Reversible Bending Fatigue Testing on Zry-4 Surrogate Rods

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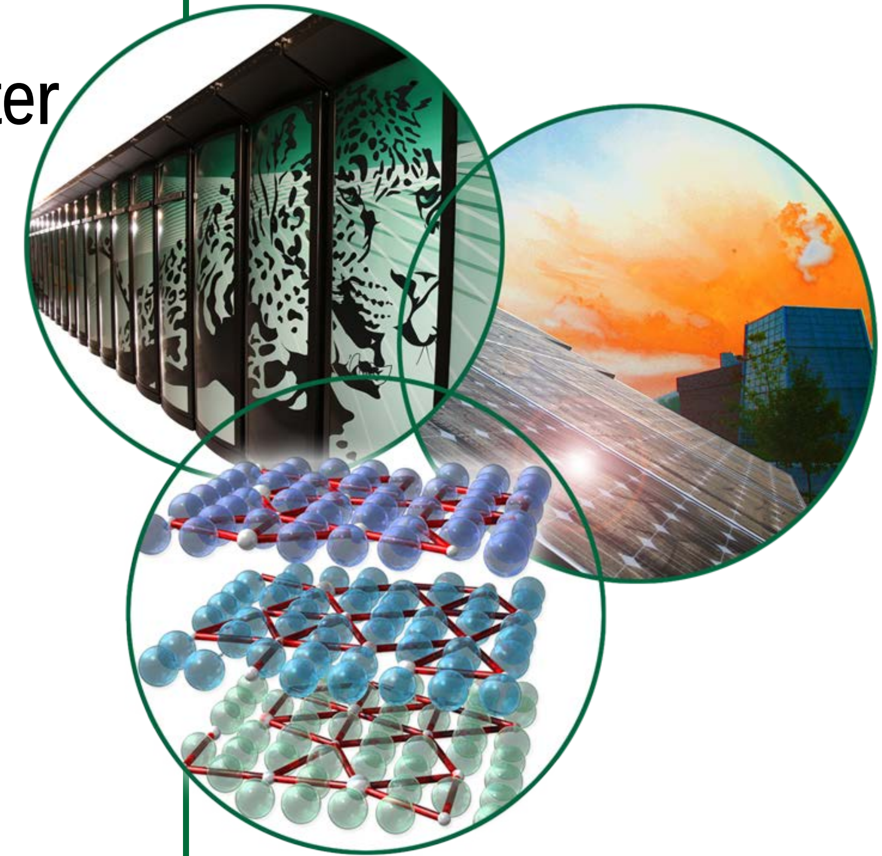

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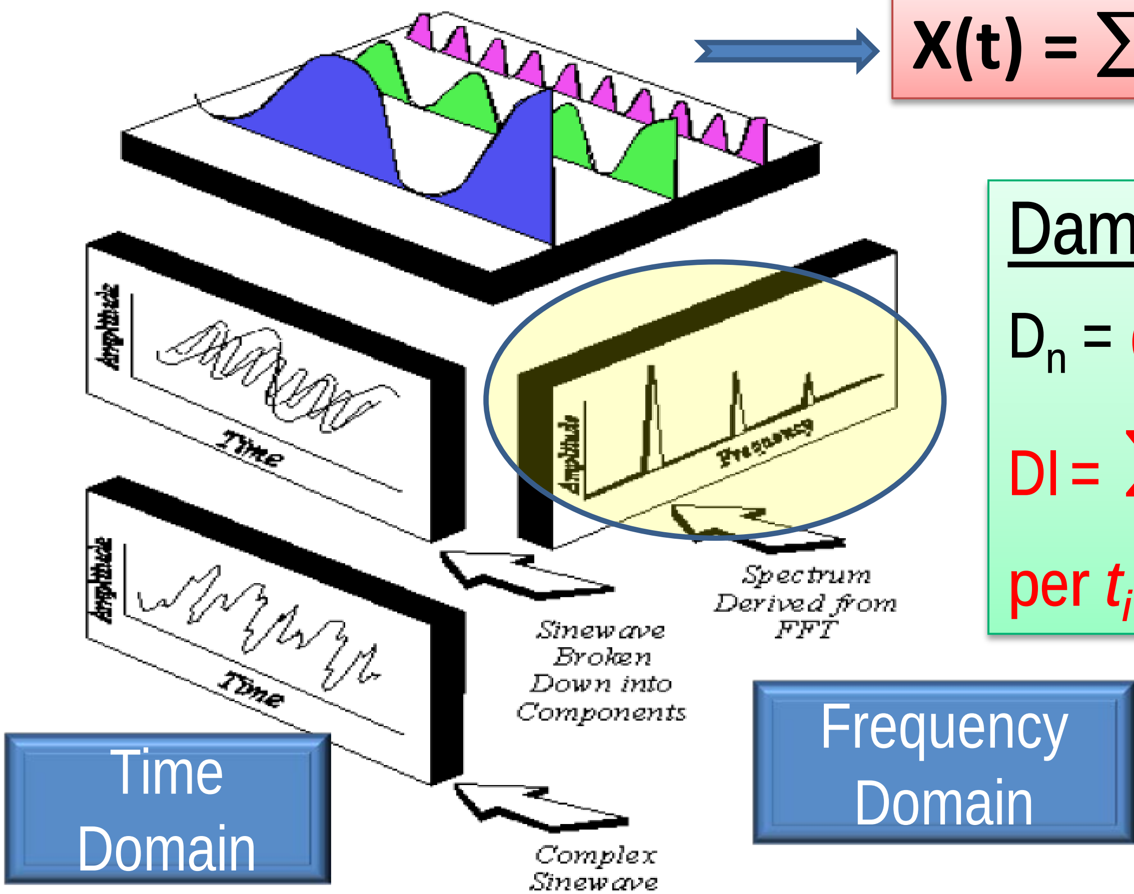
A revolutionary device (CIRFT) has been developed for investigating used nuclear fuel (UNF) vibration integrity

1. UNF transport must meet safety requirements
2. Previously, the ability to evaluate UNF vibration integrity was limited
3. A fuel/clad rod is a complicated composite system
4. Cyclic integrated reversible-bending fatigue tester (CIRFT) mimics fuel transport dynamic loading
5. A potentially important fuel-clad interaction mechanism was noted from CIRFT surrogate testing

Presentation Outline

- Background
- CIRFT system development
- Applying CIRFT to surrogate Zr-4 rod testing
- Fuel-clad interaction & interface bonding efficiency under dynamic loadings
- Conclusions

Fatigue strength data is essential for evaluating UNF structural performance under random vibration loading during normal conditions of transport (NCT)



$$X(t) = \sum_{n=1,M} C_n \, \mathrm{Sin}\,(\omega_n t)$$

Damage index evaluation

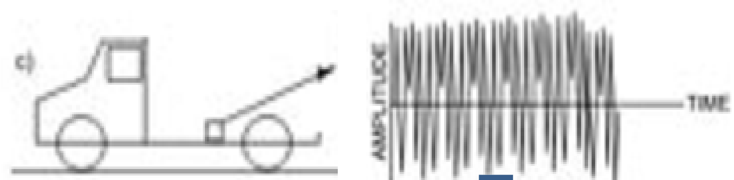
$D_n = (\omega_n t_i)$ / fatigue life, per C_n

$DI = \sum_{n=1,M} D_n$,

per t_i leg travel time interval.

UNF vibration fatigue life/limit needs to be understood during NCT operation

Reactor site



Storage site

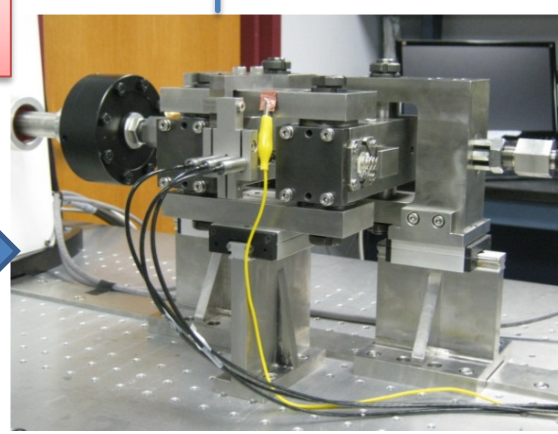
Number of cycles of individual components, depending on transportation distance: N1, N2, ...

FFT

Frequencies: F1, F2, …, Amplitudes: A1, A2, …

$$X(t) = \sum_{n=1,M} C_n \, \mathrm{Sin}\,(\omega_n t)$$

CIRFT test determines ***fatigue life*** ***at Cn*** load

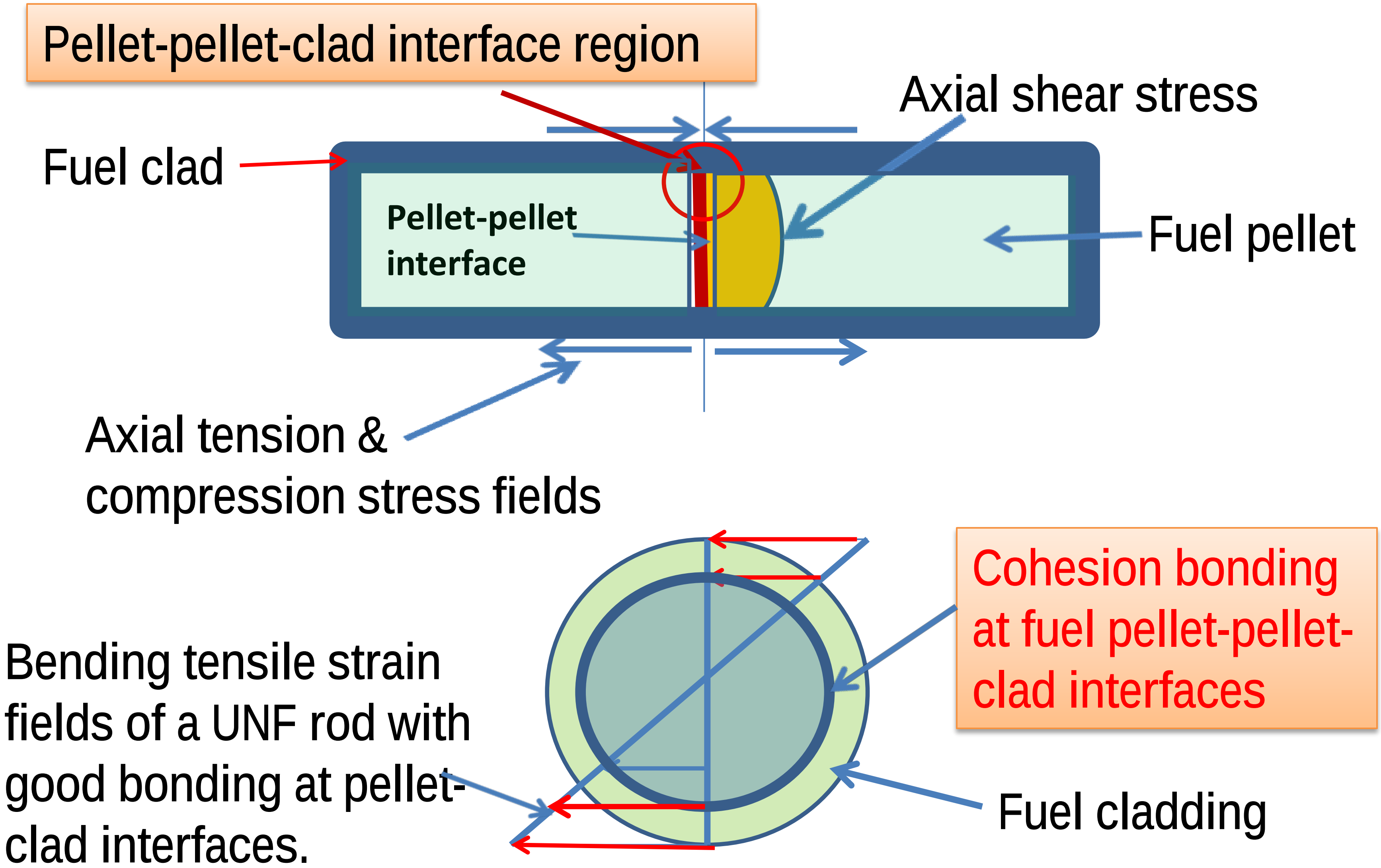


<u>Total Damage Index,</u>

$$DI_T = \sum_{i=1,N} DI_i$$

If $DI_T < 1$ then UNF will remain proper functionality at the end of trip.

UNF fatigue originates from Inertia induced bending stresses during NCT



Insufficient interface bonding can degrade flexural rigidity of a UNF composite system

Flexural Rigidity: $EI = \Delta M/\Delta k$

$EI_{System} = E_{Fuel} I_{Fuel} + E_{Clad} I_{clad}$ (*Perfect bonding condition*)

$EI_{System} = E_{Fuel} I_{Fuel} + E_{Clad} I_{Clad} - BE$ *(loading, frequency, temperature)*

E: Young's modulus, component properties dependent parameter

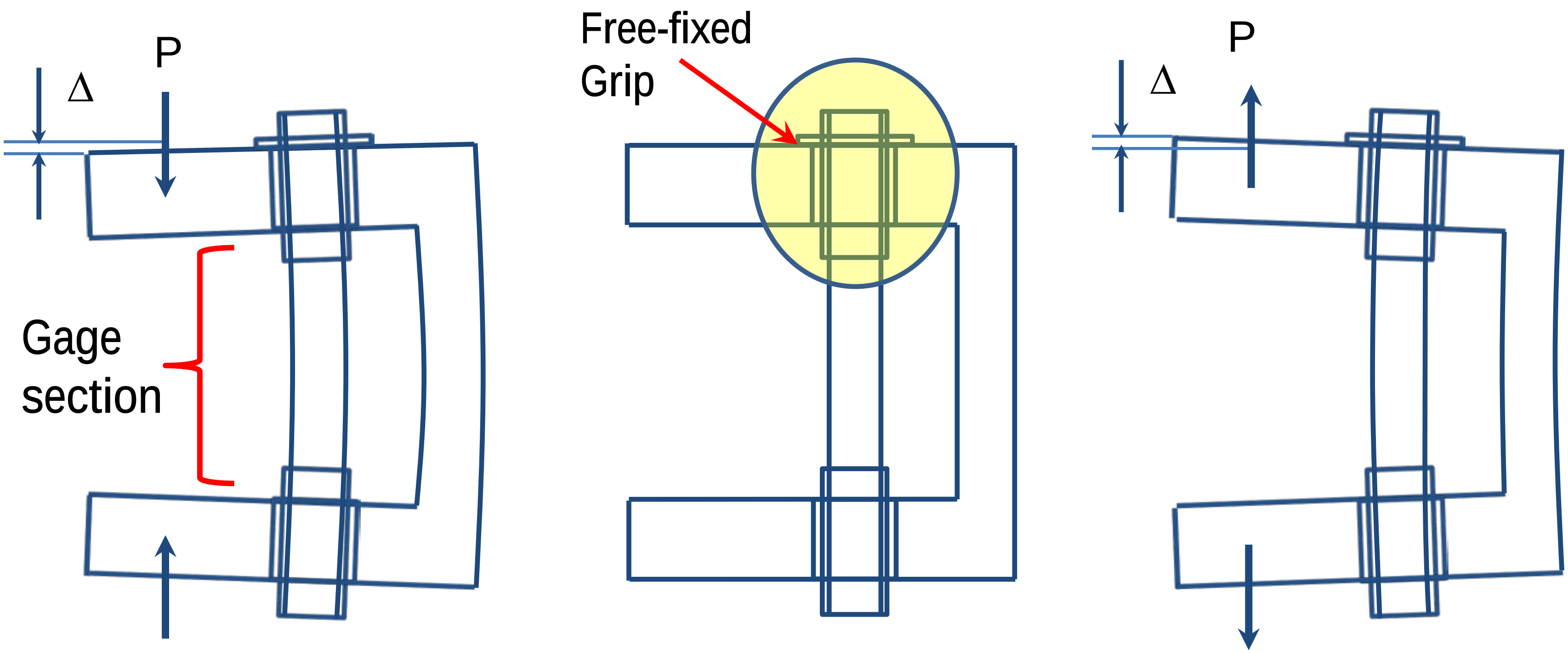
I : Components geometry dependent parameter

BE: Interfaces Bonding Efficiency at the pellet-pellet & pellet-clad interfaces

No test system has been available for accurately studying UNF integrity under normal condition transportion

- UNF is a composite structure with multi-scale discontinuities
- CIRFT system attributes include:
  - No reduced section or notch in gage section
  - A free-fixed boundary condition
  - Robust system to ensure test reproducibility
  - Testing in a hot-cell environment with ease of test sample preparation and testing

Using CIRFT, a test rod experiences reversal bending through closing and opening actions of two loading arms

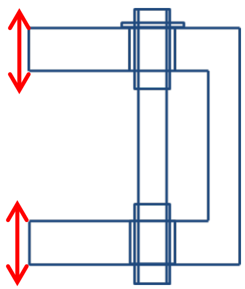


(a) rigid arms are closing.

(b) rigid arms are in neutral position.

(c) rigid arms are opening.

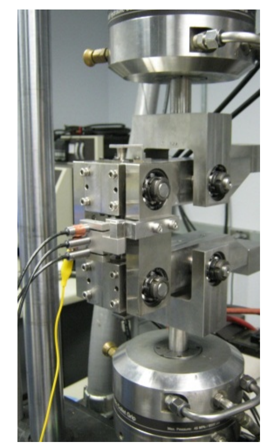
Prototyping began in 2011 and progressed through multiple iterations to address testing challenges and optimize design



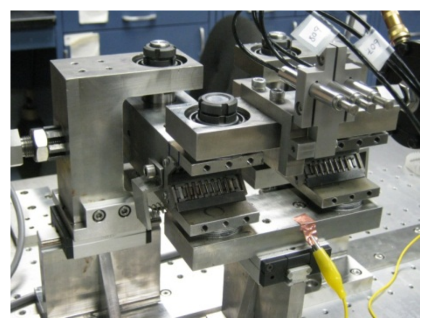
Apr. 2011: Initial Concept – Pure Bending Moment

Jun. 2011: Vertical test on servo-hydraulic machine

Sept. 2011: Setup using counter weights & Rigid Sleeves



Feb. 2012: Improved performance and reliability



Sept. 2012: Setup on Bose dual LM2 TB (no counterweight) – better high freq performance

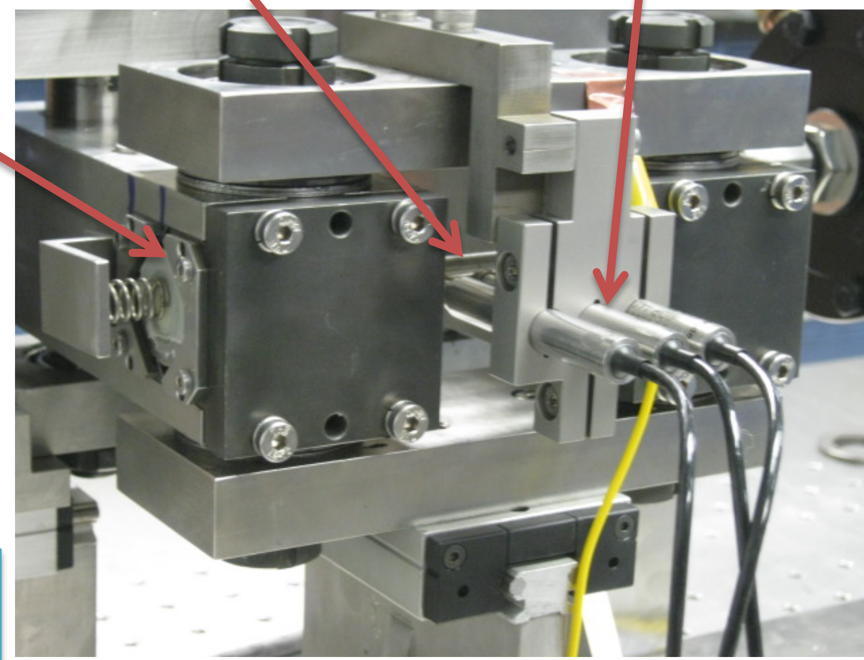
August 2013: Finalized setup on Bose dual LM2 TB and moved into hot cell

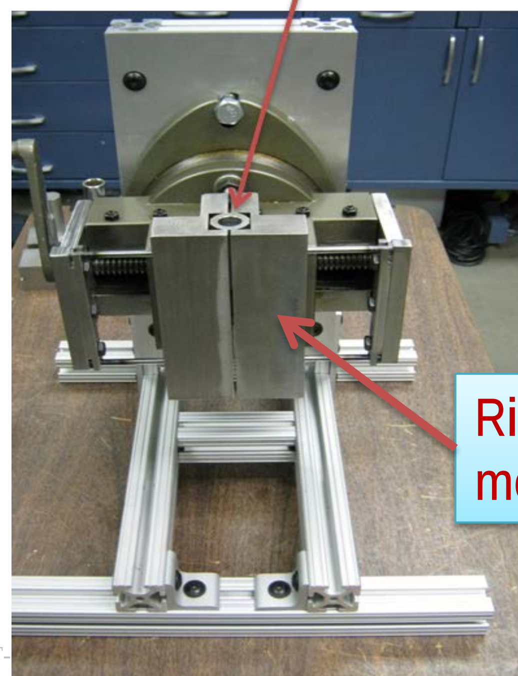
Specimen preparation is a key step for CIRFT testing

Two rigid sleeves are epoxied to test specimen to provide stability and a protective compliant layer.

3 LVDTs for real-time curvature measurement

Rod specimen





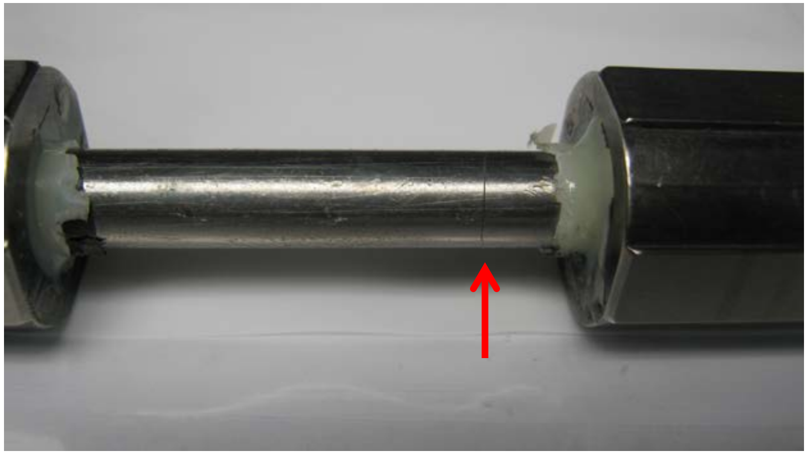
Rigid sleeve mold

Test samples were Zr-4 clad with alumina pellet inserts.

Out-of-cell test rods all failed within the gage section at pellet-pellet interface

(a)

(b)

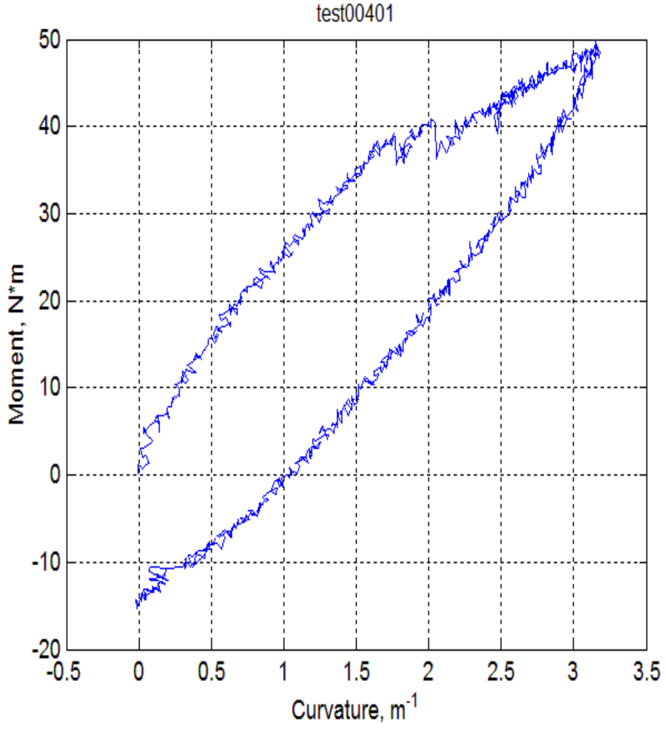


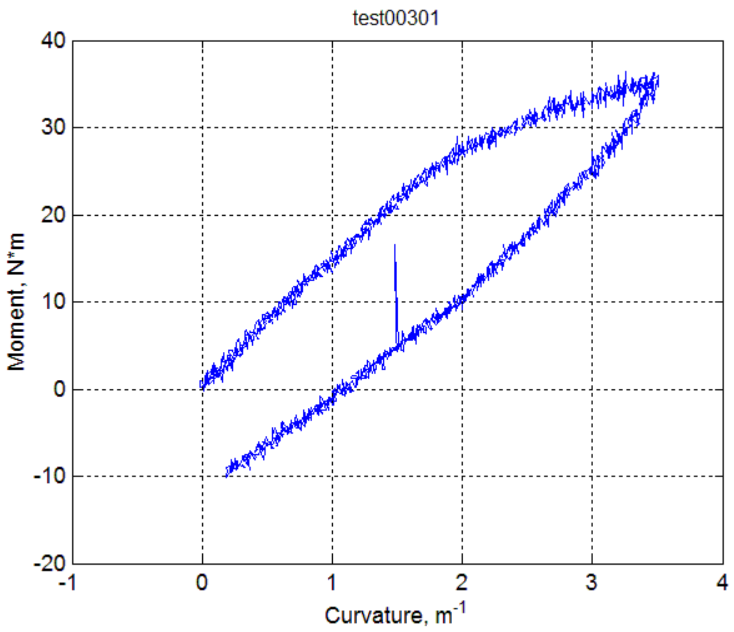
(c)

(d)

Surrogate rods made of Zr-4 clad with alumina pellet inserts.

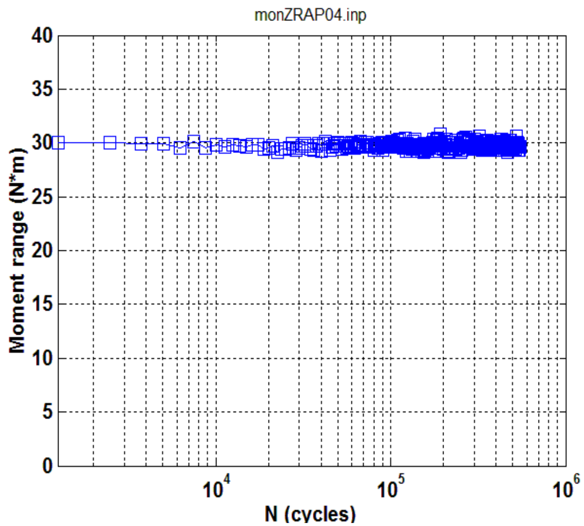
Zr-4 rod with epoxy bond has higher flexural rigidity and higher bending resistance

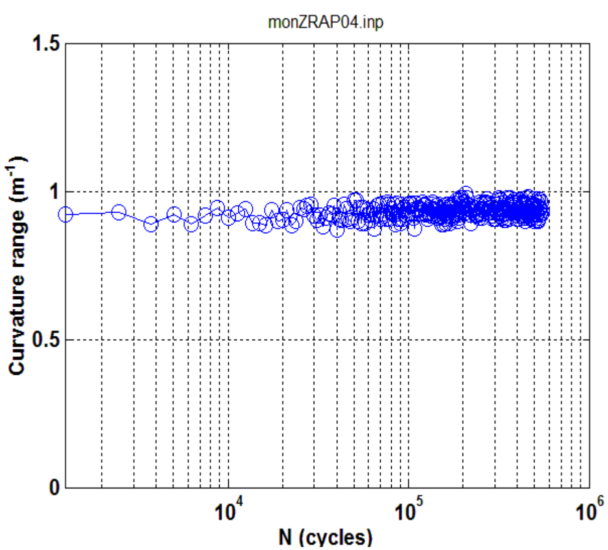


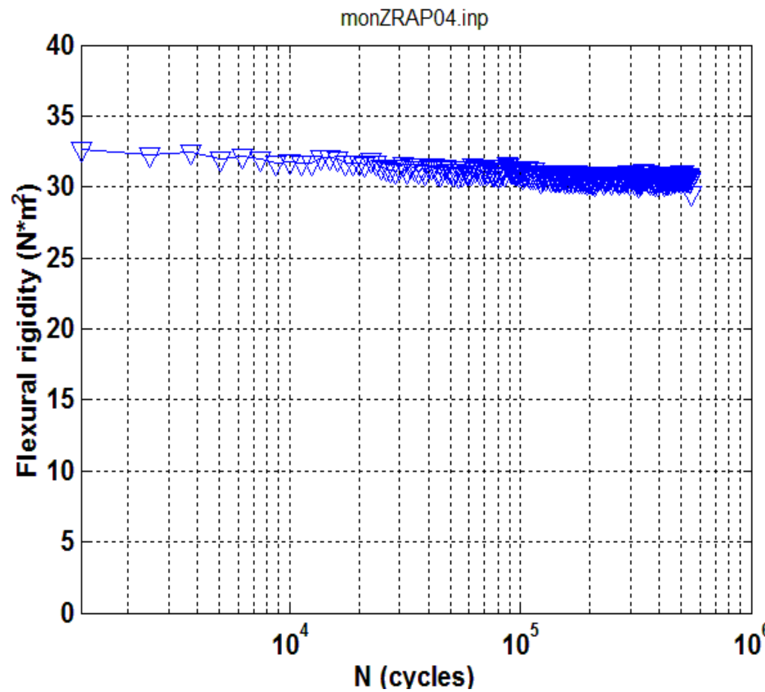


(Left) Zr-4 sample w/ epoxy, (Right) Zr-4 sample w/o epoxy, both tests under 0.2 mm/s and maximum relative displacement of 20 mm at loading points of U-frame

CIRFT real-time monitoring data shows continued decrease in flexural rigidity

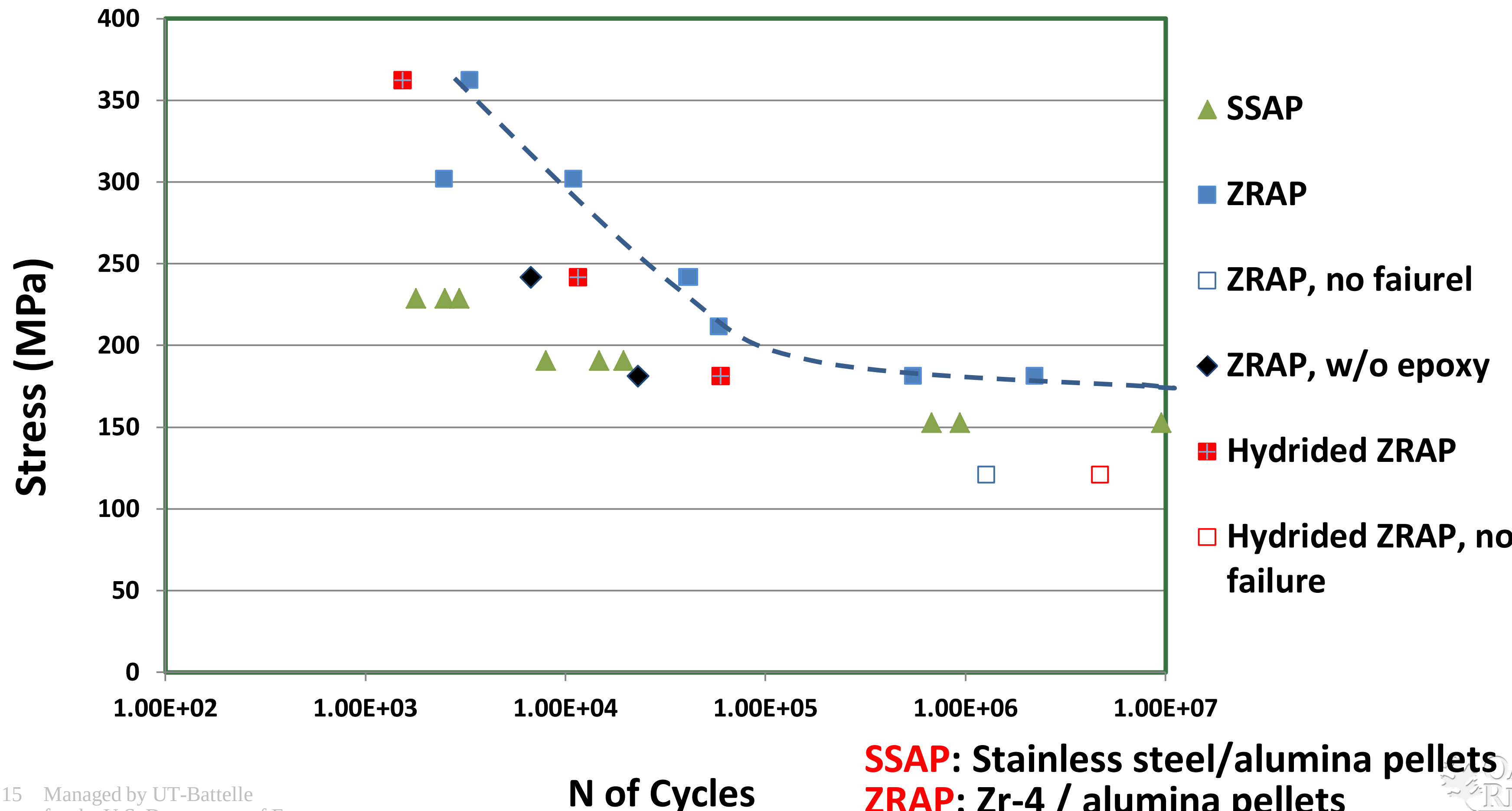






- test sample failed at 5.49E+05 cycles, ±150N, 5 Hz
- 7% flexural rigidity drop shown before final fracture

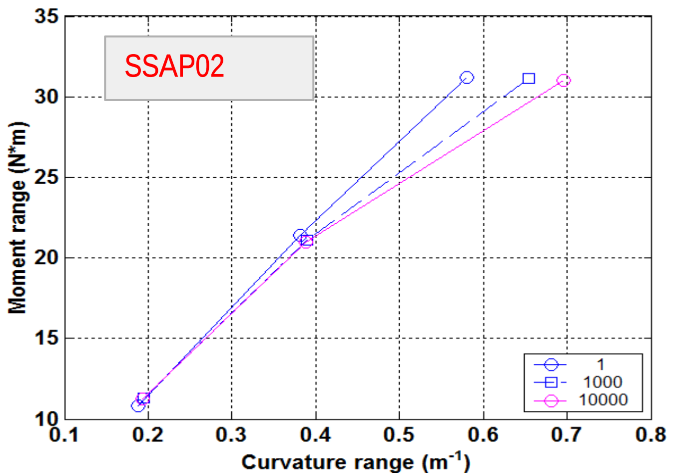
S-N fatigue trend of Zr-4 surrogate rods show distinct "KNEE"

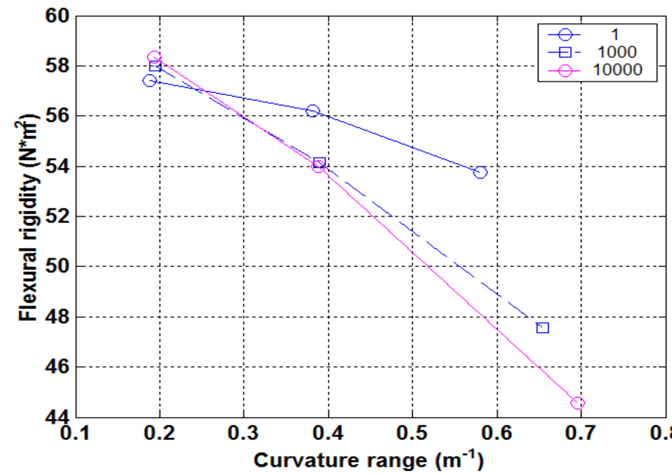


SSAP: Stainless steel/alumina pellets
ZRAP: Zr-4 / alumina pellets

Pellet-clad bonding efficiency has major impact on surrogate rod performance

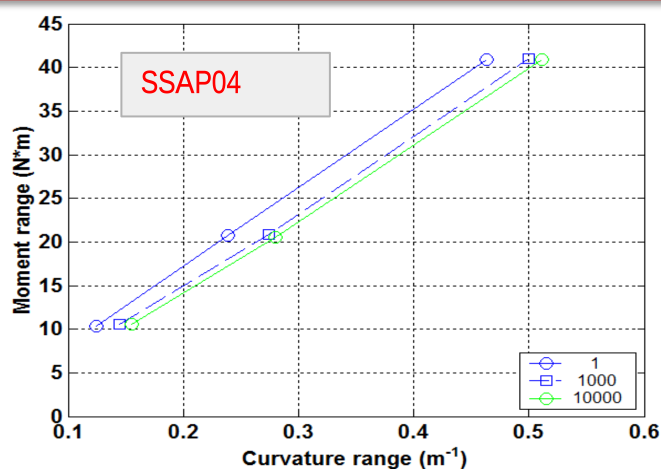
No epoxy bond

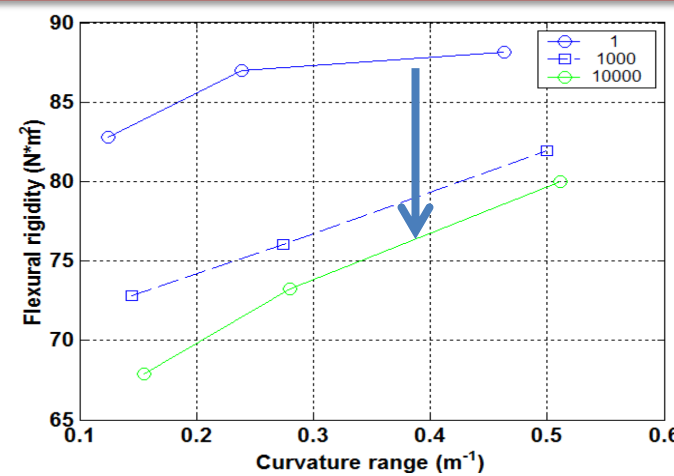




- Higher flexural rigidity of test sample due to epoxy bond
- The pellet-clad bond efficiency increases pellet bending resistance capability

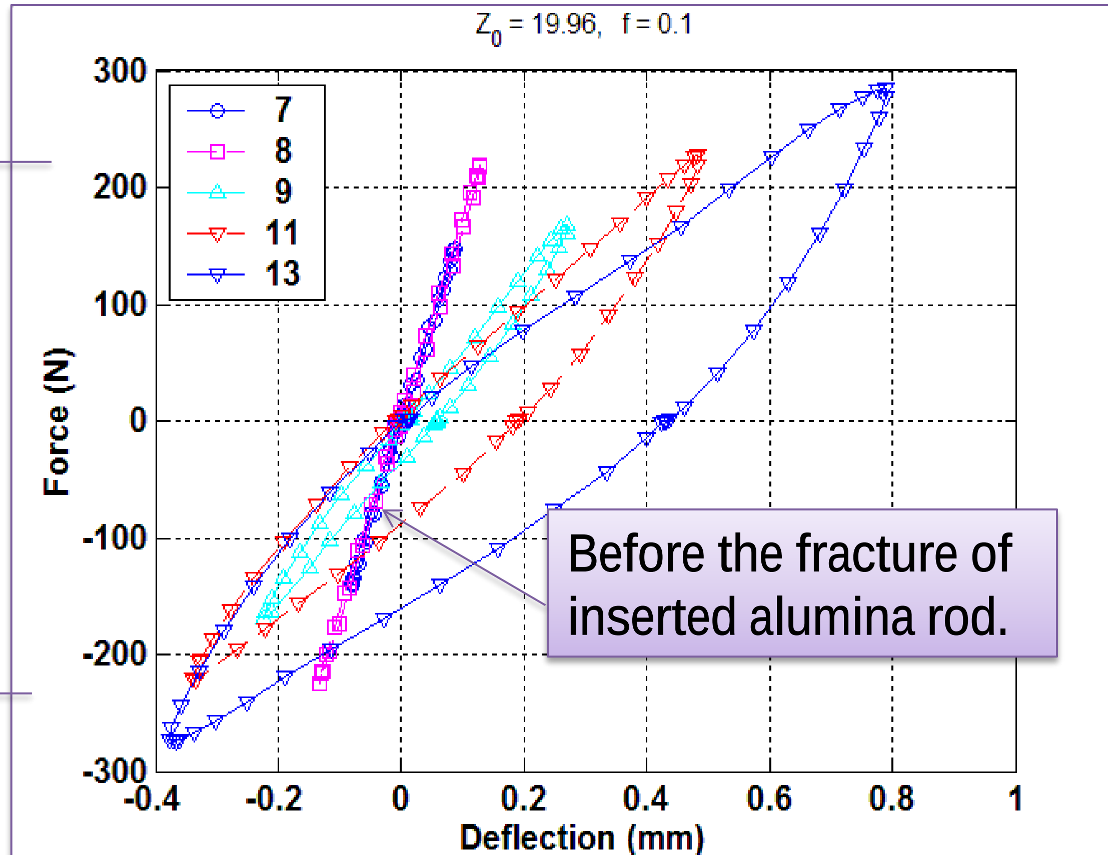
With epoxy bond





Significant bending load resistance was shifted from pellet to the clad upon insert pellet fracture

Symmetrical force output was achieved before the alumina rod was broken.



Before the fracture of inserted alumina rod.

CIRFT has been successfully tested in an out-of-hot-cell environment

- **Surrogate data shows the effect of interface bonding efficiency on UNF vibration integrity is important.**
- **The robust CIRFT testing ensures easy operation and test result reproducibility.**
- **Surrogate S-N data provides a clear roadmap and well-defined baseline data to support follow-on hot cell testing of high burnup fuel.**

Acknowledgment

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FEM Simulation Shows that EI is Critically Dependent on Interface Bonding Efficiency

Interfaces Bonding Conditions	Flexural rigidity, *EI* ($N*m^2$)	Reduction from perfect bond (%)
Perfect bond	**153**	
De-bond Pellet-Pellet Interfaces **with Gaps***	37	**76**
De-bond Pellet-Pellet and Pellet-Clad Interfaces **with Gaps**	34	78
De-bond Pellet-Pellet interfaces without Gaps	104	32
De-bond Pellet-Pellet and Pellet-Clad Interfaces without Gaps	84	45

* Gap can be formed progressively due to pellet-pellet or pellet-clad mechanical interaction under cyclic reversible bending loading