FY 2016 Status Report: CIRFT Testing Data Analyses and Updated Curvature Measurements

Fuel Cycle Research & Development

Prepared for
US Department of Energy
Used Fuel Disposition Campaign

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SUMMARY

This report provides a detailed description of FY15 test result corrections/analysis based on the FY16 Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) test program methodology update used to evaluate the vibration integrity of spent nuclear fuel (SNF) under normal transportation conditions. The CIRFT consists of a U-frame testing setup and a real-time curvature measurement method. The three-component U-frame setup of the CIRFT has two rigid arms and linkages to a universal testing machine. The curvature of rod bending is obtained through a three-point deflection measurement method. Three linear variable differential transformers (LVDTs) are used and clamped to the side connecting plates of the U-frame to capture the deformation of the rod.

The contact-based measurement, or three-LVDT-based curvature measurement system, on SNF rods has been proven to be quite reliable in CIRFT testing. However, how the LVDT head contacts the SNF rod may have a significant effect on the curvature measurement, depending on the magnitude and direction of rod curvature. It has been demonstrated that the contact/curvature issues can be corrected by using a correction on the sensor spacing. The sensor spacing defines the separation of the three LVDT probes and is a critical quantity in calculating the rod curvature once the deflections are obtained.

The sensor spacing correction can be determined by using chisel-type probes. The method has been critically examined this year and has been shown to be difficult to implement in a hot cell environment and thus cannot be implemented effectively. A correction based on the proposed equivalent gauge-length has the required flexibility and accuracy and can be appropriately used as a correction factor.

The correction method based on the equivalent gauge length has been successfully demonstrated in CIRFT data analysis for the dynamic tests conducted on Limerick (LMK) (17 tests), North Anna (NA) (6 tests), and Catawba mixed oxide (MOX) (10 tests) SNF samples. These CIRFT tests were completed in FY14 and FY15. Specifically, the data sets obtained from measurement and monitoring were processed and analyzed. The fatigue life of rods has been characterized in terms of moment, curvature, and equivalent stress and strain.
ACKNOWLEDGMENTS

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AP</td>
<td>alumina pellets</td>
</tr>
<tr>
<td>BWR</td>
<td>boiling water reactor</td>
</tr>
<tr>
<td>CIRFT</td>
<td>Cyclic Integrated Reversible-Bending Fatigue Tester</td>
</tr>
<tr>
<td>DOE</td>
<td>US Department of Energy</td>
</tr>
<tr>
<td>FCRD</td>
<td>Fuel Cycle Research &amp; Development</td>
</tr>
<tr>
<td>FEA</td>
<td>finite-element analysis</td>
</tr>
<tr>
<td>FY</td>
<td>fiscal year</td>
</tr>
<tr>
<td>GWd/MTU</td>
<td>gigawatt-days per metric ton of uranium</td>
</tr>
<tr>
<td>HBR</td>
<td>H. B. Robinson Nuclear Power Station</td>
</tr>
<tr>
<td>HBU</td>
<td>high burn-up</td>
</tr>
<tr>
<td>ID</td>
<td>identification numbers</td>
</tr>
<tr>
<td>LMK</td>
<td>Limerick Nuclear Power Station</td>
</tr>
<tr>
<td>LVDT</td>
<td>linear variable differential transformer</td>
</tr>
<tr>
<td>MOX</td>
<td>mixed uranium-plutonium oxide</td>
</tr>
<tr>
<td>NA</td>
<td>North Anna Power Station</td>
</tr>
<tr>
<td>NCT</td>
<td>normal conditions of transport</td>
</tr>
<tr>
<td>NRC</td>
<td>US Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>NUREG</td>
<td>Nuclear Regulatory Commission technical report</td>
</tr>
<tr>
<td>NUREG/CR</td>
<td>NUREG contractor report</td>
</tr>
<tr>
<td>OD</td>
<td>outer diameter</td>
</tr>
<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
</tr>
<tr>
<td>PCI</td>
<td>peripheral component interconnect</td>
</tr>
<tr>
<td>PIE</td>
<td>post-irradiation examination</td>
</tr>
<tr>
<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>PPI</td>
<td>pellet-to-pellet interface</td>
</tr>
<tr>
<td>PWR</td>
<td>pressurized water reactor</td>
</tr>
<tr>
<td>RT</td>
<td>room temperature</td>
</tr>
<tr>
<td>SNF</td>
<td>spent nuclear fuel</td>
</tr>
<tr>
<td>SS</td>
<td>stainless steel</td>
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USED FUEL DISPOSITION CAMPAIGN

FY 2016 Status Report: CIRFT Testing Data Analyses and Updated Curvature Measurements

1. CYCLIC INTEGRATED REVERSIBLE-BENDING FATIGUE TESTER

The Cyclic integrated reversible-bending fatigue tester (CIRFT), developed by ORNL\textsuperscript{1,2,3,4,5,6,7,8}, consists of a U-frame as shown in Fig 1. The U-frame includes two rigid arms, connecting plates, and universal testing machine links. The rod specimen is coupled to the rigid arms through two specially designed grips. The U-frame setup is oriented in a horizontal plane and is driven by electromagnetic-force–based Bose dual linear motors. With help from the coupling, linear motions applied at the loading points of the rigid arms are converted into bending moments. The dual linear motor (model LM2) test bench has a maximum load capacity of ±3,000 N and a maximum stroke of ±25.6 mm. Bending is imposed through a U-frame with dual driving points and a 101.60 mm loading arm. Under a pair of forces or displacements that face outward, the rigid arms are opened, and bending moments force the rod to deflect outward (away from operator). Under a pair of forces facing each other, the rigid arms are closed, forcing the rod to deflect inward. The CIRFT can deliver dynamic loading to a rod specimen in the load-control mode at 5 to 10 Hz. The current configuration enables the system to test a rod 9.70 mm to 11.74 mm in diameter, 152.40 mm (6 in.) in length, and 50.80 mm (2 in.) in gage section. Three LVDTs measure rod deflections at three adjacent points within the gage section to determine rod curvature, which is then correlated to the applied moment to characterize the mechanical property of the bending rod. Online monitoring can capture mechanical property changes to reveal fatigue behavior during testing.
Universal testing machine links
Rigid arms
Connecting plates
Rod specimen
Three LVDTs for curvature measurement
1.1 Moment and Curvature Calculations

Measurement data are converted into the applied moment and curvature based on the load channel (load1 and load2) information, the loading arm length (101.60 mm), and LVDT data (LVDT1, 2, and 3).

The moment was estimated by

\[ M = F \times L \]  

where \( F \) is the averaged value of applied loads (load1 and load2) from the Bose dual motors, and \( L \) is the loading arm length, 101.60 mm.

Theoretically, the bending radius and maximum strain of a rod can be estimated on the basis of the traveling displacement at the loading points of the rigid arm. However, the displacement measured contains the contribution of the compliant layers depending on the materials used in the compliant layers and the level of loading.

To address this issue, direct measurement of the specimen displacement at three adjacent points along the rod method was adopted\(^9\) and has been implemented to evaluate the curvature of a bending rod in this study.\(^2\,^3\)

Given the deflections from three LVDTs, \( d_1, d_2, \) and \( d_3 \), as shown in Fig. 2., the curvature \( \kappa \) of the bending rod can be evaluated as follows:

\[ \kappa = \left[ (x_0 - d_2)^2 + y_0^2 \right]^{-1/2}, \]

\[ x_0 = -\frac{2m_pm_h - m_p(d_2 + d_3) + m_p(d_4 + d_2)}{2(m_b - m_a)}, \] \( (2) \)
\[ y_0 = -\frac{1}{m_a} \left( x_0 - \frac{d_1 + d_2}{2} \right) \frac{h}{2} \]

where

\[ m_a = \frac{h}{d_2 - d_1} \]

\[ m_b = \frac{h}{d_3 - d_2} \]

and \( h \) is the sensor distance, 12 mm.

Fig. 2. Determination of the bending curvature of the rod by use of deflections measured at three points.

The arrangement of the three LVDTs and their installation in the setup can be seen in Fig. 3. An equivalent strain-stress curve (illustrated in Eq. 3) can be obtained under the assumption that the SNF rod can be idealized as a linear elastic homogeneous material without consideration of the effects induced by pellet-clad interaction. The equivalent stress was calculated using:

\[ \sigma = M \times \frac{y_{\text{max}}}{I} \quad (3) \]

where \( I \) is the moment of inertia, \( I = I_c + I_p \), \( I_c \) and \( I_p \) are moments of inertia of cladding and pellet, respectively, and \( y_{\text{max}} \) is the maximum distance to the neutral axis of the test rod of the section and is measured by the radius of the cladding. The calculation of stress disregards the difference of elastic moduli between clad and pellets.

The equivalent strain is then:

\[ \varepsilon = \kappa \times y_{\text{max}} \quad (4) \]
1.2 Sensor Spacing Correction for Curvature Measurement

The contact of LVDT probe with the rod under testing depends on the bending direction and induced curvature, especially when the contact is a disk with a flat head. This resulted in the deviation of sensor spacing from the ideal condition (Fig. 4).

For positive curvature when tensile load was applied to U-frame, actual sensor spacing $h_2$ is,

$$h_2 = h + \Delta h$$  \hspace{1cm} (5)

and for negative curvature when compressive load was applied to U-frame, actual sensor spacing $h_1$ is

$$h_1 = h - \Delta h.$$  \hspace{1cm} (6)
A polycarbonate rod (0.4375 in diameter and 6 in length) specimen PC01 was tested under -6 mm and +6 mm with disk-head LVDTs. The curvatures in positive and negative direction appeared to be quite different as seen below (Fig. 5).

The same specimen PC01 was tested under the same level of applied displacement, but curvatures were based on chisel head LVDTs. The curvatures in both directions were very close near 2 m$^{-1}$. The repeatable results indicated that the PC01 behaved elastically as designed, and at the same time, the effect of chisel head on the curvature measurement is negligible.

Analysis revealed that:

- For a positive curvature induced by tension on the U-frame, a sensor adjustment of 2.90 mm is needed to have the disk-based measurement matched with the chisel-based measurement.

- For a negative curvature induced by compression on the U-frame, a sensor adjustment of 2.40 mm is needed to have the disk-based measurement matched with the chisel-based measurement.

The obtained sensor spacing adjustments for two conditions will be used in the data analysis in Sect. 2.
Fig. 5. (a) For a positive curvature induced by tension on U-frame, a sensor adjustment of 2.9 mm is needed to have the disk-based measurement matched with the chisel-based measurement. (b) For the negative curvature induced by compression on U-frame, a sensor adjustment of 2.4 mm is needed to have the disk-based measurement matched with the chisel-based measurement.
2. VERIFICATION OF CURVATURE MEASUREMENT

2.1 Technical Issues

Technical issues exist regarding the curvature measurement in CIRFT testing:

1) Can the curvature measured by the three LVDTs be evaluated? If so, how?
2) How close is the corrected curvature to the actual curvature?
3) Is the correction method applicable to all the levels of curvature?
4) Is the correction method applicable to both static and dynamic cases?

2.2 Technical Approach

ORNL proposed to use strain gage measurements to further benchmark the three LVDT curvature measurements. The rationale behind this is as follows:

1) When using a homogenous bending rod, the maximum strain at the extreme fiber can be evaluated because the estimate of that strain has been established theoretically. The deformation of the rod shall be limited within the elastic region of the material to enable the calculation to be effective.
2) The three LVDT-based curvatures in step 1 can be converted into the strain at the extreme fiber.
3) The strain at the extreme fiber can be measured by a strain gage.
4) The strain gage-based strain in step 3 can thus be compared with the three-LVDT-based strains to verify the curvature measurement in step 1.

2.3 Experimental Results

ORNL accomplished the following:

1) Purchased a four-channel strain gage signal conditioning amplifier Micro Measurement 2310B.
2) Integrated the conditioning amplifier 2310B into the PCI-82 control box in Bose testing machine (L218, 4515).
3) Studied the strain gages for the surrogate rod in-out cell testing in both small and large deformation cases.
4) Performed the CIRFT test on the surrogate rod made of 304 cladding only (no pellets involved) in small deformation.
5) Performed the CIRFT test on the surrogate rod made of polycarbonate in large deformation.
6) Analyzed the hot cell CIRFT testing data on MOX SNF and other SNF tested under DOE sponsorship (see Sect. 3)

The 4-channel 2310B amplifier (Raleigh, NC, Fig. 6) has following features:
• Fully adjustable calibrated gain from 1 to 11,000

• Accepts all strain gage inputs (foil or piezoresistive), potentiometers, direct current differential transformers (DCDTs), etc.

• Bridge excitation from 0.7 to 15Vdc (11 steps) plus 0.2 to 7 volts continuously variable

• Input impedance above 100 megohms

• Two simultaneous buffered outputs: ±10V, ±1.4V (for tape recorders)

• Wide band operation exceeding 60 kHz, -0.5 dB at all gains and output levels

• Four-frequency active 6-pole filter (10 to 10 000 Hz)

• Dual-range (±5000 and ±25000με) automatic bridge balance, with keep-alive power to preserve balance for months without external power

• Dual-polarity two-step double-shunt calibration

![Image](image.png)

Fig. 6. Strain gage signal conditioning amplifier 2310B, Micro-Measurements.

Two types of strain gages (Micro-Measurements, Raleigh, NC) were identified for this study, and the gage factors are given in Table 1. The setups of surrogate rods with the strain gage mounted are shown in Figs. 7 and 8.

<table>
<thead>
<tr>
<th>Surrogate rod</th>
<th>Strain gage designation</th>
<th>Gage factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS304 surrogate rod</td>
<td>EA-06-250BF-350</td>
<td>2.055 +/- 0.5%</td>
</tr>
<tr>
<td>Polycarbonate rod</td>
<td>CEA-06-125UW-350</td>
<td>2.095 +/- 0.5%</td>
</tr>
</tbody>
</table>
CIRFT Testing and Data Analysis on SS304 Surrogate Rod

The proposed curvature correction was tested against several established methods including curvature measurement using a chisel type probe and a strain gage.

### 2.3.1.1 Base Considerations in Data Analysis

The following information was used in the data analysis:

1) The LVDT-based strain calculation was based on the discussion in Sect. 1.1.

2) The correction was based on the assumption of the equal gage length in both peak and valley of one data block (two cycles of sine wave). The half gage length Lg/2 was calculated according to the equation as follows

\[ Lg / 2 = \sqrt{2d_2 / \kappa} \]  

(7)
where \( d_2 \) is the middle LVDT reading in m and \( \kappa \) is the calculated curvature in m\(^{-1}\).

3) The gage-based strain was obtained according the following equation,

\[
\varepsilon = \frac{10^6}{(0.25 \times V_{BR} \times A \times S_g)}
\]  

(8)

where \( \varepsilon \) is micro strain or \( \mu \varepsilon \), \( V_{BR} \) is the bridge voltage, \( A \) is the amplification, and \( S_g \) is the gage factor.

4) The strain can be estimated according to the condition of the rod by

\[
\varepsilon = \frac{M}{EI} y_{\text{max}}
\]  

(9)

where \( M \) is the applied moment amplitude, \( EI \) is estimated 42.8 Nm\(^2\), \( y_{\text{max}} = 4.78 \)mm.

2.3.1.2 Chisel Type Probe as Calibration Method

Testing on surrogate rod SS30402 was conducted in 0.05 Hz and 5 Hz to simulate the static and dynamic loading (Table 2).

<table>
<thead>
<tr>
<th>No.</th>
<th>pk1 (mm, N)</th>
<th>pk2 (mm, N)</th>
<th>Frequency</th>
<th>Cycles</th>
<th>Sum</th>
<th>LVDT type</th>
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<tr>
<td>44</td>
<td>-0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>3</td>
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<td>Flat disk, D6</td>
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<tr>
<td>45</td>
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<td>0.05</td>
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<td>Flat disk, D6</td>
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<td>47</td>
<td>-75</td>
<td>75</td>
<td>5</td>
<td>500</td>
<td>500</td>
<td>Flat disk, D6</td>
</tr>
<tr>
<td>48</td>
<td>-0.4</td>
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<td>0.05</td>
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<td></td>
<td>Flat disk, D6</td>
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<tr>
<td>49</td>
<td>-0.6</td>
<td>0.6</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Flat disk, D6</td>
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<td>0.05</td>
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<td>Flat disk, D6</td>
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<td>51</td>
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<td>1,000</td>
<td>Flat disk, D6</td>
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<td>52</td>
<td>-0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Flat disk, D6</td>
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<td>53</td>
<td>-0.6</td>
<td>0.6</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Flat disk, D6</td>
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<td>54</td>
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<td>0.8</td>
<td>0.05</td>
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<td>Flat disk, D6</td>
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<td>500</td>
<td>1,500</td>
<td>Flat disk, D6</td>
</tr>
<tr>
<td>56</td>
<td>-0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>57</td>
<td>-0.6</td>
<td>0.6</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>58</td>
<td>-0.8</td>
<td>0.8</td>
<td>0.05</td>
<td>3</td>
<td>0</td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>59</td>
<td>-75</td>
<td>75</td>
<td>5</td>
<td>500</td>
<td>500</td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>60</td>
<td>-0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>61</td>
<td>-0.6</td>
<td>0.6</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>62</td>
<td>-0.8</td>
<td>0.8</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>63</td>
<td>-100</td>
<td>100</td>
<td>5</td>
<td>500</td>
<td>1,000</td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>64</td>
<td>-0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>65</td>
<td>-0.6</td>
<td>0.6</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>66</td>
<td>-0.8</td>
<td>0.8</td>
<td>0.05</td>
<td>3</td>
<td></td>
<td>Chisel, D6</td>
</tr>
<tr>
<td>67</td>
<td>-125</td>
<td>125</td>
<td>5</td>
<td>500</td>
<td>1,500</td>
<td>Chisel, D6</td>
</tr>
</tbody>
</table>
The curvature values based disk-type probe and the corrected are presented in the Figs. 9–12, along with those based on flexural rigidity (EI) and the chisel-type probe. The major observations can be summarized as follows,

1) Measurement with the chisel type probe showed uncertainty in curvature; no defined trend can be seen in the measured curvatures as compared to those using the disk-type probe.

2) The tests with the chisel type and disk type probes were not conducted concurrently. The probe contact condition was changed in the session when the probe was changed and the three LVDTs were remounted; the sensor spacing was sensitive to the change of contact condition.

3) The corrected curvature was shown to be close to the EI-based curvature.

4) Spacing correction (Δh) seemingly exhibited a trend to increase with the level of displacement input (disp1 on the side of motor 1). However, a large variance of correction was seen near small displacement.

5) The level of correction was also far less than those based on the calibration of chisel type probe (2.40 or 2.90 mm).
Fig. 9. Curvatures based on disk-type probe, corrected, EI-based, and chisel-type probe, for 0.05 Hz displacement at loading point of U-frame arm: (a) 0.4 mm, (b) 0.6 mm, and (c) 0.8 mm. EI=42.8 Nm².
(a) Peak

(b) Valley
Fig. 10. (a) Peak and (b) valley responses of curvature waveform and (c) spacing corrections under various displacements at 0.05Hz.

(a) 75N
Fig. 11. Curvatures based on disk-type probe, corrected, EI-based, and chisel-type probe for 5 Hz load at loading point of U-frame arm:
(a) 75 N, (b) 100 N, and (c) 125 N. EI=42.8 Nm².
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a) Peak

(b) Valley
Fig. 12. (a) Peak and (b) valley responses of curvature waveform, and (c) spacing corrections under various load1 amplitudes at 5Hz.

### 2.3.1.3 Strain Gage as Calibration Method

The strain gage was installed on the surface of the bending rod opposite the three LVDTs as shown in Fig. 7. The test conditions using 0.05 Hz sine wave with varying amplitudes are given in Table 3. The strains were acquired in #71–73 using a P3 strain indicator and recorder (Vishay Micro-Measurement, Raleigh, NC) and in #81–84 using strain signal conditioning amplifier 2310B (Vishay Micro-Measurement, Raleigh, NC).

<table>
<thead>
<tr>
<th>No.</th>
<th>pk1 (mm, N)</th>
<th>pk2 (mm, N)</th>
<th>Frequency</th>
<th>Cycles</th>
<th>LVDT type</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>-0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>3</td>
<td>Flat disk, D5</td>
</tr>
<tr>
<td>72</td>
<td>-0.6</td>
<td>0.6</td>
<td>0.05</td>
<td>3</td>
<td>Flat disk, D5</td>
</tr>
<tr>
<td>73</td>
<td>-0.8</td>
<td>0.8</td>
<td>0.05</td>
<td>3</td>
<td>Flat disk, D5</td>
</tr>
<tr>
<td>81</td>
<td>-0.4</td>
<td>0.4</td>
<td>0.05</td>
<td>3</td>
<td>Flat disk, D5</td>
</tr>
<tr>
<td>82</td>
<td>-0.6</td>
<td>0.6</td>
<td>0.05</td>
<td>3</td>
<td>Flat disk, D5</td>
</tr>
<tr>
<td>83</td>
<td>-0.8</td>
<td>0.8</td>
<td>0.05</td>
<td>3</td>
<td>Flat disk, D5</td>
</tr>
<tr>
<td>84</td>
<td>-100</td>
<td>100</td>
<td>5</td>
<td>500</td>
<td>Flat disk, D5</td>
</tr>
</tbody>
</table>

The curvatures measured using three LVDTs were converted into the maximum strain at outer fiber of bending rod. The results of tests #71–73 are illustrated in Figs. 13 and 14.

1) Overall, the strain gage has a synchronized response with curvature-based strain, although the curvature-based strain at 0.6 mm lagged a little in the first half of period.
2) The peak/valley response of the curvature-based strain with the correction applied matched the strain gage measurement well.

3) Spacing correction ($\Delta h$) demonstrated again an increasing trend with the displacements. However, the correction, especially at small displacement input, showed a lower level than in the previous test session (Fig. 10).
Fig. 13. Strain curves based on original disk-type curvature, corrected curvature, and strain gage for 0.05 Hz displacement at loading point of U-frame arm: (a) 0.4 mm, (b) 0.6 mm, and (c) 0.8 mm.

(a) Peak
Fig. 14. (a) Peak, (b) valley responses of strain waveform, and (c) spacing corrections under various disp1 amplitudes at 0.05 Hz.
The results of tests #81–84 are given in Fig. 15 for 0.05 Hz and Fig. 16 for 5 Hz. The following observations can be made:

1) The strain gage showed a lower level of strain than those of curvature-based strain.

2) The spacing correction $\Delta h$ and its variation with displacements were smaller compared with previous tests (Figs. 10 and 14). The degree of correction on $\kappa$-based strain was smaller, as well.

3) The corrected curvature-based strains were seen close to EI-based strains.

(a) Displacement amplitude 0.4 mm
Fig. 15. Strain results based on original curvature, corrected curvature, strain gage, and flexural rigidity $EI$ for $0.05$ Hz tests under three displacement amplitudes.
2.3.1.4 Summary

The use of a SS304 surrogate rod in the out-cell study provided the opportunity to examine the small curvature measurement currently used in CIRFT tests. The following summarizes the major observations:

Fig. 16. Strain results based on original curvature, corrected curvature, strain gage, and flexural rigidity EI for 5 Hz tests under amplitude 100N.
1) The corrected curvature was shown to be close to an EI-based curvature; the corrected curvature-based strain was also demonstrated to be agreed with strain gage measurement.

2) The spacing correction (Δh) was smaller than those based on large curvature measurement. The degree of correction on curvature-based strain was also smaller.

3) The spacing correction exhibited a defined trend to increase with the level of displacement input, but it also showed a large variance at the small displacements.

4) The level of spacing correction in specified displacement input varied among test sessions. The change of contact condition between probe and surface of rod is believed to contribute the variation. A systematic correction scheme was also developed accordingly.

2.3.2 CIRFT Testing on Polycarbonate Surrogate Rod Material

The test condition on a polycarbonate rod (PC01) consists of two load waveforms: ramp and sine.

2.3.2.1 Ramp Waveform Test

The displacement at each loading point of the U-frame ramped up to a designated level and then down to zero; one loading cycle was used. The bending in ramp was unidirectional with a single wave pulse pointed in either positive or negative direction.

Two types of LVDT probes were tested, namely flat disk type and chisel type. Test condition can be seen in Table 4.

<table>
<thead>
<tr>
<th>No.</th>
<th>pk1 (mm)</th>
<th>pk2 (mm)</th>
<th>rate (mm/s)</th>
<th>Cycles</th>
<th>LVDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>6</td>
<td>0.2</td>
<td>1</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-6</td>
<td>0.2</td>
<td>1</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>6</td>
<td>0.2</td>
<td>1</td>
<td>chisel, D5</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>-6</td>
<td>0.2</td>
<td>1</td>
<td>chisel, D5</td>
</tr>
</tbody>
</table>

The data sets for a specified probe were assembled to obtain a whole waveform of reversed bending. The three LVDT-based curvatures obtained with both disk type and chisel type probes are presented, along with the corrected curvature in Fig. 17, in which EI = 1.8 Nm² was used for EI-based estimate.

1) The correction procedure suggests that a sensor spacing correction of 2.50 mm is needed. With the suggested procedure, only one correction is needed instead of two corrections in positive (2.90 mm) and negative direction (2.40 mm), as used before.

2) The corrected curvature showed a good correspondence with both chisel type measurement and EI-based estimate.
2.3.2.2 Sine Waveform Test

Reverse bending was conducted directly by using a 0.05 Hz sine wave. A total of 12 amplitudes were tested with one LVDT probe, flat disk type. Strain gage measurement was enabled, and strains were acquired using a P3 strain indicator and recorder. The tests condition can be seen from Table 5.

Table 5. Test condition using sine wave

<table>
<thead>
<tr>
<th>No.</th>
<th>pk1 (mm)</th>
<th>pk2 (mm)</th>
<th>F(Hz)</th>
<th>Cycles</th>
<th>LVDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>0.5</td>
<td>-0.5</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>36</td>
<td>1</td>
<td>-1</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>37</td>
<td>1.5</td>
<td>-1.5</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>38</td>
<td>2</td>
<td>-2</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>39</td>
<td>2.5</td>
<td>-2.5</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>40</td>
<td>0.3</td>
<td>-0.3</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>41</td>
<td>0.3</td>
<td>-0.3</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>42</td>
<td>0.3</td>
<td>-0.3</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>43</td>
<td>0.5</td>
<td>-0.5</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>44</td>
<td>0.5</td>
<td>-0.5</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>45</td>
<td>0.5</td>
<td>-0.5</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>46</td>
<td>1</td>
<td>-1</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>47</td>
<td>1</td>
<td>-1</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
<tr>
<td>48</td>
<td>1.5</td>
<td>-1.5</td>
<td>0.05</td>
<td>3</td>
<td>flat disk, D5</td>
</tr>
</tbody>
</table>
The typical results from tests using a 0.05 Hz sine wave are given in Fig. 18. The peak and valley values of the strain waveforms obtained for various cases are shown in Fig. 19, including strains based on original curvature (disk-type probe), corrected curvature, and strain gage. The variation of spacing correction as a function of displacement input is also presented.

1) The strains from the strain gage usually agreed well with those based on the corrected curvatures, but they deviated from the corrected curvature-based strain at high levels.

2) The spacing correction (\( \Delta h \)) again exhibited a defined trend to increase with the displacement input and also a larger variance at the small displacements.

3) The spacing corrections were again lower than those obtained in ramping.
4) The corrected ultimate curvatures obtained in ramp and sine waveforms were the same (around 2 m⁻¹ at 6.00 mm disp1). There was perhaps a significant change of the contact condition between probe and surface of rod as the tests were carried out in different periods of the project.

![Strain wave forms obtained from original curvature, corrected curvature, and strain gage](image)

**Fig. 18.** Strain wave forms obtained from original curvature, corrected curvature, and strain gage: (a) displacement amplitude 1.00 mm, and (b) 4.00 mm.
(a) Peak

(b) Valley
2.3.2.3 Summary

Based on the tests of the polycarbonate rod, observations with respect to disk-type curvature measurement and correction can be summarized as follows:

1) The corrected curvature showed a good correspondence with chisel type measurements and the EI-based estimate. The corrected curvature-based strain has good agreement with that of strain gage measurement, particularly near small-to-intermediate levels of displacement input.

2) The spacing correction (Δh) again exhibited a defined trend to increase with the displacement input with a larger variance at the small displacements.

3) The correction procedure suggested a spacing correction of 2.50 mm (at 6.00 mm disp1) other than dual corrections reported in ramping (2.40 mm in negative curvature and 2.90 mm in positive curvature). However, the corrected ultimate curvatures obtained in ramp and sine waveforms were the same (approximately 2 m⁻¹ at 6.00 mm disp1).

4) The change of the contact condition between the probe and surface of the rod in different test sessions may be responsible for the variation of spacing correction observed.

2.4 Recommendation

It has been shown that the sensor spacing correction depends on the level of imposed displacement. The corrected curvature based on disk-type probes agrees to a varying extent with the EI-based estimate in both small and large curvature measurements and with chisel-type probe measurements in the large curvature case. The corrected curvature-based strain was also shown to correspond to the strain gage measurement, particularly at the small-to-intermediate level of displacement input.
There is some uncertainty involved with the contact of the probe against the rod during reversible bending testing. However, the proposed dynamic correction method of LVDT probes is independent of contact spacing correction mentioned earlier. The identification of sensor spacing correction dynamically accounts for the changes and evolution of contacts, this effect is still working in progress and will be reported in next performance period.

The proposed correction procedure will be applied to data analysis of the all CIRFT test results. The analysis results of LMK, NA, and MOX fuels is presented below.
3. DATA ANALYSIS OF CIRFT TESTING ON Limerick BWR SNF

3.1 Overview of CIRFT Tests on LMK Fuel Rods

A total of 16 specimens—LM1–LM4 and LM5–LM17—were tested in the hot cell. LM1 was used in the tuning and static test. The remaining 15 specimens were used in dynamic tests. The dynamic tests were conducted with a range of moment amplitudes from 7.11 to 30.48 N·m. A total of 13 specimens failed with fatigue lives from $10^4$ to $4.7 \times 10^6$ cycles. LM12 and LM17 were cycled to more than $3.4 \times 10^6$ cycles without failure. LM12 was stopped at $7.6 \times 10^6$ cycles, and LM17 was tested continuously but to an increased amplitude 30.48 Nm and failed at $1.3 \times 10^4$ cycles.

3.2 Results on Data Analysis for Dynamic Tests

The data sets for each of the dynamic tests, including measurement data and online monitoring data, were processed by using the procedure suggested in Sect. 2.

Results for each test are given in Appendix A. For each test:

1) The variations of curvature range, moment range, flexural rigidity, curvature peak/valley, and moment peak/valley are presented whenever they are available.

2) The curvature and moment plots are given for the beginning data block of a test session when the load reaches the designated level. The results for two test sessions are presented, namely, the first (tested to 1000 cycles) and last sessions.

3) Finally, the data based on online monitoring are presented, including the variations of curvature range, moment range, flexural rigidity, curvature peak/valley, and moment peak/valley as a function of number of cycles or the cycles to failure.

For each cyclic test, several measurement data sets were obtained between test sessions. These measurements were made with small displacement amplitudes at 0.05 Hz. With such input, both moment and curvature varied or decreased along with the accumulated number of cycles. The obtained rigidities were generally higher than those from monitoring data, and the degree of changes was similar to those of monitoring data.

The corrected curvature depends on the spacing correction applied. Generally, the correction observed for the curvature is not quite significant because of the small input. However, the signal-to-noise ratio becomes much smaller at the lower input. The amplitude of de-noised curvature was thus lowered relatively compared to original noisy data, which can be seen from the pots of specimen LM12 in Fig. A.40.

Major results for the dynamic tests are summarized in Table 6. The table is self-explained, including the following columns:

1) TN – test number

2) Spec – Specimen ID

3) ID – inside diameter of cladding

4) OD – outside diameter of cladding
5) Dia – diameter of pellet
6) Load – load amplitude at the loading point of U-frame
7) N – number of cycles accumulated or the cycles to failure
8) Fail – 1 as failure, and 0 as no failure
9) ma – mean of moment amplitude ($\Delta M/2$) based on de-noised monitoring data
10) ma_std – standard deviation of moment amplitude (4 inch or 101.60 mm loading arm) based on de-noised monitoring data
11) ka – mean of curvature amplitude ($\Delta \kappa/2$) based on corrected and de-noised monitoring data
12) ka_std – standard deviation of curvature amplitude based on corrected and de-noised monitoring data
13) km – mean of curvature extreme values based on corrected and de-noised monitoring data, $km = \max \{|\kappa_p|,|\kappa_v|\}$, where $\kappa_p$ and $\kappa_v$ are peak/valley values
14) km_std – standard deviation of curvature extremes based on corrected and de-noised monitoring data
15) R – mean of flexural rigidity
16) R_std – standard deviation of flexural rigidity
17) sa – mean of equivalent stress amplitude ($\Delta \sigma/2$) based on de-noised monitoring data
18) sa_std – standard deviation of equivalent stress amplitude based on de-noised monitoring data
19) ea – mean of equivalent strain amplitude ($\Delta \varepsilon/2$) based on corrected and de-noised monitoring data
20) ea_std – standard deviation of equivalent strain amplitude based on corrected and de-noised monitoring data
21) em – mean of strain extreme values based on corrected and de-noised monitoring data, $em = \max \{|\varepsilon_p|,|\varepsilon_v|\}$
22) em_std – standard deviation of strain extremes based on corrected and de-noised monitoring data
23) Lg2 – mean of half gauge length, Lg/2
24) Lg2_std – standard deviation of half gauge length
25) dh – mean of sensor spacing correction, $\Delta h$
26) dh_std – standard deviation of sensor spacing correction

The plots based on the mean values of major quantities can be found in Fig. 20 (a)–(d), where the circles represent the tests with failure and the circles with arrows designate the tests without failure. The results obtained from the follow-up tests for LM1 and LM17 are also included.
The fatigue life increased with decreasing amplitude as expected, but the variation was not continuous. A discontinuity or knee was observed near 7 Nm and 0.2 m\(^{-1}\) in the moment – N and curvature – N curves, respectively. For this SNF, these parameters correspond to 50 MPa of equivalent stress and 0.1% of equivalent strain. At the same time, curvature extreme values were generally higher than curvature amplitudes as expected, but the difference was small.

The flexural rigidity was mostly shown to be either quite flat or featuring a decreasing trend with the number of cycles. Several tests also suggested a tendency to increase with number of cycles, including LMK2, 8, and 14. Overall, the degree of variation of rigidity is limited. Meanwhile, no relation of rigidity to the number of cycles to failure can be seen.

The effective half-gage length was found out to be limited with a range between 38 and 50 mm and to increase with increased amplitude of moment. On the other hand, the sensor spacing correction did not suggest any relation to the moment amplitude.

<table>
<thead>
<tr>
<th>TN</th>
<th>Spec</th>
<th>ID inch</th>
<th>OD inch</th>
<th>Dia inch</th>
<th>Load N</th>
<th>N cycles</th>
<th>Fail ma Nm</th>
<th>ma_std Nm</th>
<th>ka m(^{-1})</th>
<th>ka_std m(^{-1})</th>
<th>km m(^{-1})</th>
<th>km_std m(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LM1</td>
<td>0.394</td>
<td>0.450</td>
<td>0.374</td>
<td>250.000</td>
<td>9.40E+03</td>
<td>1</td>
<td>23.426</td>
<td>0.087</td>
<td>0.901</td>
<td>0.027</td>
<td>1.007</td>
</tr>
<tr>
<td>2</td>
<td>LM2</td>
<td>0.391</td>
<td>0.447</td>
<td>0.374</td>
<td>125.000</td>
<td>1.71E+05</td>
<td>1</td>
<td>11.468</td>
<td>0.090</td>
<td>0.266</td>
<td>0.006</td>
<td>0.275</td>
</tr>
<tr>
<td>3</td>
<td>LM3</td>
<td>0.392</td>
<td>0.448</td>
<td>0.374</td>
<td>100.000</td>
<td>4.92E+05</td>
<td>1</td>
<td>9.016</td>
<td>0.081</td>
<td>0.243</td>
<td>0.008</td>
<td>0.258</td>
</tr>
<tr>
<td>4</td>
<td>LM4</td>
<td>0.392</td>
<td>0.448</td>
<td>0.374</td>
<td>85.000</td>
<td>2.49E+05</td>
<td>1</td>
<td>7.570</td>
<td>0.074</td>
<td>0.165</td>
<td>0.008</td>
<td>0.205</td>
</tr>
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<td>LM5</td>
<td>0.392</td>
<td>0.448</td>
<td>0.374</td>
<td>85.000</td>
<td>2.49E+05</td>
<td>1</td>
<td>7.570</td>
<td>0.074</td>
<td>0.165</td>
<td>0.008</td>
<td>0.205</td>
</tr>
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<td>6</td>
<td>LM6</td>
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<td>0.448</td>
<td>0.374</td>
<td>75.000</td>
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<td>6.888</td>
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<td>0.154</td>
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(a)
(b) $N_f$ (Cycles) vs. $\Delta \sigma^2$ (MPa)

(c) $N_f$ (Cycles) vs. $\kappa$ ($\text{m}^{-1}$)
Fig. 20. (a) Moment amplitude, (b) stress amplitude, (c) curvature amplitude/maximum, and (d) strain amplitude/maximum as a function of cycles or cycles to failure.
4. DATA ANALYSIS OF CIRFT TESTING ON North Anna FUEL

4.1 Overview

A total of 6 dynamic tests was conducted with applied amplitudes from 5.08 to 15.24 N·m; 5 specimens failed, and fatigue life ranged from $1.26 \times 10^4$ to $4.27 \times 10^5$ cycles. One specimen (NA5) was cycled to $5.11 \times 10^6$ cycles without failure and stopped.

4.2 Results on Data Analysis for Dynamic Tests

The results for each test are given in Appendix B. For each test, the plots similar to those of LMK fuels are presented for NA fuel as well, including the variations of curvature range, moment range, flexural rigidity, curvature peak/valley, and moment peak/valley values.

The results for the dynamic tests are summarized in Table 7. The items of the columns are the same as those of LMK fuels in Sect. 3.2.

The plots based on the mean values of quantities can be found in Fig. 21 (a)–(d). In the moment – N and curvature – N curve, it seemed that there are knee points near 4 Nm and 0.05 m$^{-1}$. However, the knee was not defined well because of the limited data points.

The variation of rigidity was generally limited for a specified cyclic test, but abrupt change was observed in several tests. On the other hand, the effective half-gage length was found out to be limited with a range between 40 and 49 mm, increasing with increased amplitude of moment.

### Table 7. Dynamic test results for NA SNF rods

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The plots based on the mean values of quantities can be found in Fig. 21 (a)–(d). In the moment – N and curvature – N curve, it seemed that there are knee points near 4 Nm and 0.05 m$^{-1}$. However, the knee was not defined well because of the limited data points.

The variation of rigidity was generally limited for a specified cyclic test, but abrupt change was observed in several tests. On the other hand, the effective half-gage length was found out to be limited with a range between 40 and 49 mm, increasing with increased amplitude of moment.
Fig. 21. (a) Moment amplitude, (b) stress amplitude, (c) curvature amplitude/ maximum, and (d) strain amplitude/ maximum as a function of cycles or cycles to failure.
5. DATA ANALYSIS OF CIRFT TESTING ON MOX FUEL

5.1 Overview

10 dynamic tests were completed with the applied amplitudes from 5.08 to 15.24 Nm, and all specimens failed. The fatigue life ranged from $1.29 \times 10^4$ and $2.15 \times 10^6$ cycles.

5.2 Results on Data Analysis for Dynamic Tests

The results for each test are given in Appendix C. The plots similar to those of LMK fuels are presented for MOX fuel, as well including the variations of curvature range, moment range, flexural rigidity, curvature peak/valley, and moment peak/valley values.

The results for the dynamic tests of MOX fuel are summarized in Table 8. The items of the columns are the same as those of LMK fuels in Sect. 3.2.

The plots based on the mean values of quantities can be found in Figs 22 (a)–(d). In the moment – N curve, it seemed that there is knee point near 4 Nm. However, the variation of fatigue life in curvature –N curve appeared to be continuous within the tested amplitude range.

The fatigue response of rigidity depends on the moment amplitudes applied. Under a high level such as >10.2 Nm, the rigidity was either relatively stable, or it showed a trend of decreasing with the accumulated number of cycles. Under the low level, it tended to increase during the cyclic test, but it was indeed observed that the fatigue life of MOX fuel increased with the increasing initial rigidity.

On the other hand, the effective half-gage length was determined to be limited with a range between 40 and 52 mm, increasing with increased amplitude of moment.

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<th>Dia inch</th>
<th>Load N</th>
<th>N cycles</th>
<th>Fail</th>
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<th>ma_std Nm</th>
<th>ka m^1</th>
<th>ka_std m^-1</th>
<th>km m^1</th>
<th>km_std m^-1</th>
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<td>0.378</td>
<td>0.323</td>
<td>100.000</td>
<td>3.70E+04</td>
<td>1</td>
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### Table 8b. (continued)

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<th>sa (Mpa)</th>
<th>sa_std</th>
<th>ea (%)</th>
<th>ea_std</th>
<th>em (%)</th>
<th>em_std</th>
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<th>Lg²_std (mm)</th>
<th>dh (mm)</th>
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![Graph](image.png)
(b) 

(c)
Fig. 22. (a) Moment amplitude, (b) stress amplitude, (c) curvature amplitude/maximum, and (d) strain amplitude/maximum as a function of cycles or cycles to failure.
6. DISCUSSION AND REMAINING ISSUES

6.1 Fatigue Life of SNF

The variations of fatigue life are given in Fig. 23 in terms of moment, equivalent stress, curvature and equivalent strain for the tested SNFs.

The equivalent stress indeed collapsed the data points from all of the SNFs into a single zone. A detailed examination revealed that, at same stress level, the LMK fuel showed a longer fatigue life than the other two SNFs between $10^4$ and $10^6$ cycles. The strain – N curve shows that the LMK fuel has a longer fatigue life in a wider range from $10^4$ to $10^7$ cycles.

The knee point in the curve of moment and curvature or equivalent quantities is more clearly defined for LMK fuel than for the other two fuels.
(d) 

(e)
6.2 Remaining Issues with Curvature Measurement

6.2.1 Small Amplitude Curvature

In CIRFT tests, the small curvatures usually occur in the dynamic tests. Remaining issues exists with respect to the small curvature measurement.

1) How close is the contact condition of SS cladding-only surrogate rods to that of SNF rods? This question is critical because the contact dominates the sensor spacing used in the calculation of curvature. This is mainly because the cladding material, and especially the surface condition of the SNF rod, vary from those in the surrogate rod. The initial engagement and the subsequent contact of LVDT probes with the rod will be affected by these factors.

2) How much impact of the transverse motion of LVDT probes is imposed on curvature measurement? There is a clearance between the measurement probe and LVDT cylinder designed to ensure a smooth longitudinal motion of the LVDT probe within the measurement cylinder. This clearance introduces an inevitable transverse motion of probe, which affects the initial engagement of probe with the rod and also the subsequent translational movement of the probe in measurement.

3) What is the effect of driving frequency on the curvature measurement? It has been shown that there is an effect of frequency on the response of bending rod. The issue remaining to be addressed here is to determine how the frequency will impact the curvature measurement itself. This effect occurs because the contact of probe against the rod is influenced by the dynamics of system.
6.2.2 Large Amplitude Curvature

There are some outstanding issues with regard to the large curvature measurement.

1) The impact of pellet-cladding mechanical interaction (PCMI) may be important when the deformation becomes large. This is obvious because the local plastic deformation can be substantial due to local buckling in compressive side, for instance. This alters the surface condition, and in turn, it alters the contact of the probe against the rod.

2) How will the transverse motion of the probe be changed with large deformation? The transverse motion is associated with clearance of LVDT measurement. Large deformation of the rod may close the gap between the measurement rod and the cylinder on one side and open it on other side.

3) How is the correction applicable to the real SNF rods? The spacing correction relation has been developed using a flexible rod made of materials like polycarbonate. This provides a useful approach to investigate the response of the rod system in large deformation, but it needs to be justified before being migrated into the CIRFT data analysis.
7. CONCLUSION

1) There is an effect from the contact of the probe on the curvature measurement in current CIRFT tests. The effect of the contact can be corrected by using the correction of sensor spacing that is defined between LVDT probes used for curvature measurement.

2) The sensor spacing correction can be determined by using a chisel-type probe. However, this method is limited in its application and cannot be implemented effectively.

3) The sensor spacing correction based on equivalent gage length has the required flexibility and can meet the challenge from application.

4) The correction method based on the equivalent gage length has been demonstrated in this report in CIRFT data analysis for the dynamic tests on LMK (17), NA (6), and MOX (10) fuel rods.

5) Some important issues such as the effects of large amplitude curvature, transverse movement of probes, etc., remain to be investigated in future.
REFERENCES


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APPENDIX A CIRFT TESTING RESULTS OF LIMERICK BWR SPENT NUCLEAR FUEL
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APPENDIX A  CIRFT TESTING RESULTS OF LMK................................................................. A-1

Measurement and monitoring rigidity curves of LMK....................................................... A-3
Measurement and monitoring rigidity curves for Limerick (LMK) BWR Spent Nuclear Fuel
Fig. A.1. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK01, 25.40 Nm, Ns = 1.25E+03 cycles.
(a) 

\[ \Delta K (m^{-1}) \]

\(N\) (cycles) 1000 10000

\[ \Delta M (Nm) \]

\(N\) (cycles) 1000 10000

(b)
(c) N (cycles) vs. R (Nm$^2$)

(d) N (cycles) vs. $\kappa$ (m$^{-1}$)
Fig. A.2. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK01, 25.40 Nm, Nf = 9.40E+03 cycles.
The diagrams illustrate the relationship between cycle number \( N \) and curvature/moment range.

(a) Curvature range \( (m^{-1}) \) vs. \( N \) (cycles)

(b) Moment range \( (Nm) \) vs. \( N \) (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

N (cycles) 10 0 10 1 10 2 10 3 10 4 10 5 10 6

Flexural rigidity (Nm²)
0 10 20 30 40 50 60

Curvature (m⁻¹)
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2

measlimk02.inp
0.4 0.8

N (cycles) 10 0 10 1 10 2 10 3 10 4 10 5 10 6

(d)
Fig. A.3. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK02, 12.70 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s) 5 5.1 5.2 5.3 5.4

Time (s) 5 5.1 5.2 5.3 5.4

(b) Moment (Nm) -15 -10 -5 0 5 10 15

LMK02/test00303, N=2.60E+01

Original

Δh = 0.00 mm

De-noised
Fig. A.4. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK02, 12.70 Nm, Ns = 2.60E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK02/test01202, N= 1.17E+05

(a)

LMK02/test01202, N= 1.17E+05

(b)
Fig. A.5. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK02, 12.70 Nm, Ns = 1.17E+05 cycles.
(a) 

\[ \Delta \kappa \text{ (m}^{-1}) \]

\[ N \text{ (cycles)} \]

(b) 

\[ \Delta M \text{ (Nm)} \]

\[ N \text{ (cycles)} \]
### (c) monlmk02.out

![Graph showing R (Nm²) vs. N (cycles)](image)

### (d) monlmk02.out

![Graph showing ξ (°) vs. N (cycles)](image)
Fig. A.6. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK02, 12.70 Nm, Nf = 1.71E+05 cycles.
### Graphs

**(a)**
- **Curvature range (m)**
- **N (cycles)**

**(b)**
- **Moment range (Nm)**
- **N (cycles)**

---

**N (cycles)**
- 10^0 10^1 10^2 10^3 10^4 10^5 10^6

**Curvature range (m)**
- 0 0.05 0.1 0.15 0.2 0.25 0.3

**Moment range (Nm)**
- 0 2 4 6 8 10 12

**measlmk03.inp**
- 0.4
- 0.8
CIRFT Testing Data Analyses and Updated Curvature Measurements

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N (cycles)

10^0 10^1 10^2 10^3 10^4 10^5 10^6

Flexural rigidity (Nm)

0 10 20 30 40 50

measlmk03.inp

0.4 0.8

N (cycles)

10^0 10^1 10^2 10^3 10^4 10^5 10^6

measlmk03.inp

0.4 0.8

Curvature (m)

-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2

(d)
Fig. A.7. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK03, 10.16 Nm.
(a) Time (s)

(b) Moment (Nm)
Fig. A.8. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK03, 10.16 Nm, Ns = 3.85E+01 cycles.
Fig. A.9. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK03, 10.16 Nm, Ns = 1.16E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

July 24, 2016

(a) 

(b) 

monlmk03.out

N (cycles) vs. \( \Delta \kappa \) (m\(^{-1}\))

monlmk03.out

N (cycles) vs. \( \Delta M \) (Nm)

monlmk03.out

N (cycles) vs. M (Nm)

monlmk03.out

N (cycles) vs. \( \Delta \kappa \) (m\(^{-1}\))

monlmk03.out

N (cycles) vs. M (Nm)
Fig. A.10. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK03, 10.16 Nm, Nf = 4.92E+05 cycles.
(a) Curvature range (m)

N (cycles)

(b) Moment range (Nm)

N (cycles)
Fig. A.11. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK05, 8.64 Nm.
(a)

LMK05/test00302, N= 1.35E+01

Original

$\Delta h = -2.10$ mm

(b)

LMK05/test00302, N= 1.35E+01

Original

De-noised
Fig. A.12. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK05, 8.64 Nm, Ns = 1.35E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK05/test01202, N= 1.24E+05

(a) Curvature ($\kappa$) over time

(b) Moment (Nm) over time

Original
$\Delta h = 0.15$ mm

De-noised
Fig. A.13. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK05, 8.64 Nm, $N_s = 1.24E+05$ cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a)

monlmk05.out

\[ \Delta \kappa \] (m \(^{-1}\))

N (cycles)

(b)

monlmk05.out

\[ \Delta M \] (Nm)

N (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

July 24, 2016

N (cycles) | R (Nm²)
---|---
10 | 0
1 | 10
2 | 20
3 | 30
4 | 40
5 | 50
6 | 60

Monlmk05.out

(c)

Monlmk05.out

(d)
Fig. A.14. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK05, 8.64 Nm, Nf = 2.49E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

July 24, 2016

(a)

(b)
Fig. A.15. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK06, 7.62 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK06/test00604, N=3.85E+01

(a) Time (s)

(b) Moment (Nm)

Original

Δh = -1.95 mm

De-noised

LMK06/test00604, N=3.85E+01

Original

De-noised
Fig. A.16. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK06, 7.62 Nm, Ns = 3.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK06/test01802, N= 1.12E+06

(a) Original

Δh = -1.80 mm

LMK06/test01802, N= 1.12E+06

(b) Original

De-noised
Fig. A.17. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK06, 7.62 Nm, Ns = 1.12E+06 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) $\Delta \kappa$ (m$^{-1}$) vs. N (cycles)

(b) $\Delta M$ (Nm) vs. N (cycles)
Fig. A.18. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK06, 7.62 Nm, Nf = 1.79E+06 cycles.
(a) Curvature range (m)

(b) Moment range (Nm)
Fig. A.19. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK07, 15.24 Nm.
(a)  \[ K_e \, [m^{-1}] \]

\[ \begin{array}{cccccc}
7.5 & 7.6 & 7.7 & 7.8 & 7.9 \\
-0.5 & 0 & 0.5 & -1 & -0.5 \\
\end{array} \]

LMK07/test00304, N=3.85E+01

Original \( h = -0.45 \text{ mm} \)

(b)  \[ \text{Moment (Nm)} \]

\[ \begin{array}{cccccc}
7.5 & 7.6 & 7.7 & 7.8 & 7.9 \\
-15 & -10 & -5 & 0 & 5 \\
\end{array} \]

LMK07/test00304, N=3.85E+01

Original

De-noised
Fig. A.20. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK07, 15.24 Nm, Ns = 3.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK07/test01002, N=1.17E+05

(a)

LMK07/test01002, N=1.17E+05

(b)
Fig. A.21. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK07, 15.24 Nm, Ns = 1.17E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) $\Delta \kappa$ (m$^{-1}$)

(b) $\Delta M$ (Nm)

$N$ (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(c) monlmk07.out

(d) monlmk07.out

max
min
mean
Fig. A.22. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK07, 15.24 Nm, Nf = 1.22E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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N (cycles)
10 0 10 1 10 2 10 3 10 4 10 5 10 6 10 7

Flexural rigidity (Nm²)
0 10 20 30 40 50 60

Curvature (m⁻¹)
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2

measlmk08.inp

(c)

measlmk08.inp

(d)
Fig. A.23. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK08, 7.62 Nm.
Fig. A.24. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK08, 7.62 Nm, Ns = 3.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) LMK08/test02902, N=4.46E+06

(b) LMK08/test02902, N=4.46E+06
Fig. A.25. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK08, 7.62 Nm, Ns = 4.46E+06 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) N (cycles) vs. $\Delta_K$ (m$^{-1}$)

(b) N (cycles) vs. $\Delta M$ (Nm)

monlmk08.out
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(c) monlmk08.out

(d) monlmk08.out

max

min

mean
Fig. A.26. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK08, 7.62 Nm, Nf = 4.70E+06 cycles.
Fig. A.27. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK09, 10.16 Nm.
Fig. A.28. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK09, 10.16 Nm, Ns = 3.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s)  

(b) Moment (Nm)

LMK09/test01202, N= 1.24E+05

Original  

De-noised
Fig. A.29. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK09, 10.16 Nm, Ns = 1.24E+05 cycles.
(a)

(b)
(c)

monlmk09.out

N (cycles)

R (N m$^{-2}$)

0 10 20 30 40

10 100 1000 10000 100000 1000000

monlmk09.out

(d)

max

min

mean

N (cycles)
Fig. A.30. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK09, 10.16 Nm, Nf = 7.31E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Curvature range (m)

(b) Moment range (Nm)
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(c) Flexural rigidity (Nm$^2$) vs N (cycles)

(d) Curvature (m$^{-1}$) vs N (cycles)
Fig. A.31. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK10, 20.32 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a)

(b)
Fig. A.32. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK10, 20.32 Nm, Ns = 8.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s)  250 250.1 250.2 250.3 250.4

LMK10/test00902, N= 1.23E+04

Original

De-noised

(b) Time (s)  250 250.1 250.2 250.3 250.4

LMK10/test00902, N= 1.23E+04

Original

De-noised
Fig. A.33. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK10, 20.32 Nm, Ns = 1.23E+04 cycles.
Fig. A.34. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK10, 20.32 Nm, Nf = 5.20E+04 cycles.
Flexural rigidity (Nm$^2$)

Curvature (m$^{-1}$)

(c)

(d)
Fig. A.35. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK11, 8.64 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK11/test00302, N=1.35E+01

(a) Original
\( \Delta h = -1.50 \text{ mm} \)

LMK11/test00302, N=1.35E+01

(b) Original
De-noised
Fig. A.36. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK11, 8.64 Nm, Ns = 1.35E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a)

LMK11/test01202, N= 1.24E+05

\[ \kappa (m^{-1}) \]

\( \Delta h = -1.05 \text{ mm} \)

(b)

LMK11/test01202, N= 1.24E+05

Original

De-noised
Fig. A.37. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK11, 8.64 Nm, Ns = 1.24E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a)

(b)
CIRFT Testing Data Analyses and Updated Curvature Measurements

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N (cycles) [10 1 10 2 10 3 10 4 10 5 10 6]

R (Nm²) [0 10 20 30 40 50 60]

N (cycles) [10 10 2 10 3 10 4 10 5 10 6]

(c)

monlmk11.out

max
min
mean

(d)
Fig. A.38. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK11, 8.64 Nm, Nf = 3.55E+05 cycles.
Fig. A.39. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK12, 7.11 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a)  
LMK12/test00303, N= 2.60E+01

Time (s)  | 5  | 5.1 | 5.2 | 5.3 | 5.4

K (1/m)   | -0.3 | -0.2 | -0.1 | 0 | 0.1 | 0.2 | 0.3 | 0.4

(b)  
LMK12/test00303, N= 2.60E+01

Time (s)  | 5  | 5.1 | 5.2 | 5.3 | 5.4

Moment (Nm) | -8 | -6 | -4 | -2 | 0 | 2 | 4 | 6 | 8

Legend: Original  |  \( \Delta h = 0.00 \text{ mm} \)  
Legend: Original  |  De-noised  

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Fig. A.40. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK12, 7.11 Nm, Ns = 2.60E+01 cycles.
(a) CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK12/test02502, N = 4.88E+06

\( \kappa \) vs. Time (s)

(b) CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK12/test02502, N = 4.88E+06

Moment (Nm) vs. Time (s)
Fig. A.41. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK12, 7.11 Nm, $N_s = 4.88E+06$ cycles.
(a) 

\[ \Delta \kappa (m^{-1}) \]

\[ \Delta M (Nm) \]

(b)
CIRFT Testing Data Analyses and Updated Curvature Measurements
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(c) monlmk12.out

(d) monlmk12.out

max
min
mean

N (cycles)

R (Nm²)

ξ

N (cycles)
Fig. A.42. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK12, 7.11 Nm, Nf = 7.58E+06 cycles.
(a) Curvature range (m) vs. N (cycles)

(b) Moment range (Nm) vs. N (cycles)
Fig. A.43. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK13, 25.40 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a)

(b)
Fig. A.44. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK13, 25.40 Nm, Ns = 8.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK13/test00902, N= 1.23E+04

(a) Original

(b) De-noised
Fig. A.45. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK13, 25.40 Nm, Ns = 1.23E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) N (cycles) vs. $\Delta \kappa$ (m$^{-1}$)

(b) N (cycles) vs. $\Delta M$ (Nm)

monlmk13.out
Fig. A.46. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK13, 25.40 Nm, Nf = 2.10E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a) Curvature range (m) vs. N (cycles)

(b) Moment range (Nm) vs. N (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(c) N (cycles) vs. Flexural rigidity (Nm$^2$)

(d) N (cycles) vs. Curvature (m$^{-1}$)

measlmk14.inp

(c) Flexural rigidity (Nm$^2$) vs. N (cycles)

(d) Curvature (m$^{-1}$) vs. N (cycles)
Fig. A.47. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK14, 10.16 Nm.
Fig. A.48. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK14, 10.16 Nm, Ns = 2.60E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s) 900 900.1 900.2 900.3 900.4

LMK14/test01202, N= 1.02E+05

K (m⁻¹)

-0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3

Time (s) 900 900.1 900.2 900.3 900.4

Original

De-noised

(b) Moment (Nm)

-15 -10 -5 0 5 10

LMK14/test01202, N= 1.02E+05

Original

De-noised

Time (s) 900 900.1 900.2 900.3 900.4

Δh = -1.95 mm
Fig. A.49. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK14, 10.16 Nm, Ns = 1.02E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a)

(b)
CIRFT Testing Data Analyses and Updated Curvature Measurements
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\[ R (Nm^{-1}) \]

\[ \kappa (m^{-1}) \]

\[ N \text{ (cycles)} \]

(c)

(d)
Fig. A.50. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK14, 10.16 Nm, Nf = 3.90E+05 cycles.
(a) Curvature range (m) vs. N (cycles)

(b) Moment range (Nm) vs. N (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

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Flexural rigidity (Nm²)

Curvature (m⁻¹)

(c)

(d)
Fig. A.51. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK15, 10.16 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s) 7.5 7.6 7.7 7.8 7.9

(b) Moment (Nm)

LMK15/test00304, N=3.85E+01

Original

\[ \Delta h = -0.15 \text{ mm} \]

De-noised
Fig. A.52. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK15, 10.16 Nm, Ns = 3.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s) 250 250.1 250.2 250.3 250.4

(b) Time (s) 250 250.1 250.2 250.3 250.4

LMK15/test01202, N= 4.12E+05

Original

h = 1.20 mm

De-noised

Original

-10 -5 0 5 10

Moment (Nm)

LMK15/test01202, N= 4.12E+05

-10 -5 0 5 10

Moment (Nm)
Fig. A.53. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK15, 10.16 Nm, Ns = 4.12E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) 

(b)
Fig. A.54. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK15, 10.16 Nm, Nf = 4.41E+05 cycles.
(a) Curvature range (m^-1)

- N (cycles)
  - 10^0
  - 10^1
  - 10^2
  - 10^3
  - 10^4
  - 10^5

- Curvature range (m)
  - 0
  - 0.05
  - 0.1
  - 0.15
  - 0.2
  - 0.25
  - 0.3

(b) Moment range (Nm)

- N (cycles)
  - 10^0
  - 10^1
  - 10^2
  - 10^3
  - 10^4
  - 10^5

- Moment range (Nm)
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12
Fig. A.55. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK16, 30.48 Nm.
(a) 

LMK16/test00313, $N = 1.51E+02$

Original $\Delta h = -0.30$ mm

(b) 

LMK16/test00313, $N = 1.51E+02$

Original

De-noised
Fig. A.56. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK16, 30.48 Nm, Ns = 1.51E+02 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s) 250 250.1 250.2 250.3 250.4

(b) Time (s) 250 250.1 250.2 250.3 250.4

LMK16/test00902, N= 1.23E+04

Original

\( \Delta h = 0.75 \text{ mm} \)

De-noised
Fig. A.57. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK16, 30.48 Nm, Ns = 1.23E+04 cycles.
(a) N (cycles) vs. $\Delta \kappa$ (m$^{-1}$)

(b) N (cycles) vs. $\Delta M$ (Nm)

monlmk16.out
Fig. A.58. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK16, 30.48 Nm, Nf = 1.36E+04 cycles.
(a) Curvature range (m) vs. N (cycles)

(b) Moment range (Nm) vs. N (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(c)

(d)
Fig. A.59. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK17, 8.64 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Time (s) 7.5 7.6 7.7 7.8 7.9

(b) Moment (Nm) -10 -5 0 5 10

LMK17/test00304, N= 3.85E+01

Original
Δh = -0.75 mm

LMK17/test00304, N= 3.85E+01

Original
De-noised
Fig. A.60. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK17, 8.64 Nm, Ns = 3.85E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

LMK17/test02402, N= 2.96E+06

(a) Original
\[ \Delta h = -0.90 \text{ mm} \]

LMK17/test02402, N= 2.96E+06

(b) Original
\[ \text{De-noised} \]
Fig. A.61. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK17, 8.64 Nm, Ns = 2.96E+06 cycles.
## CIRFT Testing Data Analyses and Updated Curvature Measurements

### (a)

<table>
<thead>
<tr>
<th>N (cycles)</th>
<th>Δκ (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>10³</td>
<td>0.2</td>
</tr>
<tr>
<td>10⁵</td>
<td>0.3</td>
</tr>
<tr>
<td>10⁷</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### (b)

<table>
<thead>
<tr>
<th>N (cycles)</th>
<th>ΔM (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>10³</td>
<td>10</td>
</tr>
<tr>
<td>10⁵</td>
<td>15</td>
</tr>
<tr>
<td>10⁷</td>
<td>20</td>
</tr>
</tbody>
</table>
(c) monlmk17.out

(d) monlmk17.out
Fig. A.62. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK17, 8.64 Nm, Nf = 3.37E+06 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a)  

LMK18/test02503, N= 2.51E+02

-1.5
-1
-0.5
0
0.5
1
1.5

K [1/m]

Time (s)
50 50.1 50.2 50.3 50.4

(b)  

LMK18/test02503, N= 2.51E+02

-40
-30
-20
-10
0
10
20
30

Moment (Nm)

Time (s)
50 50.1 50.2 50.3 50.4

Original

De-noised
Fig. A.63. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK18, 30.48 Nm, Ns = 2.51E+02 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements
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(a)

LMK18/test02602, N= 1.25E+04

Time (s)
500 500.1 500.2 500.3 500.4

\( \kappa \) [m^{-1}]
-1.5 -1 -0.5 0 0.5 1

(b)

LMK18/test02602, N= 1.25E+04

Time (s)
500 500.1 500.2 500.3 500.4

Moment (Nm)
-40 -30 -20 -10 0 10 20 30

Original
\( \Delta h = 1.50 \text{ mm} \)
De-noised

Original
De-noised
Fig. A.64. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, LMK18, 30.48 Nm, Ns = 1.25E+04 cycles.
The images show plots from the analysis of CIRFT testing data and updated curvature measurements.

(c) shows a plot of the radius of curvature (R) in N m\(^2\) vs. the number of cycles (N) on a logarithmic scale. The data is from `monlmk18.out`.

(d) displays another set of plots, also from `monlmk18.out`, showing max, min, and mean values over the same scale for radius of curvature.
Fig. A.65. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, LMK18, 30.48 Nm, Nf = 1.31E+04 cycles.
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TABLE OF CONTENTS

APPENDIX B  CIRFT TESTING RESULTS OF NA................................................................. B-1
  Measurement and monitoring rigidity curves of NA....................................................... B-3
Measurement and monitoring rigidity curves of North Anna Spent Nuclear Fuel
(a) CIRFT Testing Data Analyses and Updated Curvature Measurements

Time (s)

Moment (Nm)

NA1/test00405, N= 5.10E+01

Original

\( \Delta = 0.00 \text{ mm} \)

(b) CIRFT Testing Data Analyses and Updated Curvature Measurements

Time (s)
Fig. B.1. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA1, 12.70 Nm, Ns = 5.10E+01 cycles.
Fig. B.2. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA1, 12.70 Nm, Ns = 1.23E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

\[ \Delta K (m^{-1}) \]

\[ M (Nm) \]

\[ N \text{ (cycles)} \]

(a)

(b)
monna1.out

(c)

monna1.out

(d)
Fig. B.3. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA1, 12.70 Nm, Nf = 1.57E+04 cycles.
(a) 

NA2/test00304, N = 3.85E+01

\[ \kappa (m^{-1}) \]

Time (s) 7.5 7.6 7.7 7.8 7.9

\(\Delta h = 1.65 \text{ mm}\)

(b) 

NA2/test00304, N = 3.85E+01

\[ \text{Moment (Nm)} \]

Time (s) 7.5 7.6 7.7 7.8 7.9
Fig. B.4. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA2, 10.16 Nm, $N_s = 3.85E+01$ cycles.
Fig. B.5. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA2, 10.16 Nm, Ns = 1.35E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(c)

(d)

monna2.out

N (cycles)

R (Nm$^{-2}$)

0
5
10
15
20
25
30

10^1
10^2
10^3
10^4
10^5

max
min
mean

monna2.out

K (m$^{-1}$)

0
-0.2
-0.4
-0.6

10^1
10^2
10^3
10^4
10^5

N (cycles)
Fig. B.6. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA2, 10.16 Nm, $N_f = 2.20 \times 10^4$ cycles.
Fig. B.7. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA4, 7.62 Nm, Ns = 1.35E+01 cycles.
NA4/test00902, N= 1.23E+04

(a) $\kappa (\rho, t)$

(b) Moment (Nm)
Fig. B.8. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA4, 7.62 Nm, Ns = 1.23E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) 

(b) 

monna4.out

\[ \Delta K (m^{-1}) \]

\[ \Delta M (Nm) \]

N (cycles)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

10^1 10^2 10^3 10^4 10^5

monna4.out

N (cycles)

0 2 4 6 8 10 12 14 16

10^1 10^2 10^3 10^4 10^5
Fig. B.9. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA4, 7.62 Nm, Nf = 6.10E+04 cycles.
Fig. B.10. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA5, 5.08 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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NA5/test00303, N= 2.60E+01

(a) Time (s) 5 5.1 5.2 5.3 5.4

K (m⁻¹)
-0.3
-0.2
-0.1
0
0.1
0.2
0.3

(b) Time (s) 5 5.1 5.2 5.3 5.4

NA5/test00303, N= 2.60E+01

Original
Δ h = 0.90 mm

Original
De-noised

NA5/test00303, N= 2.60E+01

Time (s)

Moment (Nm)
-6
-4
-2
0
2
4
6
Fig. B.11. Monitoring-based responses: (a) curvature, (b) moment,
(c) curvature, NA5, 5.08 Nm, Ns = 2.60E+01 cycles.
(a) NA5/test03002, N= 4.12E+06

(b) NA5/test03002, N= 4.12E+06
Fig. B.12. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA5, 5.08 Nm, Ns = 4.12E+06 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a)  

(b)
CIRFT Testing Data Analyses and Updated Curvature Measurements

(c)

(d)
Fig. B.13. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA5, 5.08 Nm, Nf = 5.11E+06 cycles.
Fig. B.14. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA6, 5.08 Nm.
NA6/test00304, N=3.85E+01

(a) De-noised

NA6/test00304, N=3.85E+01

(b) De-noised
Fig. B.15. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA6, 5.08 Nm, Ns = 3.85E+01 cycles.
(a) NA6/test00902, N= 1.64E+04

- Original
- $\Delta h = 1.50$ mm

(b) NA6/test00902, N= 1.64E+04

- Original
- De-noised
Fig. B.16. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA6, 5.08 Nm, Ns = 1.64E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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Figure (c) shows the variation of curvature with the number of cycles. The graph displays the relationship between the number of cycles (N) and the curvature (R). The data points are scattered, indicating a non-linear relationship. The minimum and maximum values of R are highlighted, with the mean value also shown.

Figure (d) presents similar data but includes an additional line representing the mean curvature. The max and min values are again marked, with the mean value clearly visible. The graph provides a comprehensive view of the curvature's behavior across the range of cycles.
Fig. B.17. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA6, 5.08 Nm, Nf = 4.27E+05 cycles.
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N (cycles)
10 0 10 1 10 2 10 3 10 4 10 5

Flexural rigidity (Nm^2)
0 5 10 15 20 25 30 35

measna7.inp

N (cycles)
10 0 10 1 10 2 10 3 10 4 10 5

Curvature (m^{-1})
-0.3 -0.2 -0.1 0 0.1 0.2

measna7.inp

(c)

(d)
Fig. B.18. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA7, 15.24 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

NA7/test00309, N=1.01E+02

(a) Original

(b) De-noised
Fig. B.19. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA7, 15.24 Nm, Ns = 1.01E+02 cycles.
(a) NA7/test00902, N=1.11E+04

(b) NA7/test00902, N=1.11E+04
Fig. B.20. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, NA7, 15.24 Nm, Ns = 1.11E+04 cycles.
(a) 

![Graph showing variation with cycles](image)

(b) 

![Graph showing variation with cycles](image)
(c) monna7.out

(d) monna7.out
Fig. B.21. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, NA7, 15.24 Nm, Nf = 1.26E+04 cycles.
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  Measurement and monitoring rigidity curves of MOX.............................................. C-3
Measurement and monitoring rigidity curves of CATAWBA MOX Spent Nuclear Fuel
CIRFT Testing Data Analyses and Updated Curvature Measurements

N (cycles)

Curvature range ($m^{-1}$)

0
0.1
0.2
0.3
0.4
0.5
0.6
10^0
10^1
10^2
10^3
10^4
10^5

measmox02.inp

N (cycles)

Moment range (Nm)

0
5
10
15
10^0
10^1
10^2
10^3
10^4
10^5

measmox02.inp

(a)

(b)
Fig. C.1. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX02, 10.16 Nm.
Fig. C.2. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX02, 10.16 Nm, Ns = 3.85E+01 cycles.
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(a)

(b)
Fig. C.3. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX02, 10.16 Nm, Ns = 1.23E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(c)  

(d)
Fig. C.4. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX02, 10.16 Nm, Nf = 3.70E+04 cycles.
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(a)

(b)
(c) Plots showing the relationship between flexural rigidity (Nm²) and number of cycles (N) for different materials. The plots demonstrate a decreasing trend with increasing cycles.

(d) Plots showing the relationship between curvature (m⁻¹) and number of cycles (N) for different materials. The plots indicate a steady state or slight decrease in curvature as the number of cycles increases.
Fig. C.5. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX04, 5.08 Nm.
(a) MOX04/test00302, N=1.35E+01

Original
Δh = -1.20 mm

(b) MOX04/test00302, N=1.35E+01

Original
De-noised
Fig. C.6. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX04, 5.08 Nm, Ns = 1.35E+01 cycles.
(a) MOX04/test01802, N= 1.56E+06

Time (s)

K (m -1 )

-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
2500 2500.1 2500.2 2500.3 2500.4

Original
Δh = -3.00 mm

(b) MOX04/test01802, N= 1.56E+06

Time (s)

Moment (Nm)

-5
0
5
2500 2500.1 2500.2 2500.3 2500.4

Original
De-noised
Fig. C.7. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX04, 5.08 Nm, \( N_s = 1.56E+06 \) cycles.
(a) 

$\Delta K$ (m$^{-1}$) vs. $N$ (cycles) 

(b) 

$\Delta M$ (Nm) vs. $N$ (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

monmax04.out

(c)

R (Nm⁻²)

N (cycles)

monmax04.out

(d)

\( \kappa (m^{-1}) \)

N (cycles)
Fig. C.8. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX04, 5.08 Nm, Nf = 2.15E+06 cycles.
(a) Curvature range (m)

- N (cycles): 10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6
- Curvature range (m): 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3

measmox05.inp

(b) Moment range (Nm)

- N (cycles): 10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6
- Moment range (Nm): 0, 1, 2, 3, 4, 5, 6, 7

measmox05.inp
CIRFT Testing Data Analyses and Updated Curvature Measurements
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(c) Flexural rigidity (Nm$^2$)

(d) Curvature (m$^{-1}$)
Fig. C.9. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX05, 6.10 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements
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(a) Time (s)
5 5.1 5.2 5.3 5.4

(b) MOX05/test00303, N= 2.60E+01

-0.3
-0.2
-0.1
0
0.1
0.2
0.3

Original

De-noised

Δh = -0.30 mm

Original

De-noised

K (m
-1)

Time (s)
5 5.1 5.2 5.3 5.4

MOX05/test00303, N= 2.60E+01

-6
-4
-2
0
2
4
6

Moment (Nm)

Time (s)
5 5.1 5.2 5.3 5.4

(b)
Fig. C.10. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX05, 6.10 Nm, Ns = 2.60E+01 cycles.
Fig. C.11. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX05, 6.10 Nm, Ns = 1.24E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(c) N (cycles)

(d) N (cycles)
Fig. C.12. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX05, 6.10 Nm, Nf = 4.49E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a)

N (cycles)

Curvature range (m)

0.05
0.1
0.15
0.2

0
0.1
0.2
0.3

measmox06.inp

0.4
0.7

(b)

N (cycles)

Moment range (Nm)

0
1
2
3
4
5
6

0
1
2
3
4
5
6

measmox06.inp

0.4
0.7
Fig. C.13. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX06, 5.08 Nm.
Fig. C.14. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX06, 5.08 Nm, Ns = 5.10E+01 cycles.
(a) MOX06/test01202, N= 1.24E+05

(b) MOX06/test01202, N= 1.24E+05
Fig. C.15. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX06, 5.08 Nm, Ns = 1.24E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(c) monmax06.out

(d) monmax06.out

N (cycles)

R (Nm⁻²)

max

min

mean

monmax06.out
Fig. C.16. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX06, 5.08 Nm, Nf = 5.42E+05 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) Curvature range (m$^{-1}$) vs. N (cycles)

(b) Moment range (Nm) vs. N (cycles)
Fig. C.17. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX07, 15.24 Nm.
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MOX07/test00310, N= 1.14E+02

(a)

MOX07/test00310, N= 1.14E+02

(b)
Fig. C.18. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX07, 15.24 Nm, Ns = 1.14E+02 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a) Time (s)  
75 75.1 75.2 75.3 75.4

(b) MOX07/test00902, N=1.14E+04

Original

De-noised

Δh = 0.30 mm

Time (s)
Fig. C.19. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX07, 15.24 Nm, Ns = 1.14E+04 cycles.
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(a) 

\[ \Delta K \; (\text{m}^{-1}) \]

N (cycles)

(b) 

\[ \Delta M \; (\text{Nm}) \]

N (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

(c) monmox07.out

(d) monmox07.out
Fig. C.20. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX07, 15.24 Nm, Nf = 1.55E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a) Time (s)

(b) Time (s)
Fig. C.21. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX08, 12.70 Nm, Ns = 7.60E+01 cycles.
Fig. C.22. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX08, 12.70 Nm, Ns = 1.23E+04 cycles.
(c) and (d) show graphs from `monmax08.out`. Graph (c) plots `R (Nm²)` against `N (cycles)`, while graph (d) plots `κ (m⁻¹)` against `N (cycles)`. The graphs illustrate the relationship between cycles and curvature measurements.
Fig. C.23. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX08, 12.70 Nm, Nf = 1.29E+04 cycles.
(a) Curvature range (m/m)

(b) Moment range (Nm)
CIRFT Testing Data Analyses and Updated Curvature Measurements

N (cycles) vs. Flexural rigidity (Nm)

-0.3
-0.2
-0.1
0
0.1
0.2

Curvature (m-1)

measmo09.inp

(c)

(d)
Fig. C.24. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX09, 7.62 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

MOX09/test00307, N= 7.60E+01

(a)

MOX09/test00307, N= 7.60E+01

(b)
Fig. C.25. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX09, 7.62 Nm, Ns = 7.60E+01 cycles.
(a) 

CIRFT Testing Data Analyses and Updated Curvature Measurements

MOX09/test00902, N= 1.23E+04

Time (s)

(b) 

MOX09/test00902, N= 1.23E+04

Time (s)
Fig. C.26. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX09, 7.62 Nm, Ns = 1.23E+04 cycles.
(a) 

(b)
### CIRFT Testing Data Analyses and Updated Curvature Measurements

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#### Table 1: Curvature Measurements

<table>
<thead>
<tr>
<th>N (cycles)</th>
<th>10</th>
<th>1</th>
<th>10</th>
<th>2</th>
<th>10</th>
<th>3</th>
<th>10</th>
<th>4</th>
<th>10</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (Nm⁻¹)</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

#### Graphs (c) and (d):

- **Graph (c)**: Monomax09.out, showing R (Nm⁻¹) vs. N (cycles).
- **Graph (d)**: Monomax09.out, showing curvature (km⁻¹) vs. N (cycles).

The graphs illustrate the updated curvature measurements obtained from the testing data analyses, highlighting the relationship between the number of cycles (N) and curvature (R) or curvature (K), respectively.
Fig. C.27. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX09, 7.62 Nm, Nf = 8.98E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a) Curvature range (m) vs. N (cycles)

(b) Moment range (Nm) vs. N (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(c) N (cycles)

Flexural rigidity (Nm)

0 10 20 30 40 50 60

-0.3 -0.2 -0.1 0 0.1 0.2

Curvature (m⁻¹)

N (cycles)

0 10 20 30 40 50 60

(d)
Fig. C.28. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX10, 10.16 Nm.
(a) Time (s) vs. Curvature $(K)$

(b) Time (s) vs. Moment (Nm)

MOX10/test00307, N=7.60E+01

Original

$\Delta h = -0.60$ mm

De-noised
Fig. C.29. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX10, 10.16 Nm, Ns = 7.60E+01 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

(a) MOX10/test00702, N=1.23E+04

(b) MOX10/test00702, N=1.23E+04

Original

\( \Delta h = -0.75 \text{ mm} \)

De-noised

MOX10/test00702, N=1.23E+04

Original

De-noised

MOX10/test00702, N=1.23E+04

MOX10/test00702, N=1.23E+04

MOX10/test00702, N=1.23E+04

MOX10/test00702, N=1.23E+04

MOX10/test00702, N=1.23E+04

MOX10/test00702, N=1.23E+04

MOX10/test00702, N=1.23E+04

MOX10/test00702, N=1.23E+04
Fig. C.30. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX10, 10.16 Nm, Ns = 1.23E+04 cycles.
Fig. C.31. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX10, 10.16 Nm, Nf = 3.85E+04 cycles.
(a) Curvature range vs. N (cycles)

Moment range (Nm) vs. N (cycles)

(b)
Fig. C.32. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX11, 10.16 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

MOX11/test00308, N= 8.85E+01

(a)

(b)
Fig. C.33. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX11, 10.16 Nm, Ns = 8.85E+01 cycles.
(a) MOX11/test00902, N=1.23E+04

\[ \kappa (s^{-1}) \]

\[ \Delta h = -0.45 \, \text{mm} \]

(b) MOX11/test00902, N=1.23E+04

\[ \text{Moment (Nm)} \]

Original
De-noised
Fig. C.34. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX11, 10.16 Nm, Ns = 1.23E+04 cycles.
Fig. C.35. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX11, 10.16 Nm, Nf = 4.23E+04 cycles.
CIRFT Testing Data Analyses and Updated Curvature Measurements

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(a) Curvature range (m$^{-1}$) vs. N (cycles)

(b) Moment range (Nm) vs. N (cycles)
CIRFT Testing Data Analyses and Updated Curvature Measurements

(c)

(d)
Fig. C.36. Measurement-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX12, 10.16 Nm.
CIRFT Testing Data Analyses and Updated Curvature Measurements

MOX12/test00305, N= 5.10E+01

(a)

(b)

MOX12/test00305, N= 5.10E+01
Fig. C.37. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX12, 10.16 Nm, Ns = 5.10E+01 cycles.
MOX12/test00902, N = 1.23E+04

Original

\( h = -0.75 \text{ mm} \)

(a)

(b)
Fig. C.38. Monitoring-based responses: (a) curvature, (b) moment, (c) curvature, MOX12, 10.16 Nm, $N_s = 1.23E+04$ cycles.
Figure (a) shows the variation of $\Delta K$ (mm$^{-1}$) with the number of cycles $N$ (cycles). The data is plotted on a log-log scale.

Figure (b) displays the change in torque $\Delta M$ (Nm) against the number of cycles $N$ (cycles). The graph also uses a log-log scale.
Fig. C.39. Monitoring-based responses: (a) curvature range, (b) moment range, (c) rigidity, (d) curvature peak/valley, (e) moment peak/valley, MOX12, 10.16 Nm, Nf = 4.23E+04 cycles.