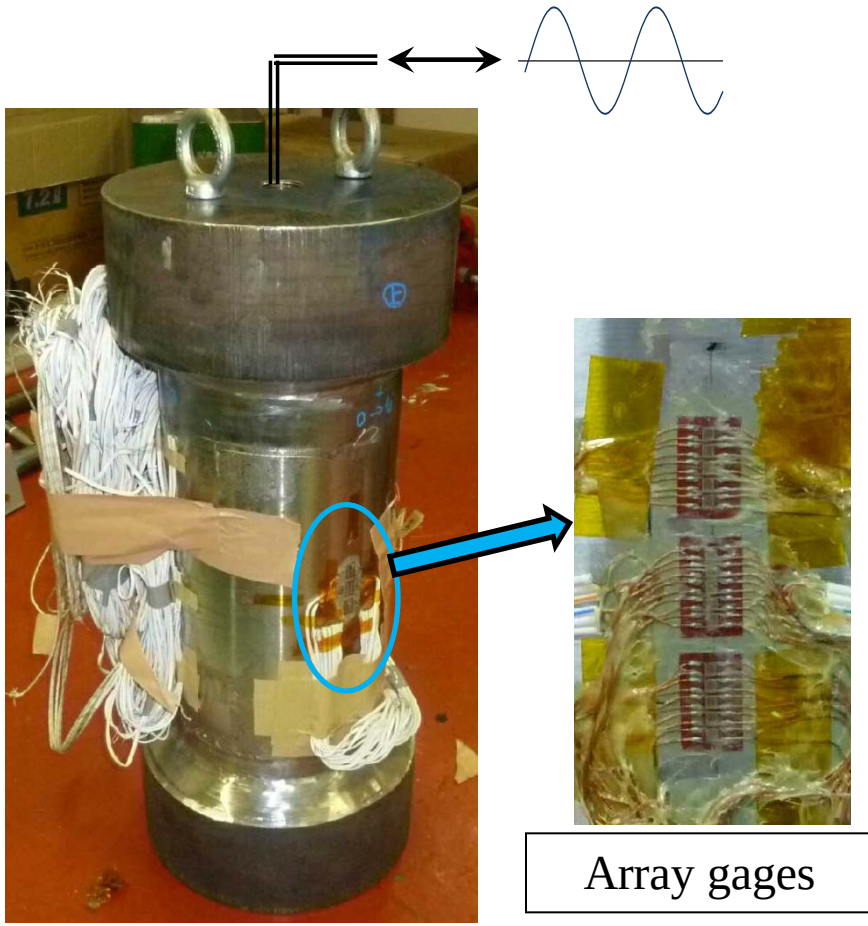


Geometry of welding groove

Strain measurements

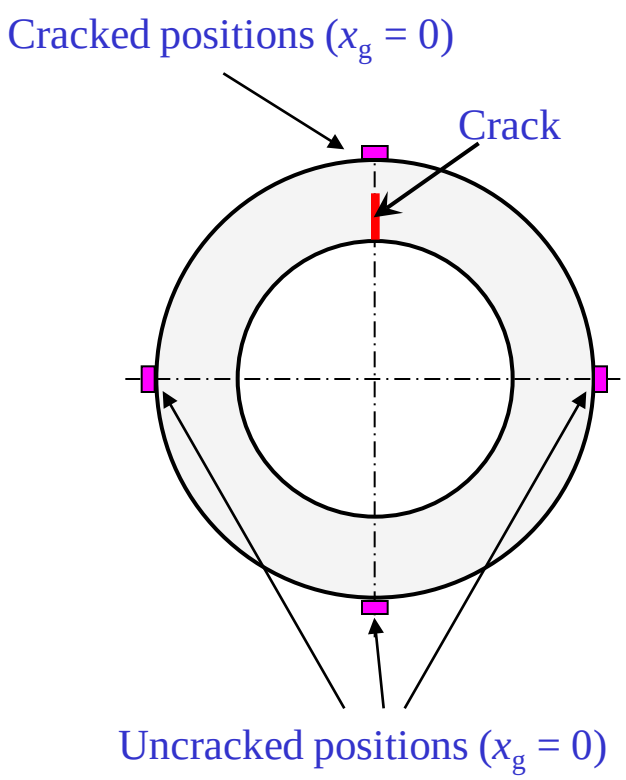
- Array gages (5 bi-axial gages) was used

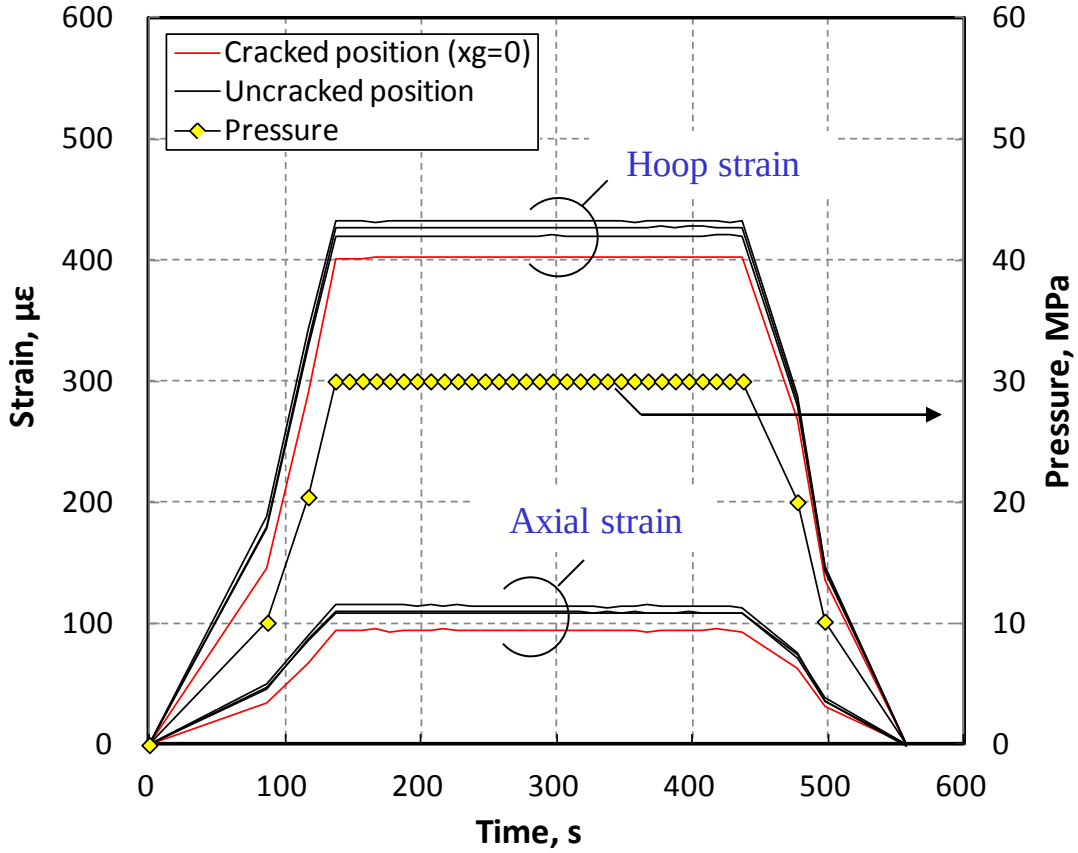




Strain measurements

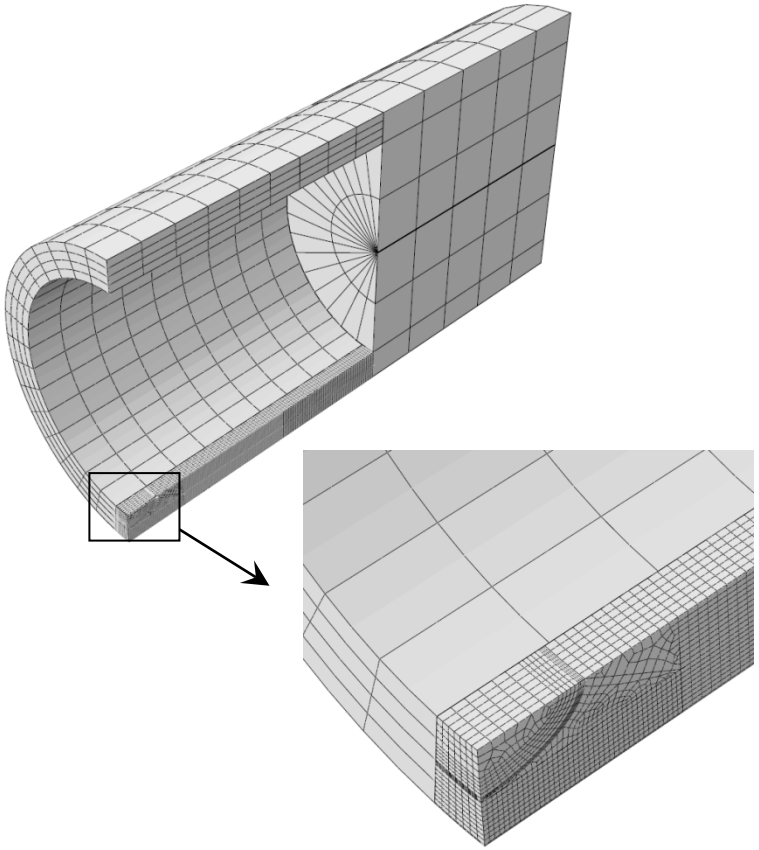
- Stain is reduced by internal crack

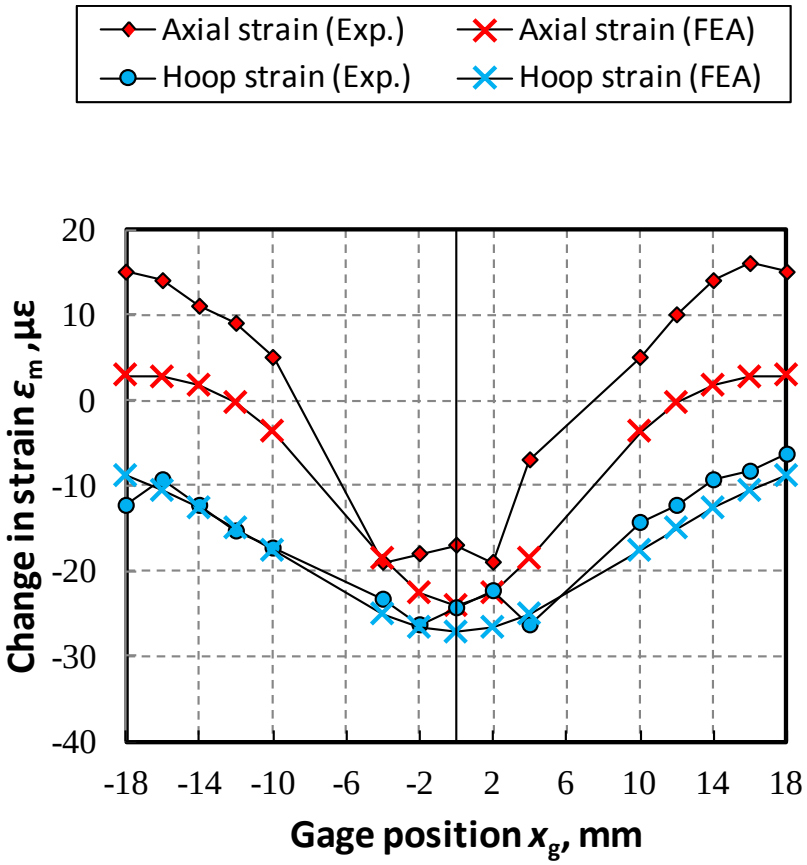




Expected strains

- Database for strain was developed by finite element analyses
  - Crack size: 486 cases

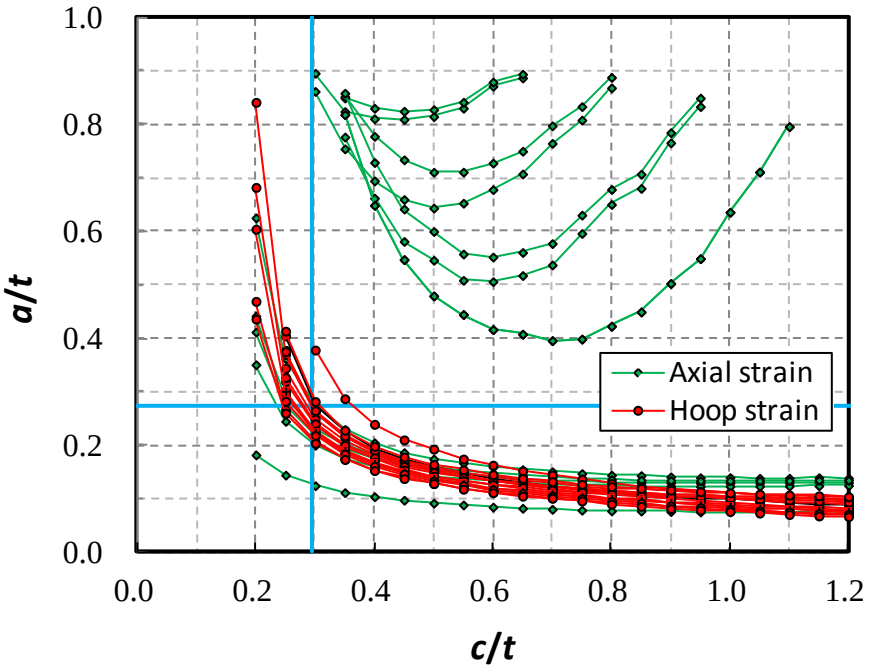




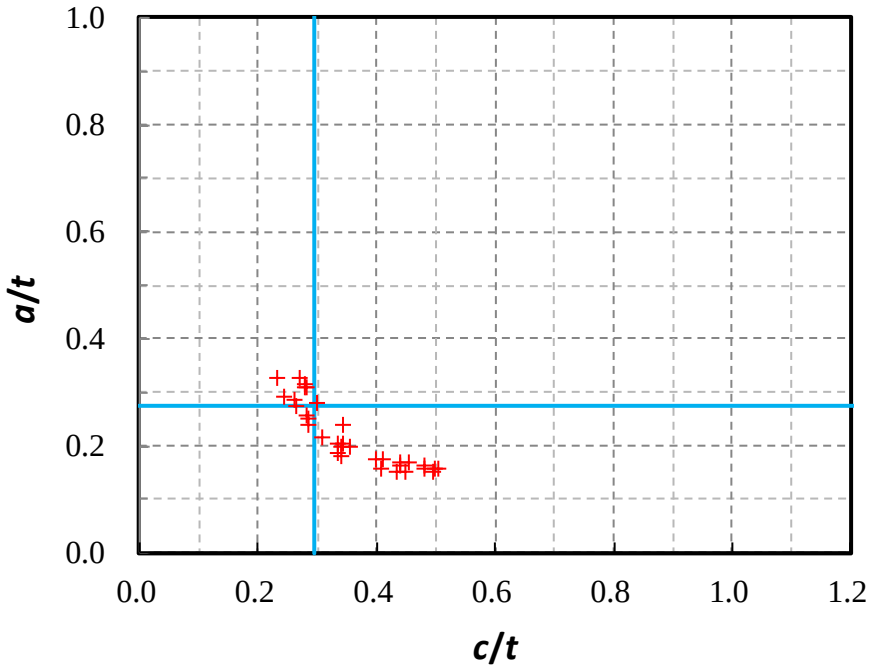
Strains measured and expected strain by FEAs

Possible combinations of "*a*" and "*c*"

- The size of machined notch was estimated
- Crossing point was derived as the estimated crack size
- Multiple results from multiple crossing points (no. of crossing point: 33)



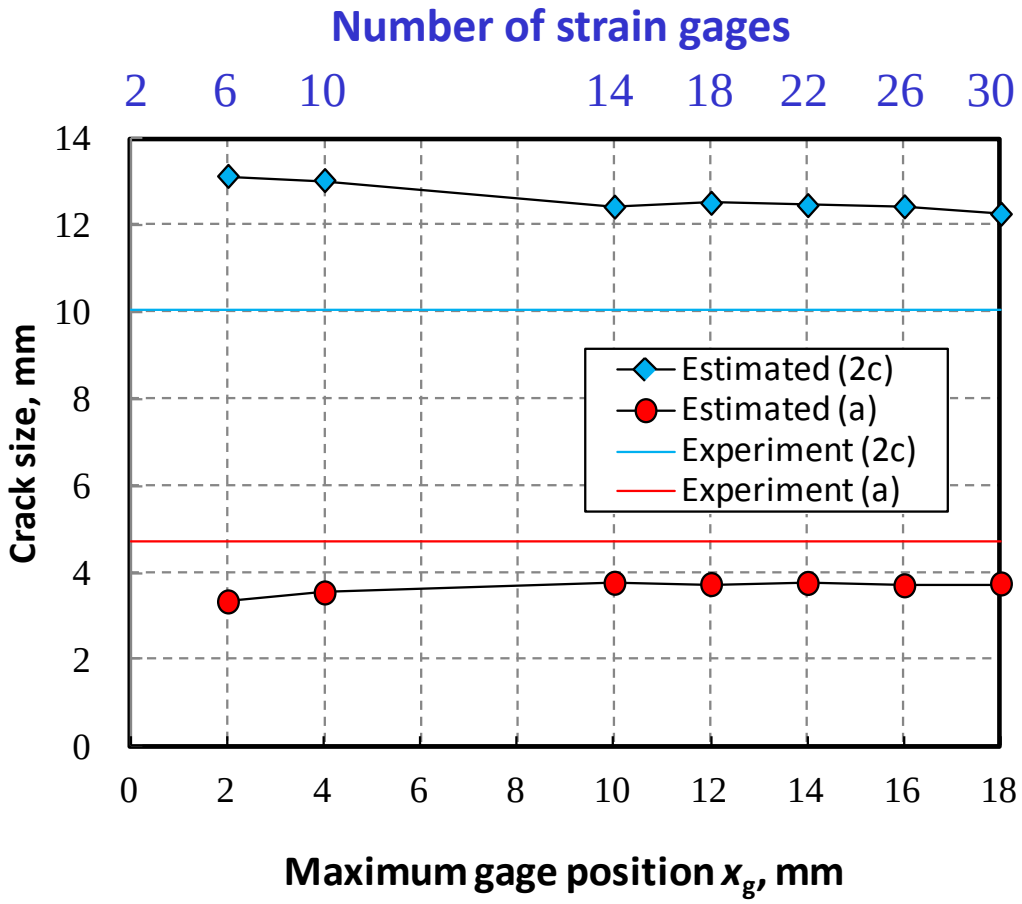
Ac-curves from measured strains

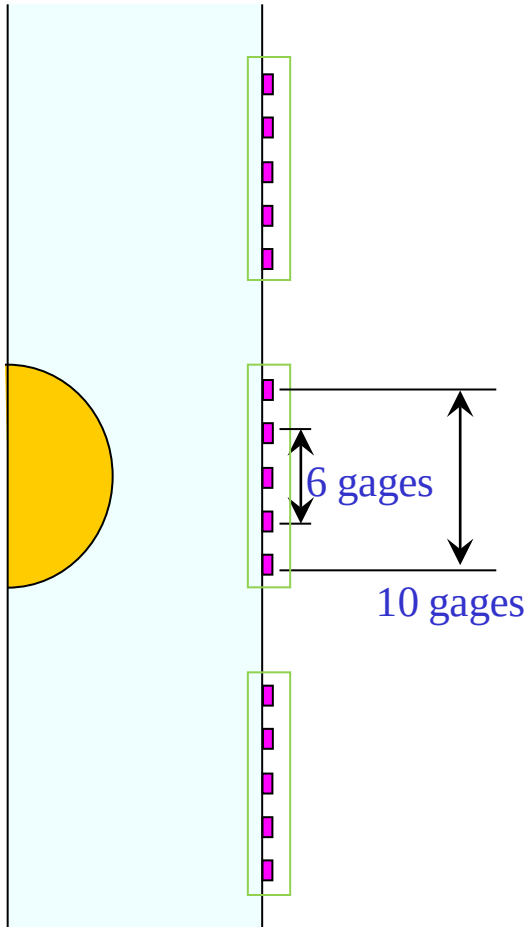


Estimated crack sizes (crossing points)

Effect of number of strain gages

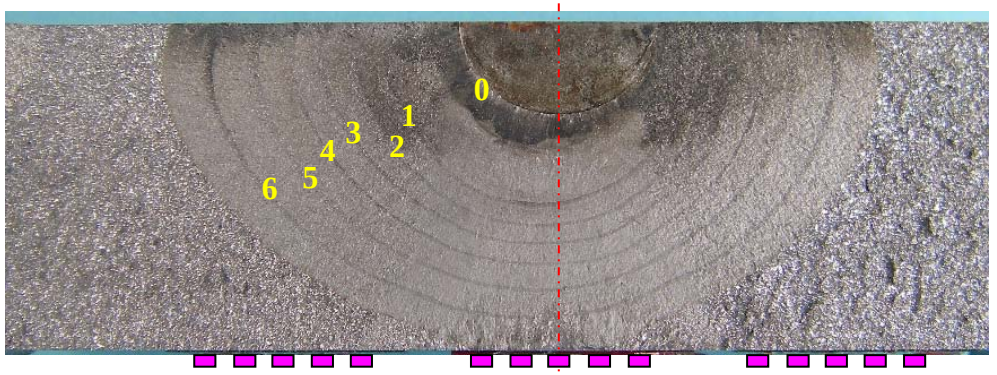
- Accuracy of size estimation improved by increasing the number of strain gages



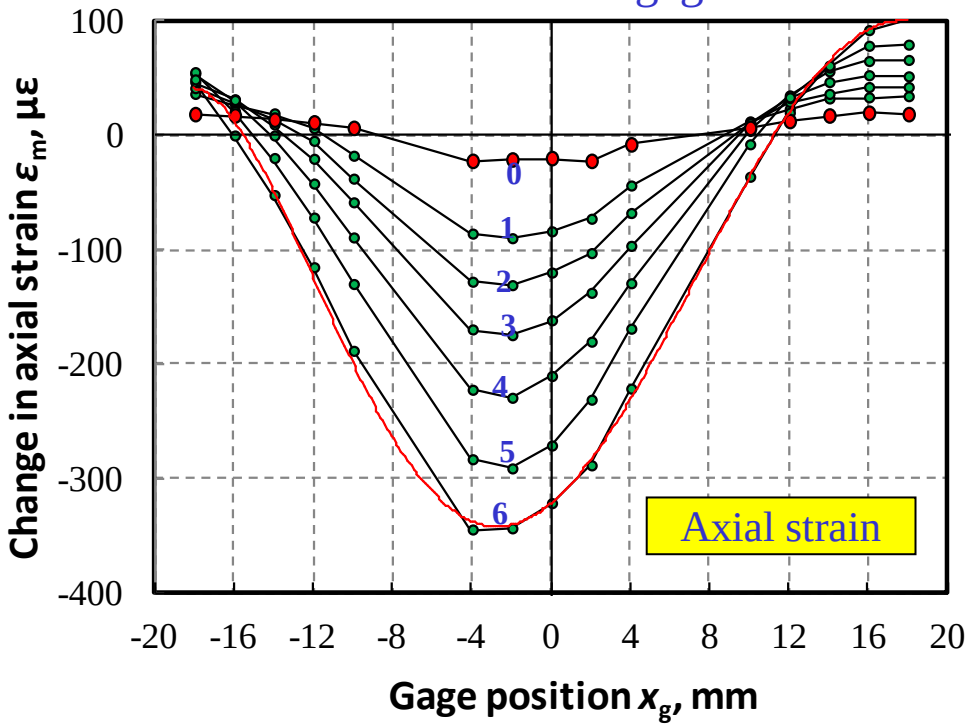


Crack growth by cyclic internal pressure

- Fatigue crack were initiated from machined notch and propagated
- Beach marks introduced in order to identify the crack size

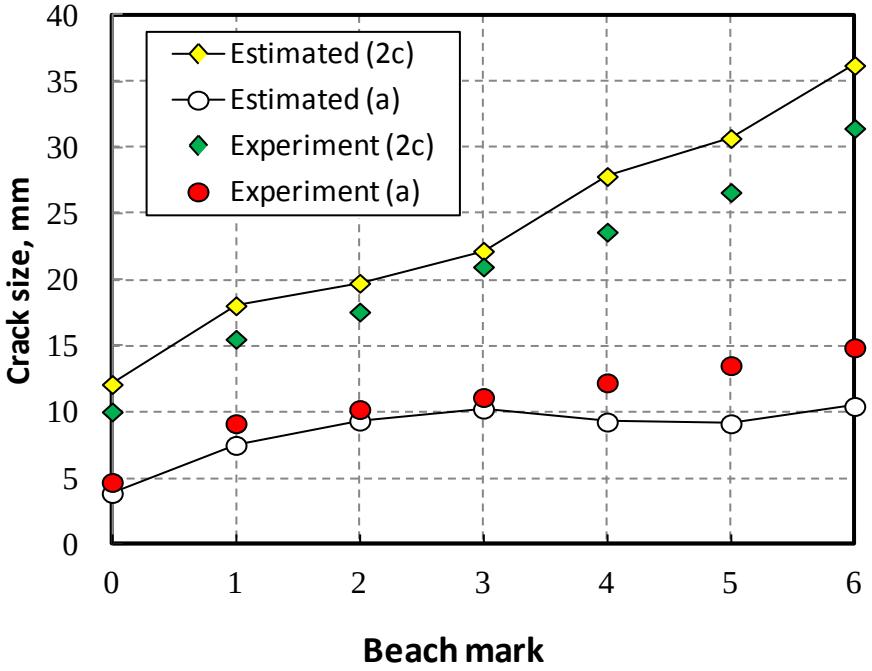


Position of strain gages

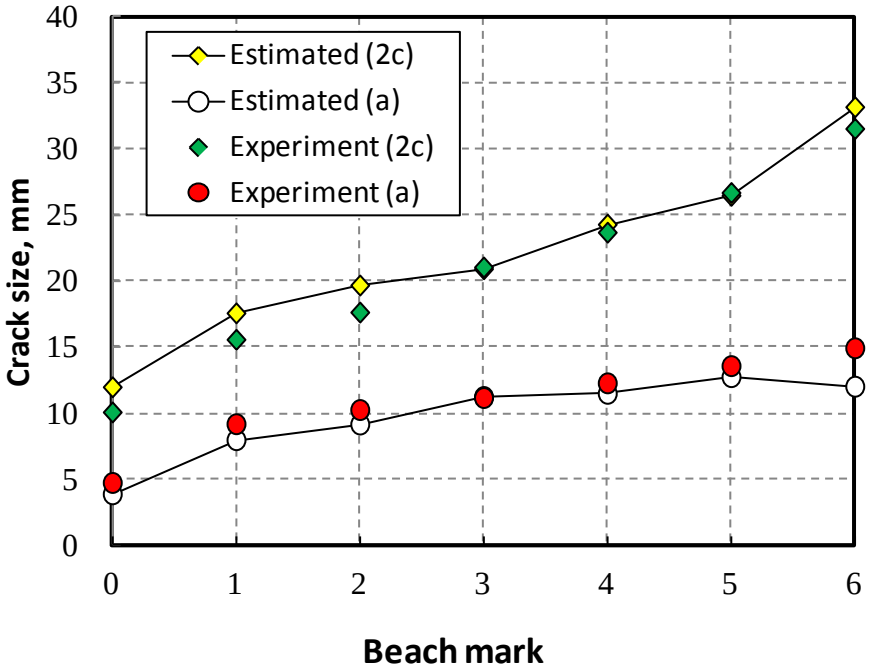


Estimation of crack size

- Change in crack size was successfully identified
- Weights in the averaging of estimated crack sizes from crossing points
  - Significant improvement of estimation accuracy



w/o considering weights for averaging



Consider weights for averaging

Conclusions

- It is possible to monitor the crack growth by measuring external strain of cracked pipe.
  - Both circumferential and axial crack can be monitored.
  - The error in estimation is expected to be less than 0.28 mm for 1 mm growth in the depth direction.

- Characteristics of OS-monitoring
  - Completely non-destructive
  - Simple and less expensive
  - Accuracy of monitoring can be improved by measuring multiple strains