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# Development of C-Ring Geometry to Explore Fatigue Crack Extension and Verification in High-Pressure Vessels

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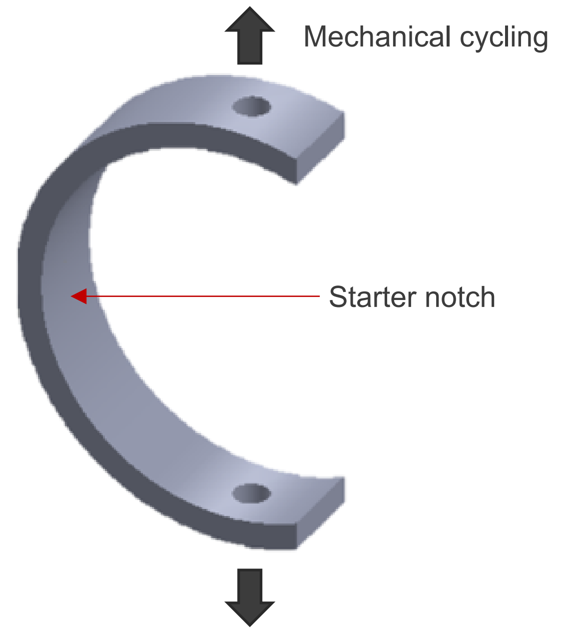
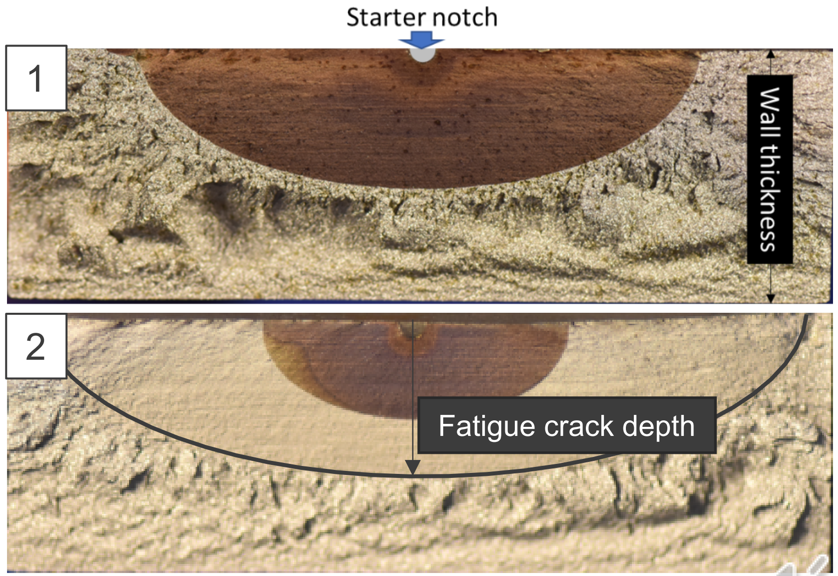
# Outline

- Background and motivation
- Sample design and test methods
- Experimental results and comparison with simulated crack growth
- Summary and conclusions

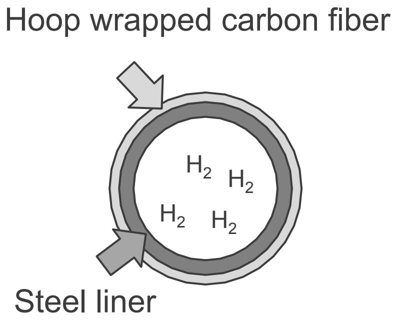


# Motivation: Avenues for Life Extension of Pressure Vessels

- High pressure hydrogen storage vessels, such as those used at hydrogen refueling stations, are retired upon reaching their designed number of pressure cycles
  - Design cycle life is defined in User's Design Specification (UDS) based on pressure range

- One avenue for extending the life of hydrogen vessels is recertification through non-destructive evaluation (NDE)
  - Currently no commercially available means to perform NDE on Type 2 vessels, therefore vessels are retired

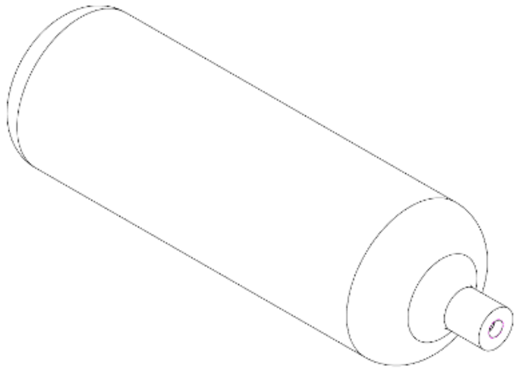



Type 2 vessels are commonly used at Hydrogen Refueling Stations (HRS)

# Motivation: Avenues for Life Extension of Pressure Vessels

- Goal: Development of a representative NDE sample/methodology that can:
  - ➢ Develop fatigue cracks to prescribed depths
  - ➢ Provide NDE calibration data based on sharp fatigue cracks (as opposed to machined notches)
  - ➢ Provide a testing platform to simulate compressive residual stresses induced by autofrettage or proof testing

- The scope of this paper includes the development and analysis of a representative NDE sample from a type 1 pressure vessel
  - ➢ NDE validation and calibration is planned but not discussed in this presentation

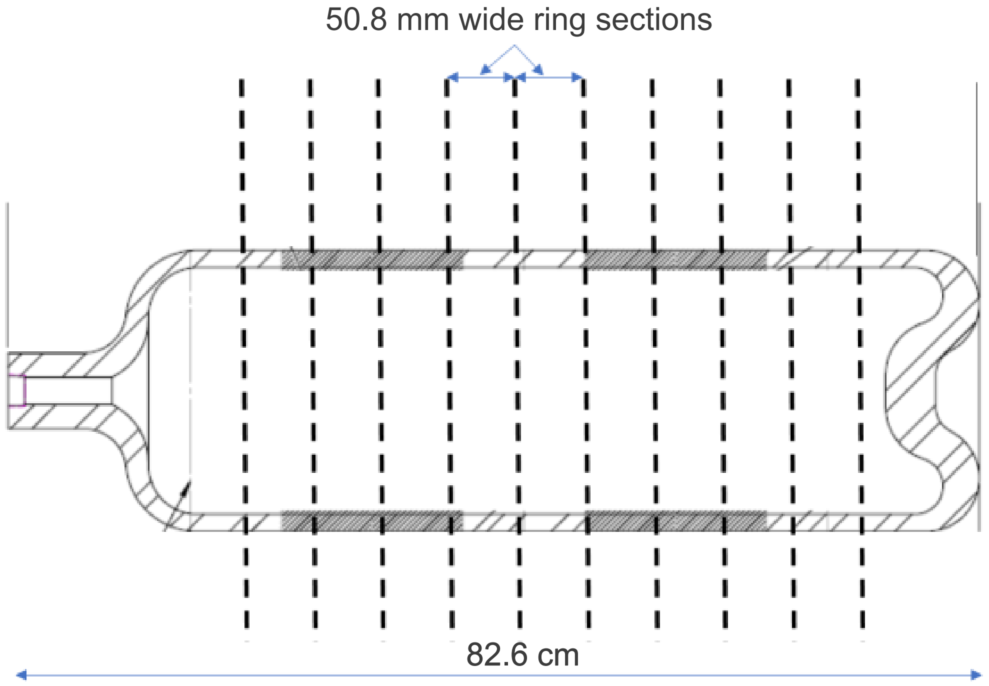


Schematic of type 1 pressure vessel (above) and ring section extracted from a type 1 vessel (below)

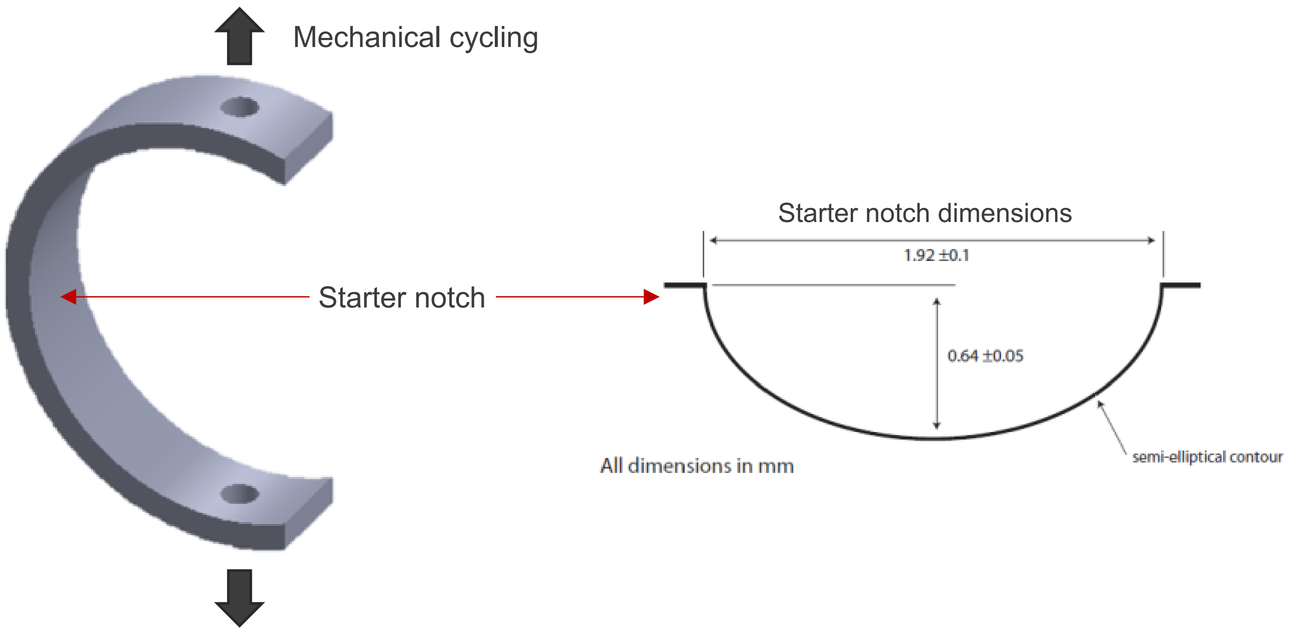
OD = 238mm
t = 14.5mm

# Material and C-ring Sample Design

**Type 1 Pressure Vessel**




**C-ring Sample Geometry**




- C-ring samples were machined by extracting ring sections from an all-steel transportable pressure vessel (type 1)
  - Sides of the ring sections were removed (giving the sample a “C” shape) and ¾’’ bolt holes were added to allow for mechanical cycling or static loading during NDE
- Starter notches were added (plunge EDM) to ensure crack growth initiated at the center of the C-ring samples

# Crack Growth Monitoring through DCPD and Backface Strain

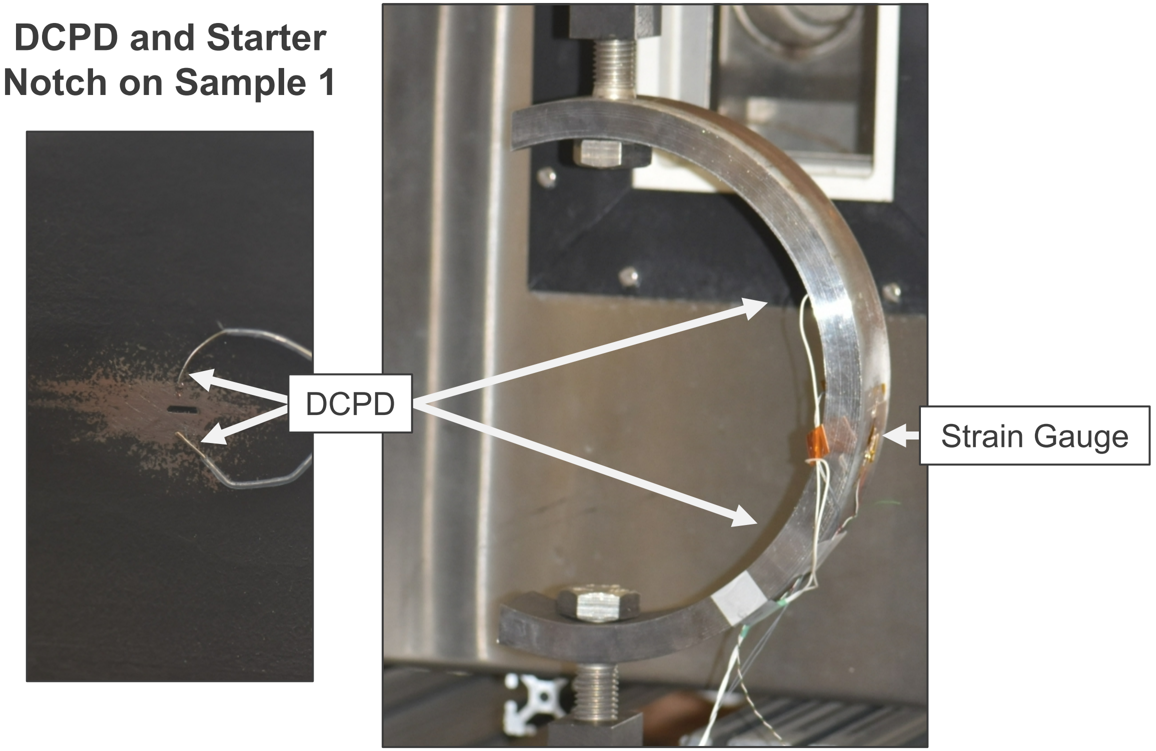
- To monitor crack growth, C-ring samples were instrumented with:
  - Direct current potential difference (DCPD)
  - Backface strain gauge

- Post-fatigue, samples were submerged in $LN_2$ and fractured open

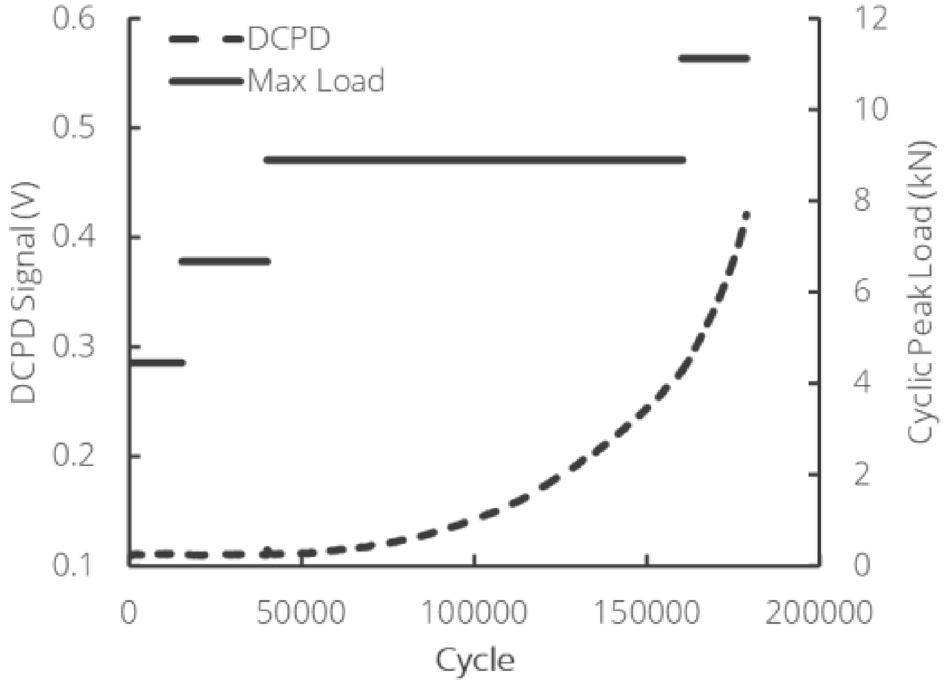
- Heat tinting (275°C / 30 min) was utilized to mark fatigue crack growth at specific stages of the test

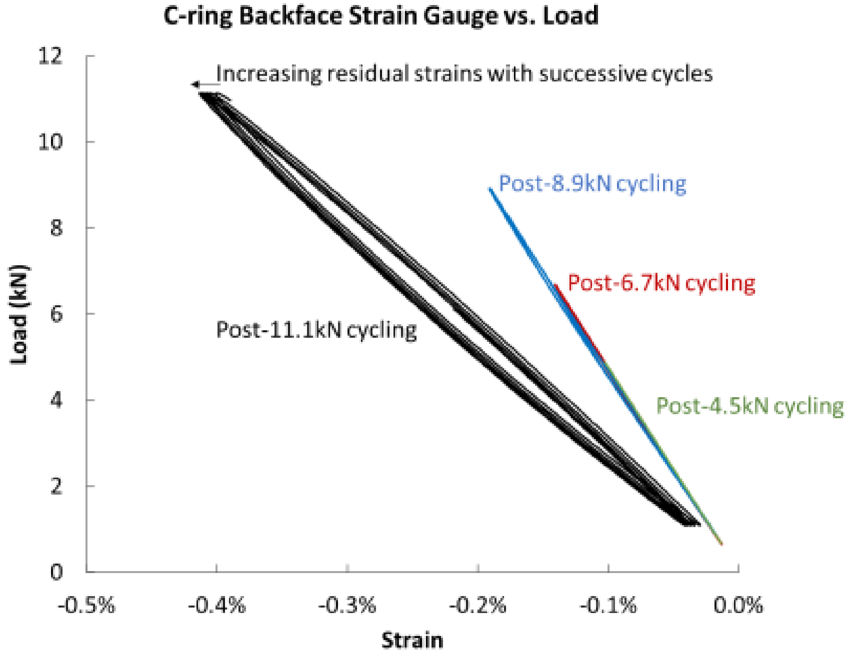
**DCPD and Starter Notch on Sample 1**

**C-ring Sample 1 on Load Frame**



# Fatigue Cycling at Increasing Maximum Loads

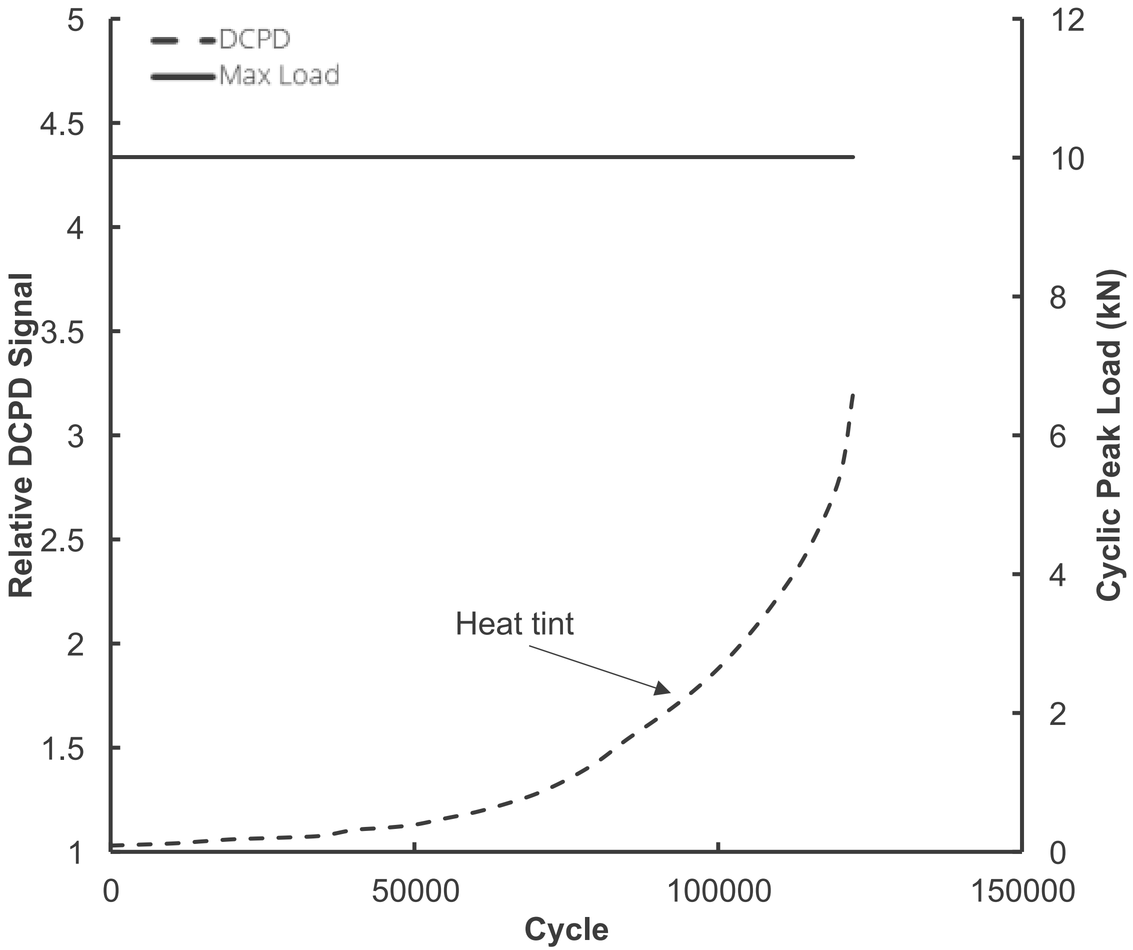



- Two C-ring samples were mechanically cycled to induce fatigue crack growth
  - R = 0.1 (Min/Max load)
  - Both DCPD and backface compliance (slope of the load-strain curve) monitored throughout tests
- Loads below 8.9kN (2000 lbf) had minimal effect on the measured compliance and DCPD
- Higher loads resulted in crack propagation, as indicated by the increasing DCPD and compliance

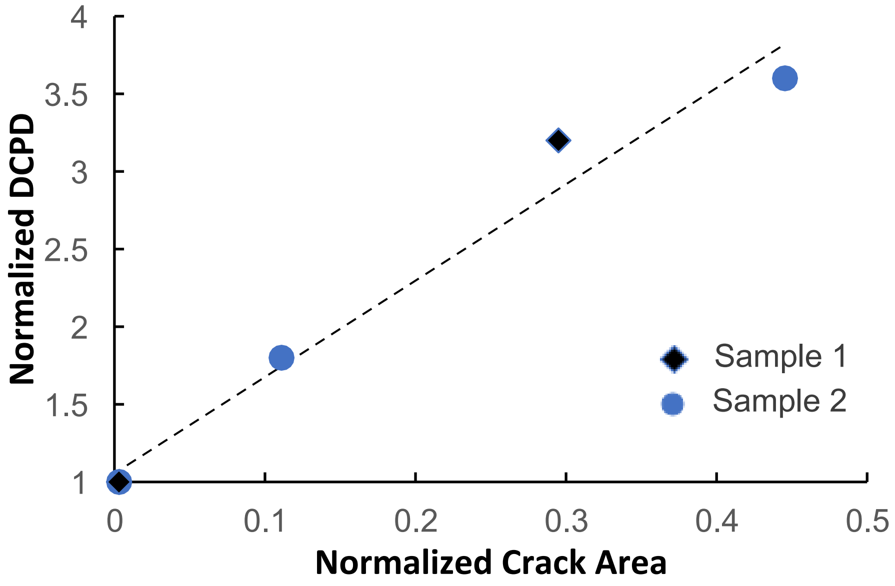
# Fatigue Crack Growth at Constant (10kN) Max Load

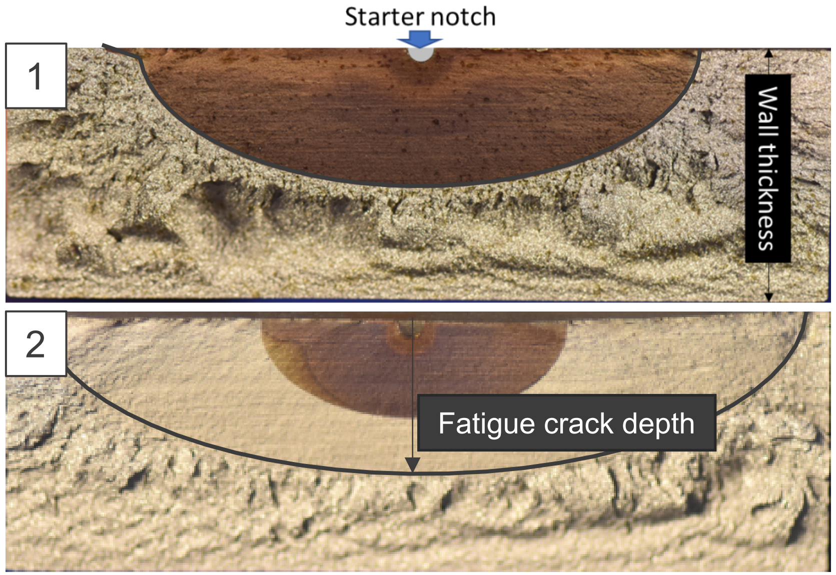
- A second C-ring sample was cycled with a peak load of 10kN (2250 lbf) and R = 0.1
- The measured DCPD can be seen to increase at the beginning of the test, indicating the immediate onset of crack growth
  - ➢ The test was interrupted for heat tinting after the relative DCPD (measured/initial) reached a value of 2, which happened after ~100,000 cycles



# Linear Trend Observed between DCPD and Crack Area

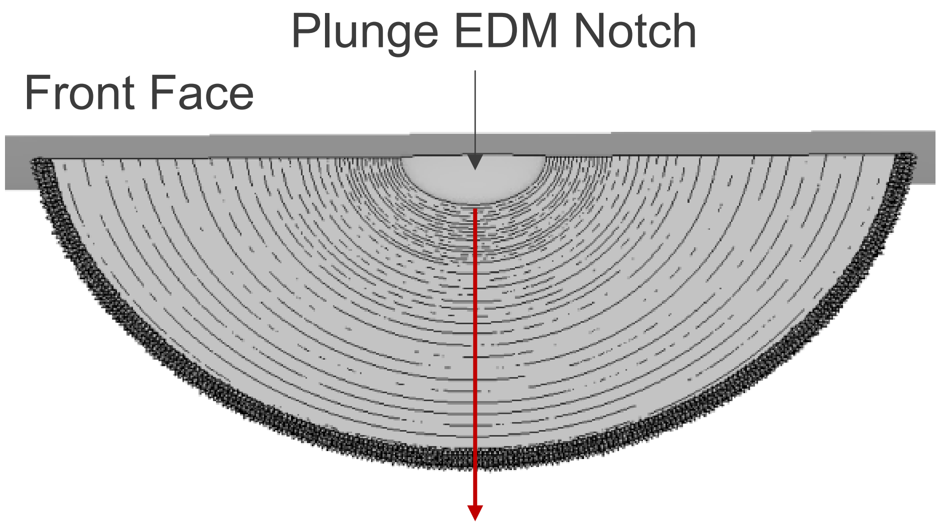
- The DCPD (normalized by the initial measurement) was found to increase approximately linearly for increasing crack areas (normalized by cross-sectional area)
  - ➢ The linear estimation (dashed line) is fit to experimental data from both samples
  - ➢ Heat tinting during testing of sample 2 allowed for the collection of an additional data point

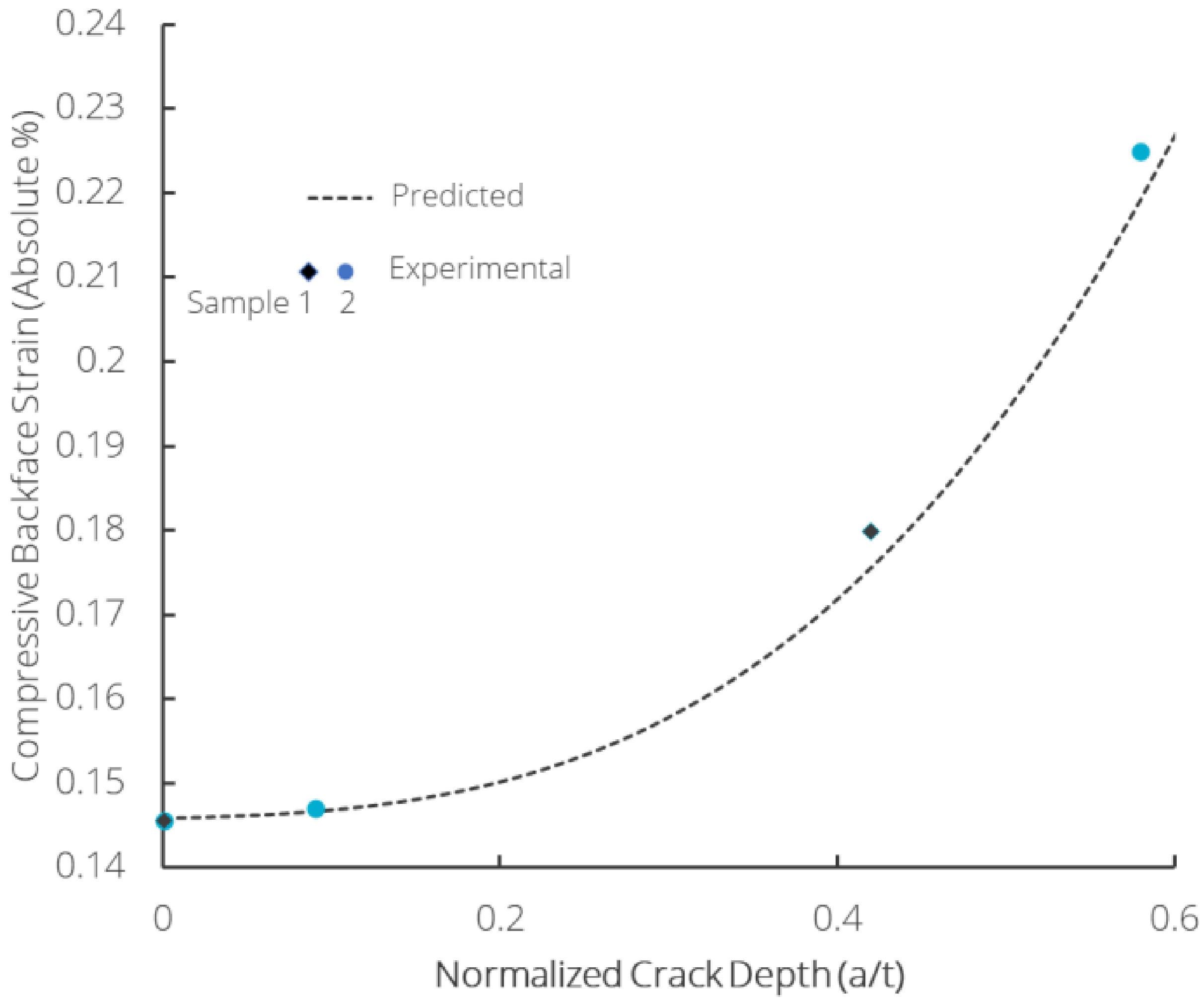


# Comparison of Modeling and Experimental Backface Strains

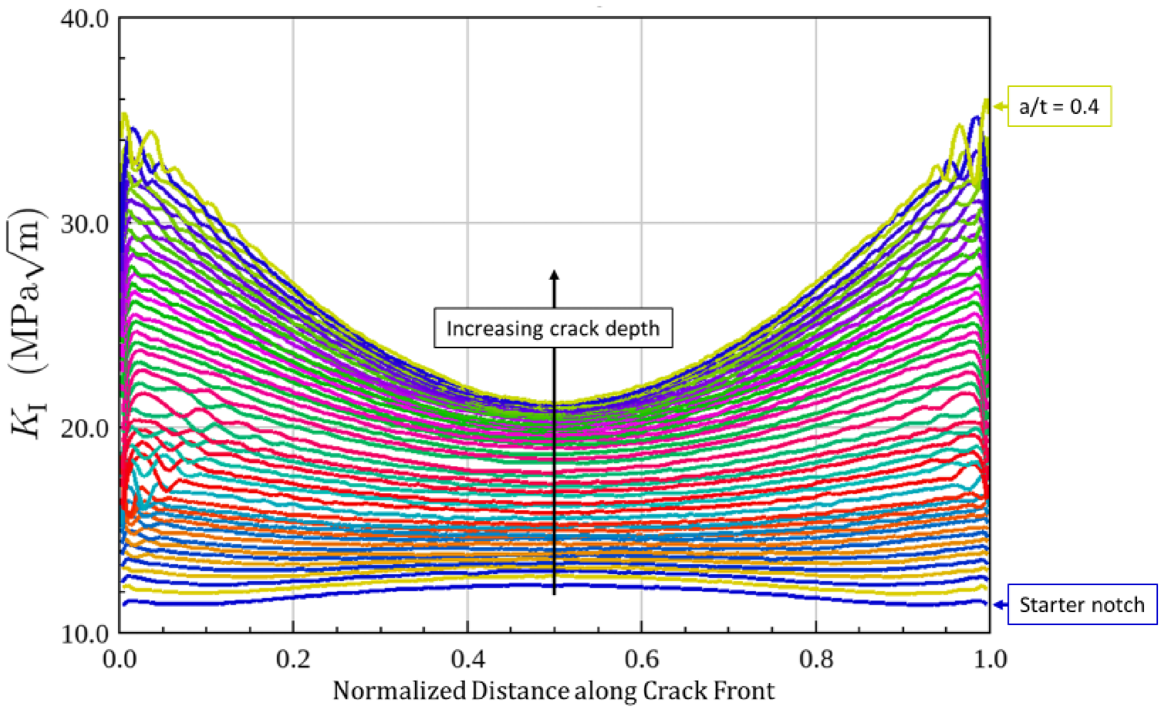
- Simulations were performed to better understand the crack propagation and provide a relationship between the crack depth (a/t) and the measured strain on the backface of the C-ring samples
  - ➢ Simulations performed with Sierra/SM and FRANC3D



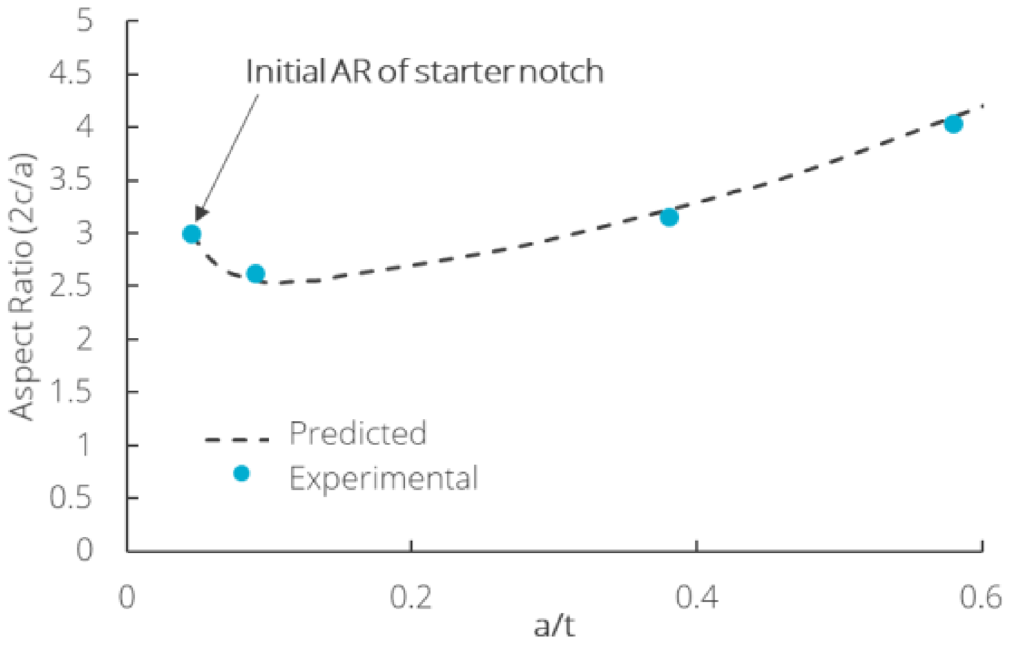




**Compressive backface strain at a load of 6.7kN vs. crack depth**

# Model Predicts Evolution of Crack Geometry




**$K_I$ vs. position along crack front at a load of 6.7kN**



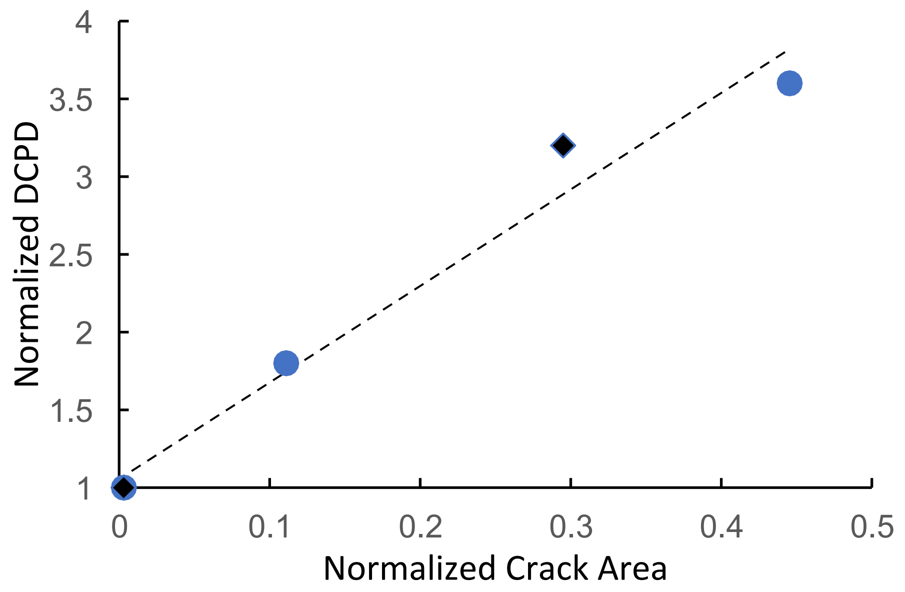

**Aspect ratio of crack (width/depth) vs. normalized crack depth**

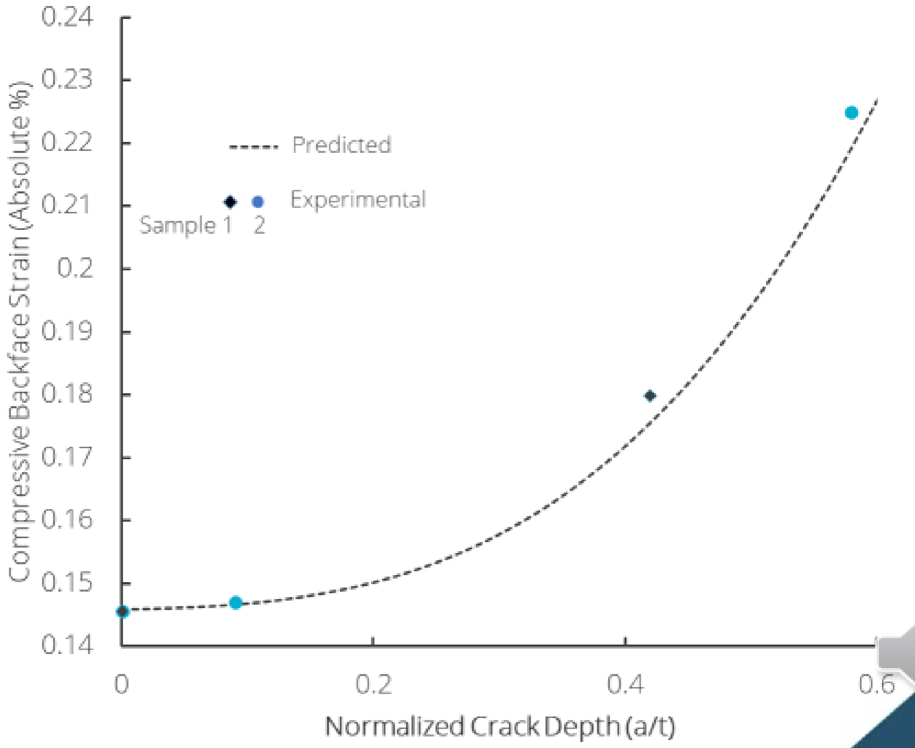
- Initially, the maximum stress intensity factor ($K_I$) is located at the center (deepest portion) of the crack
- As the crack propagates deeper into the sample, the stress intensity factor becomes higher on the edges
  - ➢ This is due to the bending nature of the applied mechanical load, which induces compressive stresses at the backface

# Summary and Conclusions

- C-ring specimens were extracted from a type 1 pressure vessel and mechanically cycled to induced fatigue crack growth

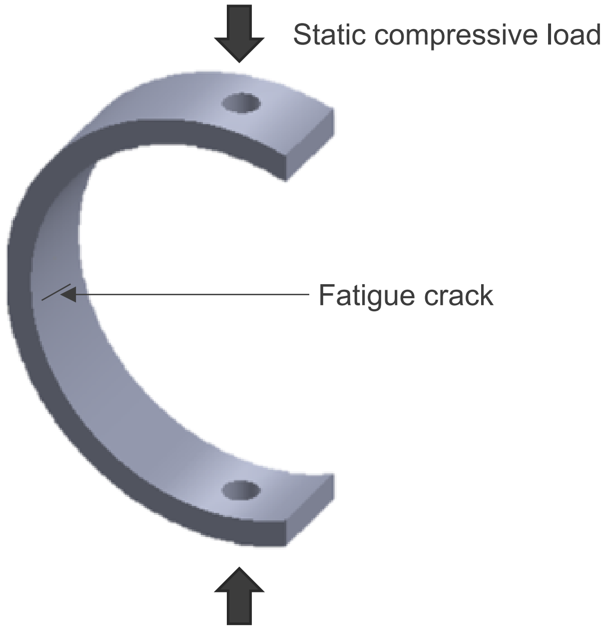
- Both DCPD and backface strain were found to be good indicators of crack area and depth (respectively)
  - ➢The measured DCPD varied approximately linearly with crack area



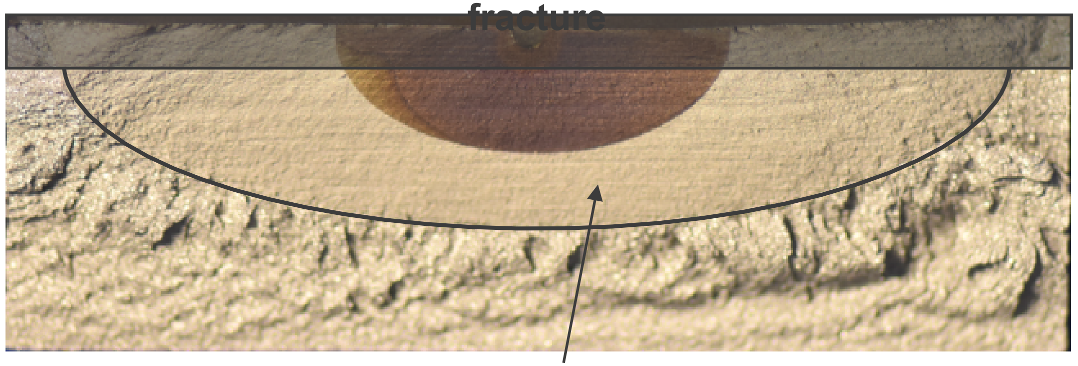



# Summary and Conclusions

- Using this C-ring geometry, cracks could be extended to prescribed flaw depths, which could then be inspected via NDE methods (e.g., eddy current)
  - The machined notch could be removed via grinding or polishing so that only the fatigue crack remains
  - After NDE, the C-ring can be heat tinted and fractured open to calibrate the NDE measurements with the true crack size
- The unique nature of the C-ring allows for either static compressive or tensile loading such that flaws could be scanned concurrent with applied stresses
  - Such as those that represent residual stresses from proof testing or autofrettage




**Sample 2 cross-section post fracture**



**Remaining fatigue cracked region if the machined notch was removed**

Thank you for your attention!

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