Summary of Results for High-Burnup North Anna ZIRLO Cladding Oxidized at ≤1200ºC, Cooled with or without Quench, and Ring-Compressed at 135ºC

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Six LOCA oxidation tests and 13 ring-compression ductility tests were conducted with defueled ZIRLO cladding from a high-burnup rod irradiated in one of the North Anna reactors. Pre-test characterization results have been documented ("North Anna ZIRLO Characterization and LOCA Apparatus Benchmark Results," M.C. Billone, Y. Yan and T. Burtseva, May 20, 2008). Cladding test samples were selected from three segments sectioned from Rod AM2-L17: one from a location ≈3.4 m (3320-3400 mm) above rod bottom, where local burnup was ≈60 GWd/MTU; and two from ≈2.9 m (2800-2960 mm) above rod bottom, where local burnup was 76 GWd/MTU. Rod-averaged burnup was 70 GWd/MTU. Measured parameters of interest are: 43±2 µm corrosion-layer thickness, 544±2 µm (≈0.54 mm) cladding-wall thickness, 7±2 µm fuel-cladding-bond thickness, and 9.50±0.02 mm cladding outer diameter, which is the same as the nominal as-fabricated diameter. Measured pre-test hydrogen content was: 670±40 wppm and 620±140 wppm for the lower and higher burnup segments, respectively.

Table 1 summarizes the oxidation test conditions, post-test hydrogen measurements and ring-compression ductility results. The temperature history is shown in Fig. 1. Three samples were oxidized in steam at a hold temperature of 1200ºC to CP-ECR values in the range of 6.3 to 10.2% and cooled without quench. Three tests were conducted with quench following oxidation to 4.0%, 5.1% and 6.3% CP-ECR. Based on previous experience, the 6.3% CP-ECR samples were expected to have negligible weight gain due to partial loss of corrosion layer offsetting oxygen pickup from steam. This was confirmed for the quenched sample. Post-test samples were sectioned to give two 8-mm-long rings for compression testing, two ≈2-mm-long rings for hydrogen analysis and one ring for metallographic imaging. Post-test hydrogen measurements are reported in Table 1. They are significantly lower than values measured for the pre-test samples: 540±100 vs. 670±40 wppm and 510±110 to 540±100 vs. 620±110 wppm. The results strongly suggest that about 110 wppm of the measured pre-test hydrogen is in the corrosion layer.

The offset strains measured for high-burnup ZIRLO cladding are compared in Fig. 2 to those measured for high-burnup Zry-4 cladding tested under similar conditions. Based on both offset and permanent strains, the ductile-to-brittle transition CP-ECR is 9% for ZIRLO cooled without quench and 5% for ZIRLO cooled with quench at 800ºC. Quenching at 800ºC following oxidation to 6.3% caused a significant reduction in offset and permanent strains, as well as embrittlement. However, both rings from the sample quenched at 800ºC following oxidation to 4.0% were highly ductile. It should be noted that the 4.0% CP-ECR sample reached a maximum temperature of only 1132ºC during the ramp, while the 6.3% CP-ECR sample reached a maximum temperature of 1176ºC prior to cooling. The results indicate a very strong sensitivity of post-quench ductility to maximum oxidation temperature and time at temperature. Because of the dramatic decrease in ductility between 4.0% and 6.3% CP-ECR, a confirmation test was run at 5.1% CP-ECR. The results confirmed that post-quench ductility is maintained at about 5% CP-ECR with a maximum oxidation temperature of 1162ºC. Two of the rings tested from this oxidation-quench sample exhibited no through-wall failure up to the limits of displacement for the TC-instrumented ring. The third ring – only 5.5-mm long – failed with two through-wall cracks after an offset strain of 9.5%. The results suggest that the ductility of high-burnup ZIRLO is very sensitive to peak oxidation temperature, test time above 1000ºC, and the peak hydrogen content. For the ZLI#6 ring that failed at 9.5% offset strain, the hydrogen distribution in the circumferential direction will be measured to determine if the failure locations correspond to the local peak in hydrogen concentration. Based on two end samples (≈1.5-mm long) sectioned so that the end rings would not be affected by end effects, the measured hydrogen content was only 420±80 wppm for 0.23-g total sample mass. These results may not be representative of the three rings sectioned for ring-compression tests. Based on the relatively low ductility of the 9.5% offset-strain ring, hydrogen-concentration results for this ring would be more representative than the two thin end samples. In Fig. 2, the post-quench-ductility results for the 5.1% CP-ECR sample are listed to correspond to 520±110 wppm. This hydrogen content may be revised somewhat based on the hydrogen-content results for the low-ductility ring from the ZLI#6 LOCA sample.

To the nearest percent CP-ECR, the recommended ductile-to-brittle transition CP-ECR of high burnup ZIRLO is 5%.

Load-displacement curves for the 13 ring compression tests are presented in Figs. 3-15.

Table 1 Post-Test Ductility Results for High-Burnup North Anna ZIRLO Cladding Oxidized at ≤1200ºC, Cooled with (ZLI#4) or without (ZLI#1-3) Quench at 800ºC, and Ring-Compressed at 135ºC; SC= slow cooled without quench

Test #	Hydrogen Content wppm		Test Time[a] s	Peak Temperature ºC	CP-ECR %	Strain %	
	Pre-Test	Post-Test				Offset	Permanent
ZLI#2 SC	670±40 for 0.1-g sample	540±100 for 1-g sample	85	1176	6.3	29 9.5	25 6.5
ZLI#1 SC	670±40 for 0.1-g sample	510±100 for 0.5-g sample	110	1191	8.1	5.0 4.0	--- ---
ZLI#3 SC	670±40 for 0.1-g sample	490±120 0.34-g sample	145	1200	10.2	1.0 0.9	--- 0.3
ZLI#4 Quench at 800ºC	620±140 for 0.55-g sample	510±110 0.26-g sample[b]	85	1176	6.3	1.1 0.4	--- 0.2
ZLI#5 Quench at 800ºC	620±140 for 0.55-g sample	540±100 0.27-g sample[c]	55	1132	4.0	>43 >43	>43 >45
ZLI#6 Quench at 800ºC	560±140 for 0.55-g sample	420±80 0.23-g sample[b]	70	1162	5.1	>58 49 9.5	>48 --- ---

[a]From beginning of ramp at 300ºC to end of heating phase.
[b]No weight gain; pre- and post-test sample weights were within 0.3%.
[c]Hydrogen reading corrected for sample weight loss of 1%.

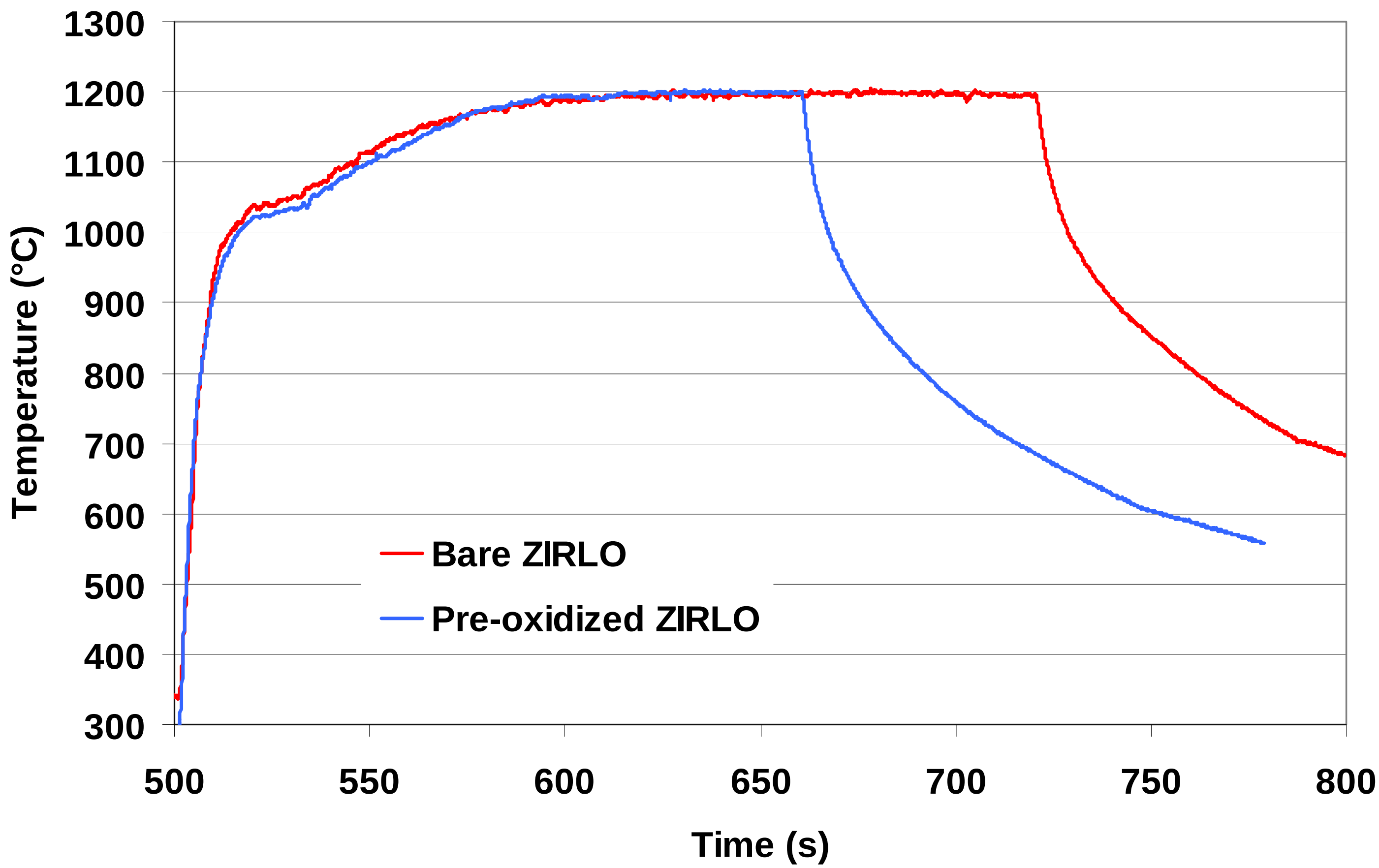

Fig. 1. Comparison of thermal benchmark temperature histories for pre-oxidized (≈14-μm OD and ID) ZIRLO and bare ZIRLO.

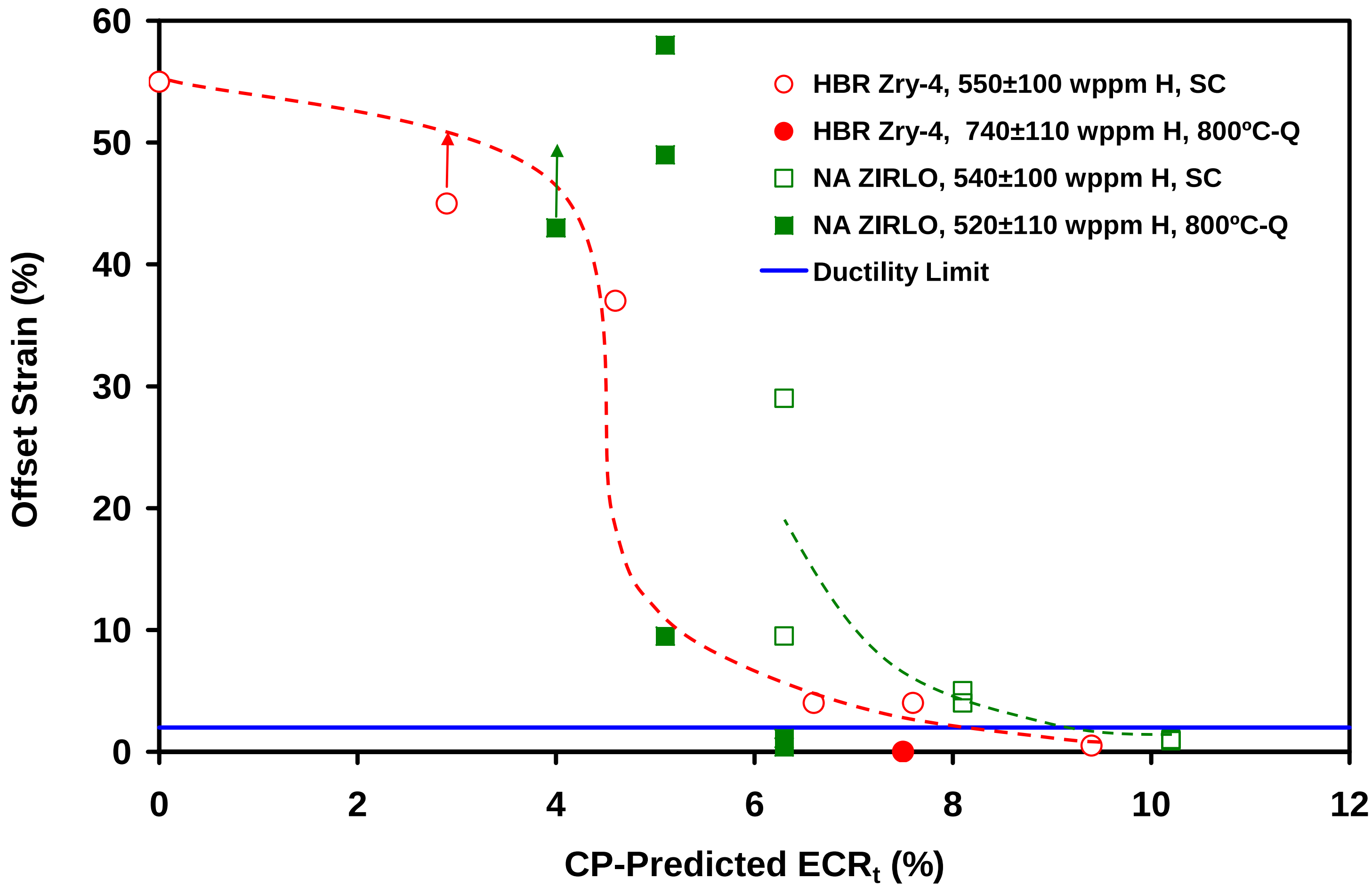

Fig. 2. Comparison of post-test offset strains at 135ºC for high-burnup North Anna ZIRLO and H.B. Robinson Zry-4 cladding, oxidized at ≤1200 ºC and cooled with or without quench at 800 ºC.

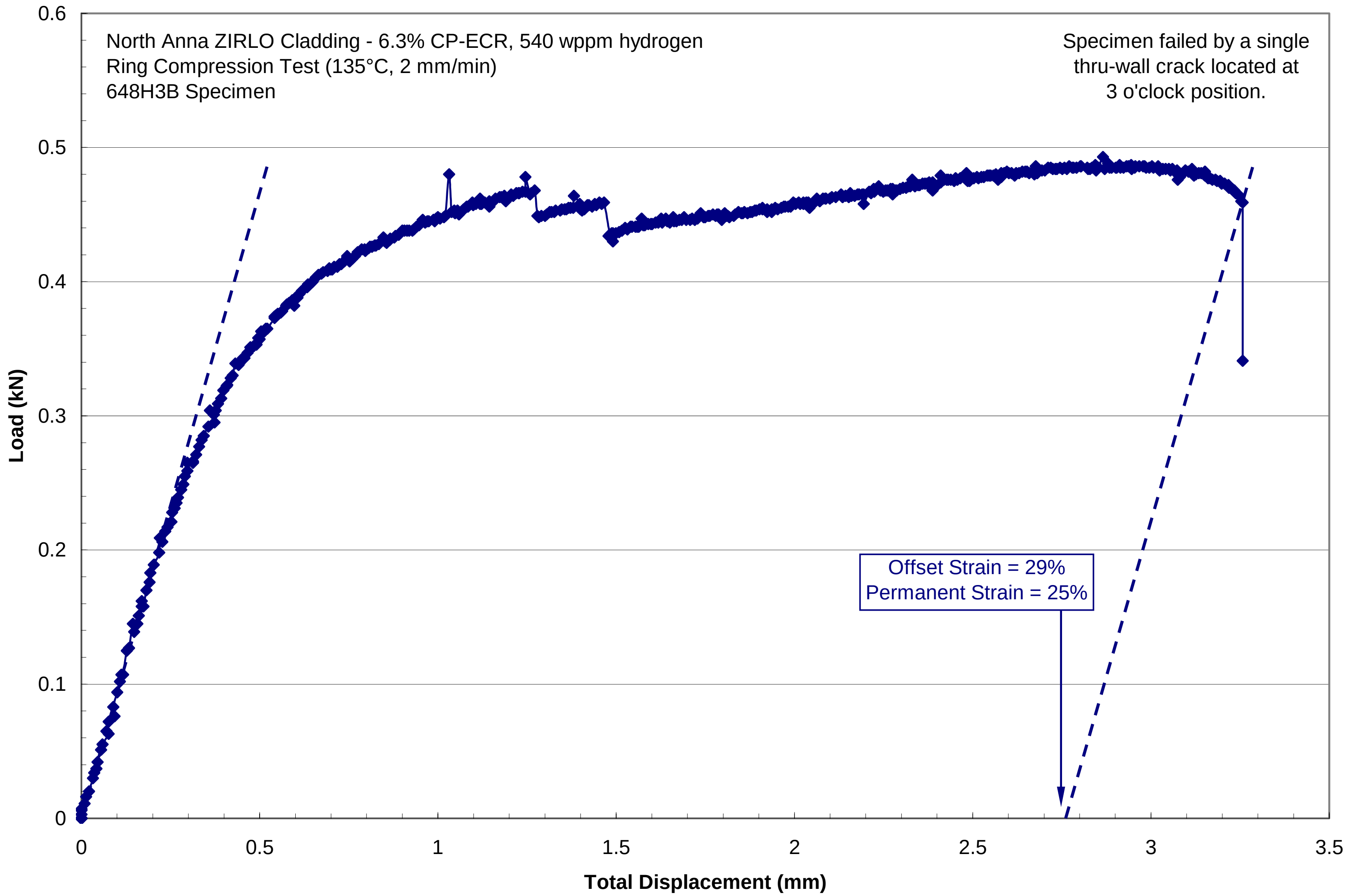

Fig. 3. Load-displacement curve for high-burnup ZIRLO cladding oxidized to 6.3% CP-ECR and cooled without quench: Ring #1.

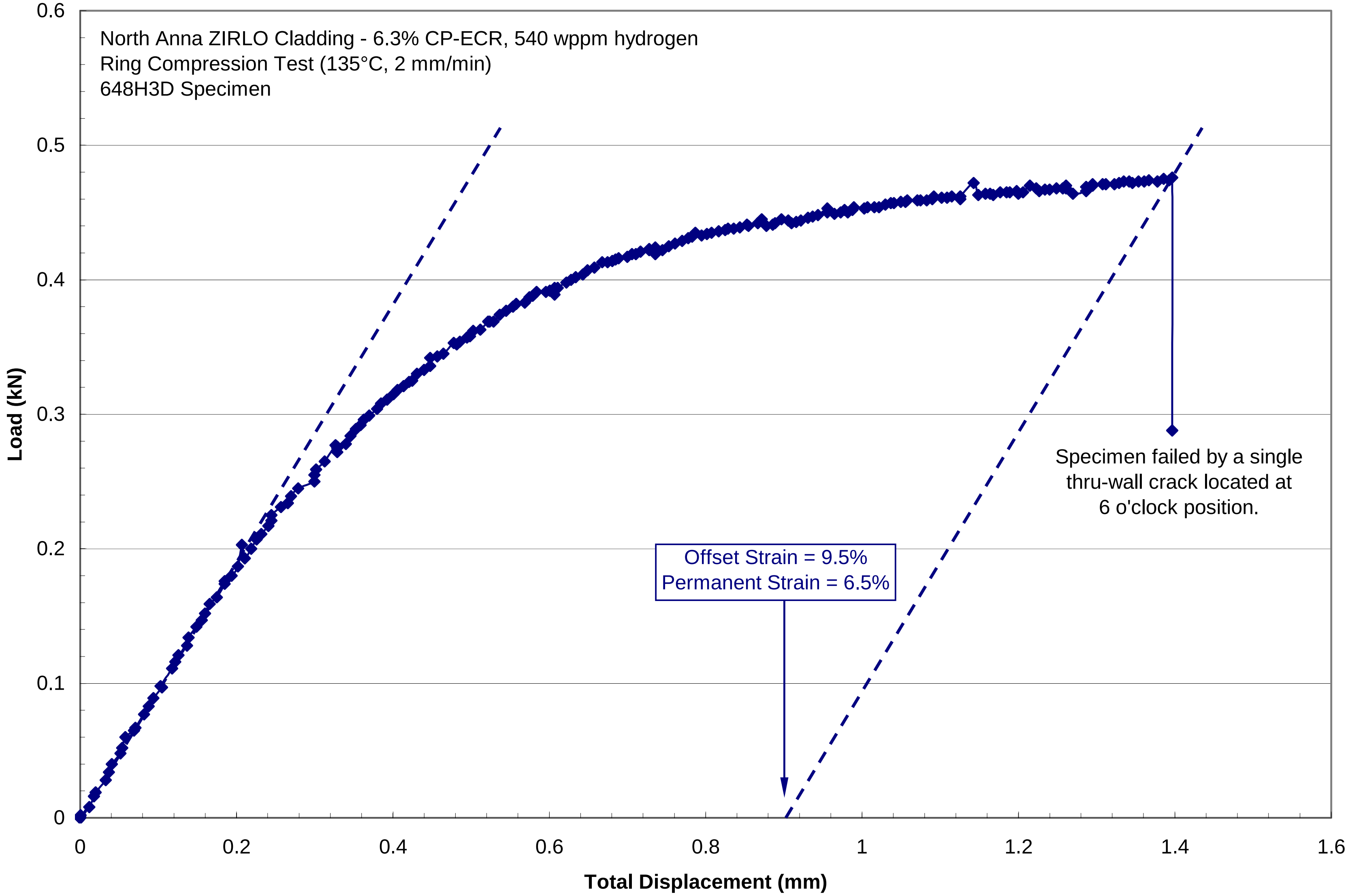

Fig. 4. Load-displacement curve for high-burnup ZIRLO cladding oxidized to 6.3% CP-ECR and cooled without quench: Ring #2.

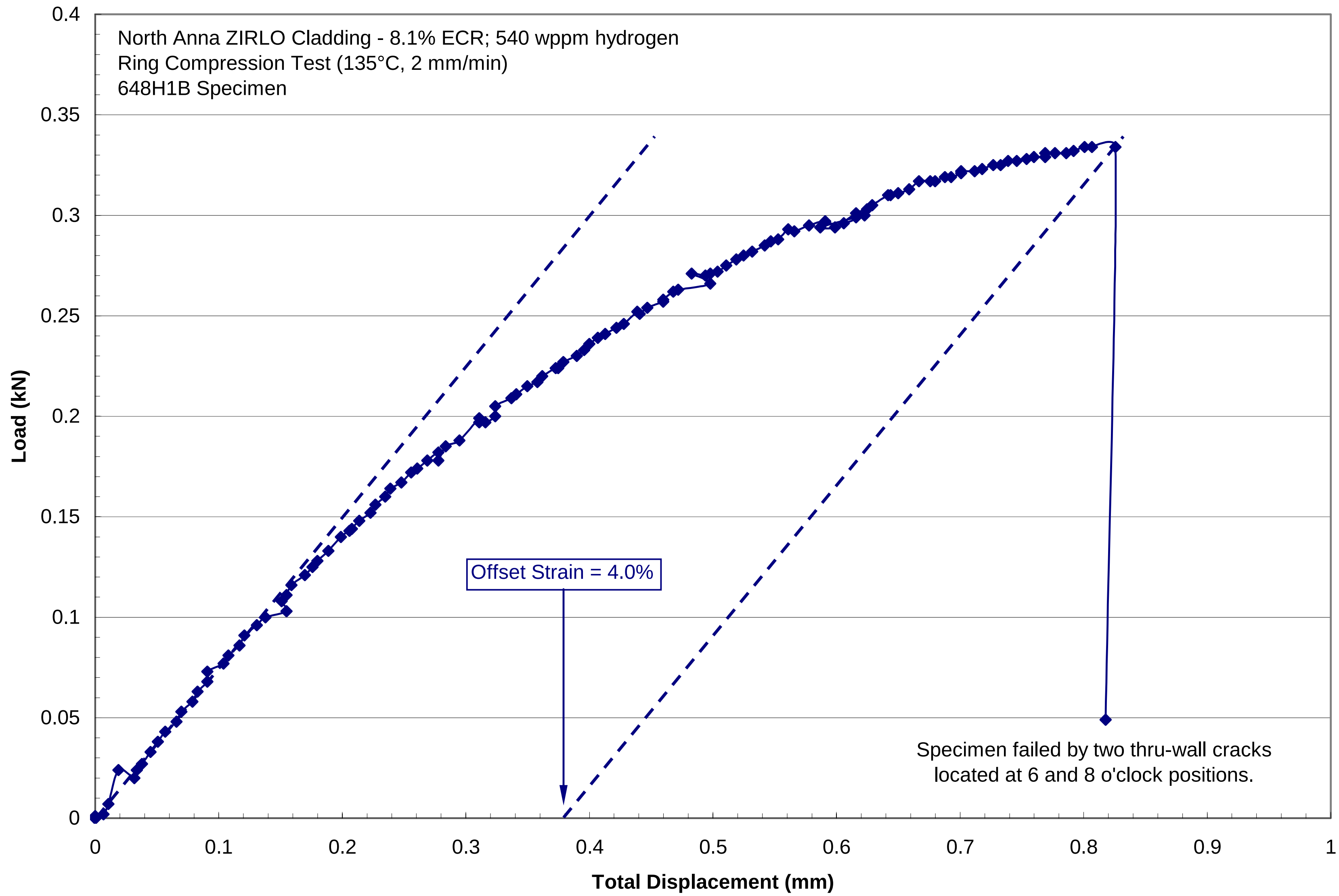

Fig. 5. Load-displacement curve for high-burnup ZIRLO cladding oxidized to 8.1% CP-ECR and cooled without quench: Ring #1.

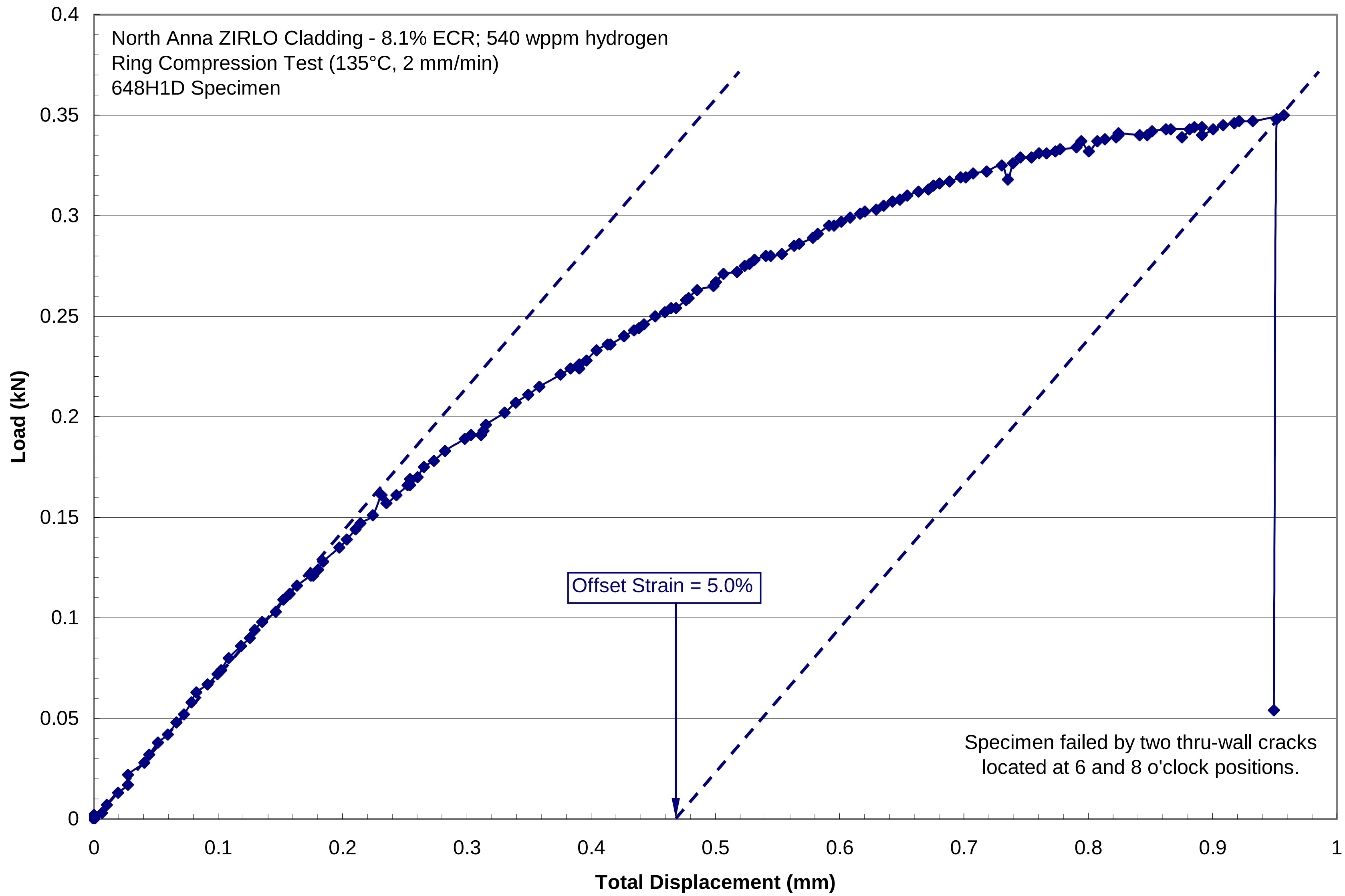

Fig. 6. Load-displacement curve for high-burnup ZIRLO cladding oxidized to 8.1% CP-ECR and cooled without quench: Ring #2.

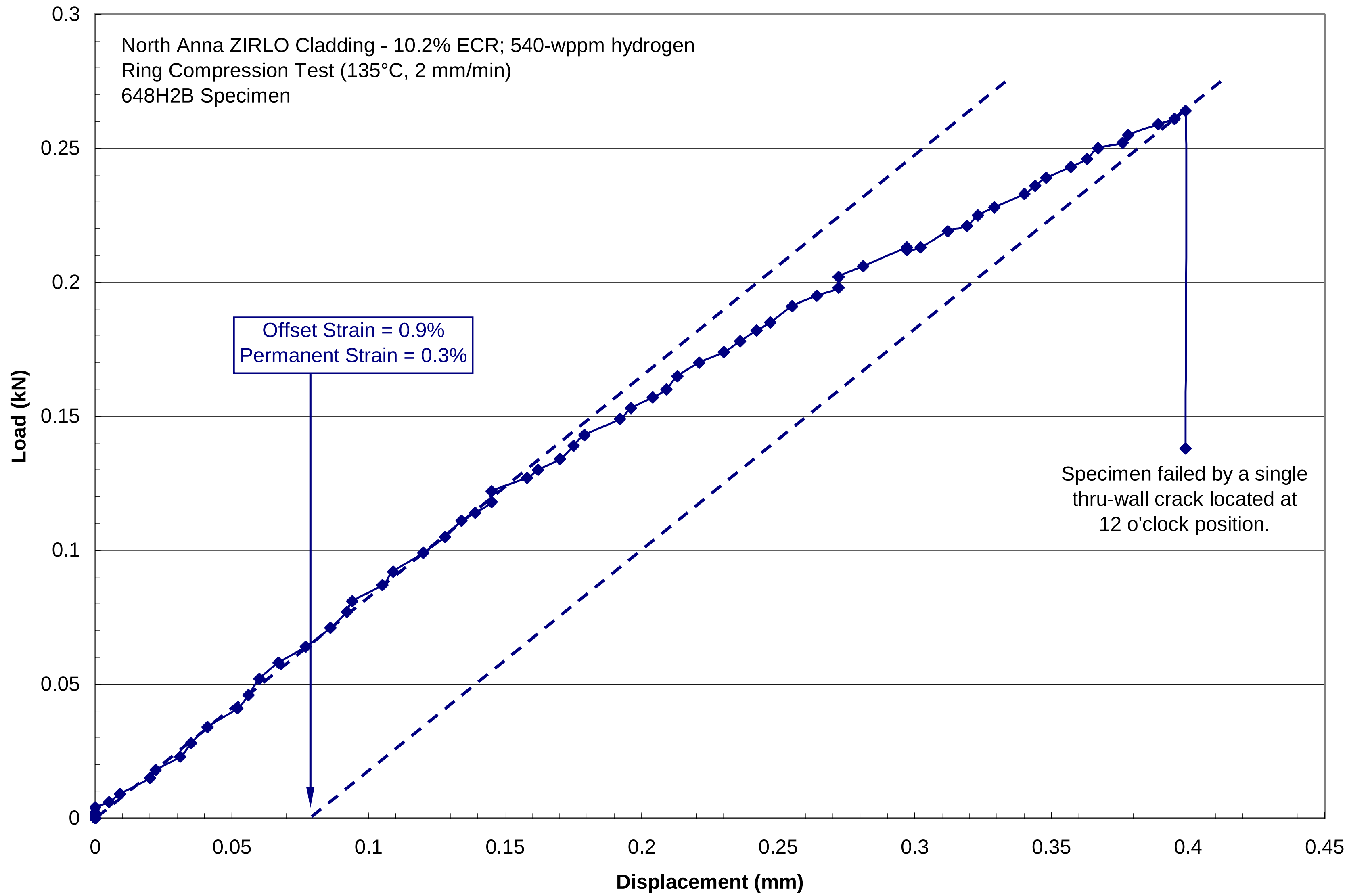

Fig. 7. Load-displacement curve for high-burnup ZIRLO oxidized to 10.2% CP-ECR and cooled without quench: Ring #1.

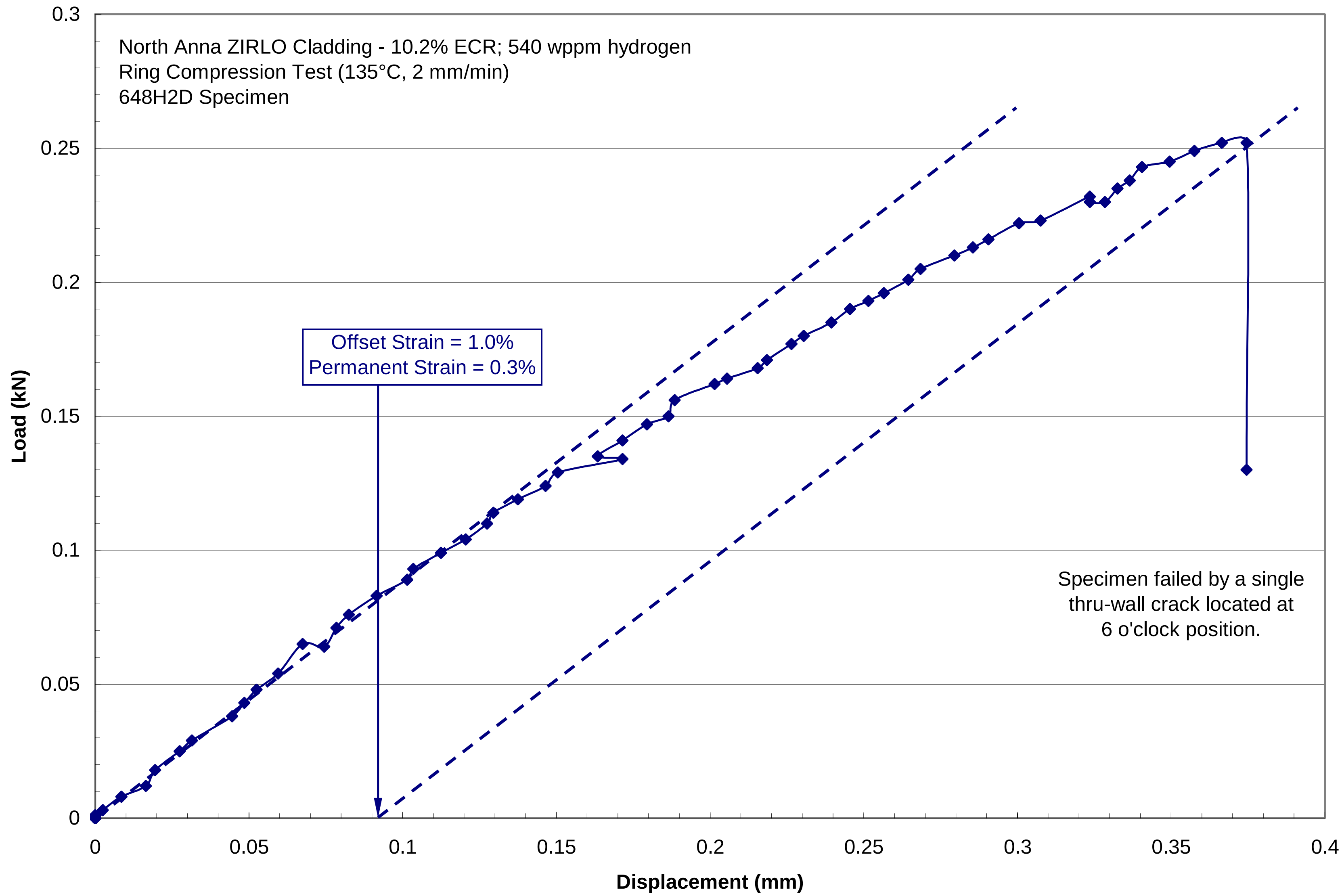

Fig. 8. Load-displacement curve for high-burnup ZIRLO oxidized to 10.2% CP-ECR and cooled without quench: Ring #2.

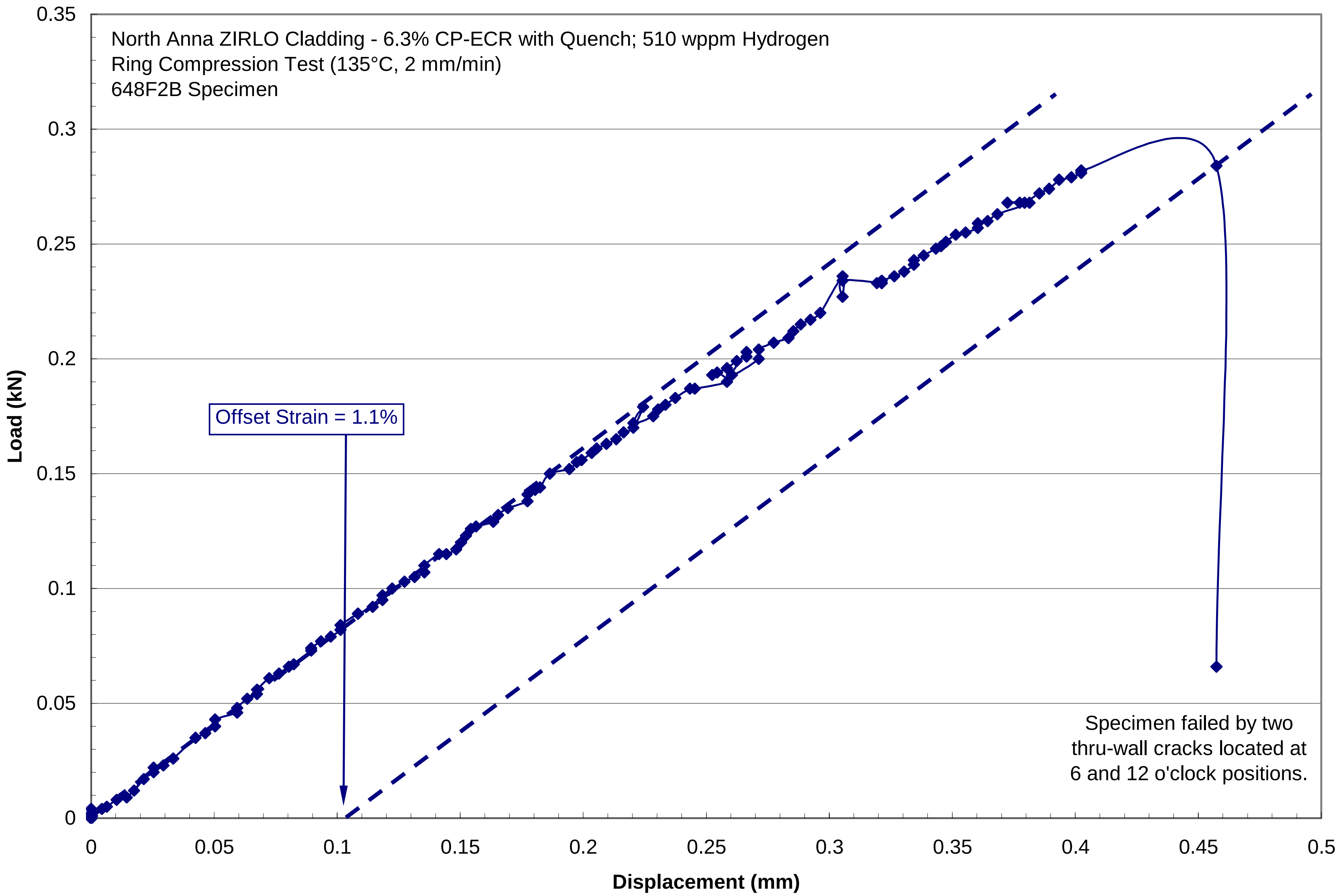

Fig. 9. Load-displacement curve for high-burnup ZIRLO oxidized to 6.3% CP-ECR and cooled with quench at 800ºC: Ring #1.

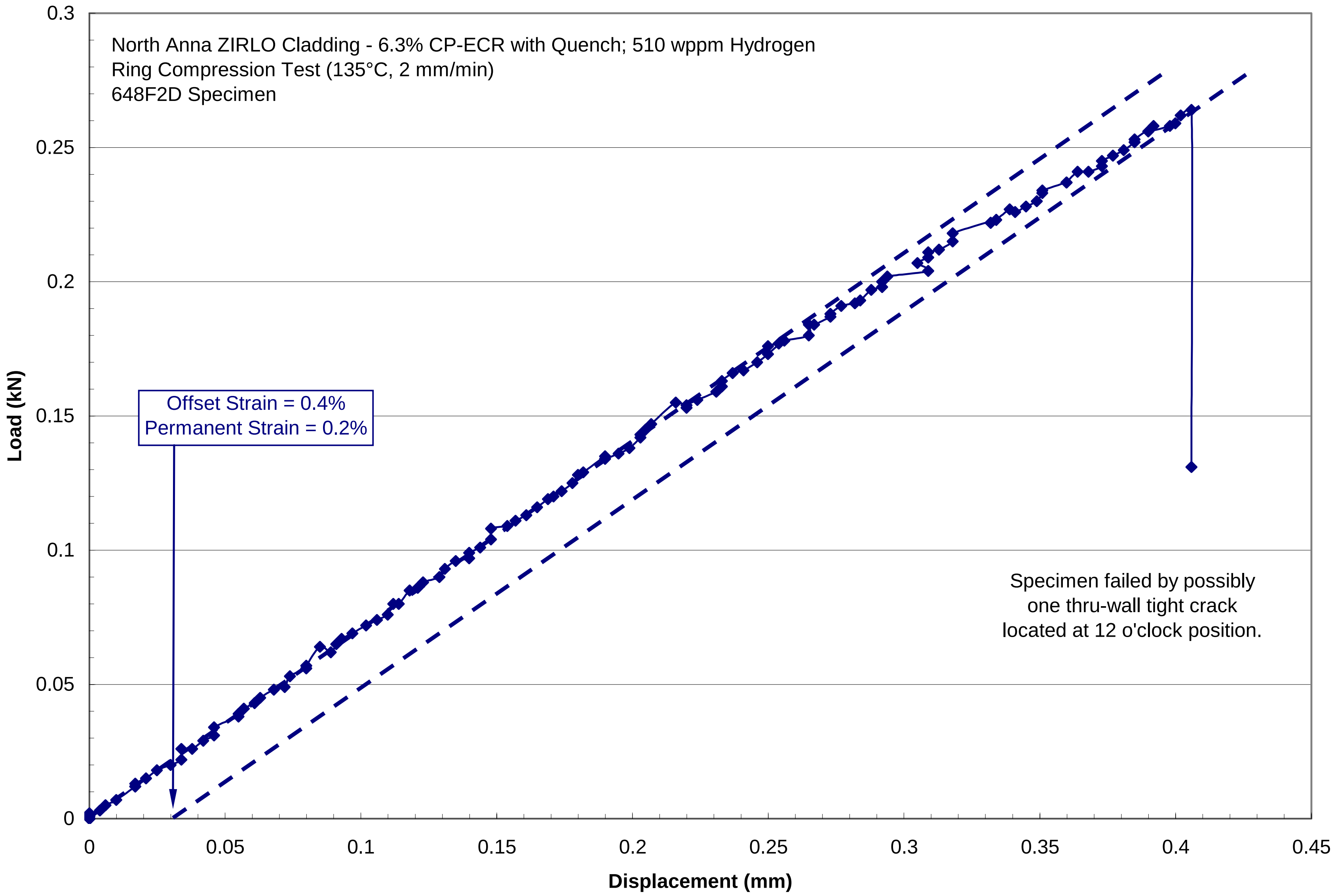

Fig. 10. Load-displacement curve for high-burnup ZIRLO oxidized to 6.3% CP-ECR and cooled with quench at 800ºC: Ring #2.

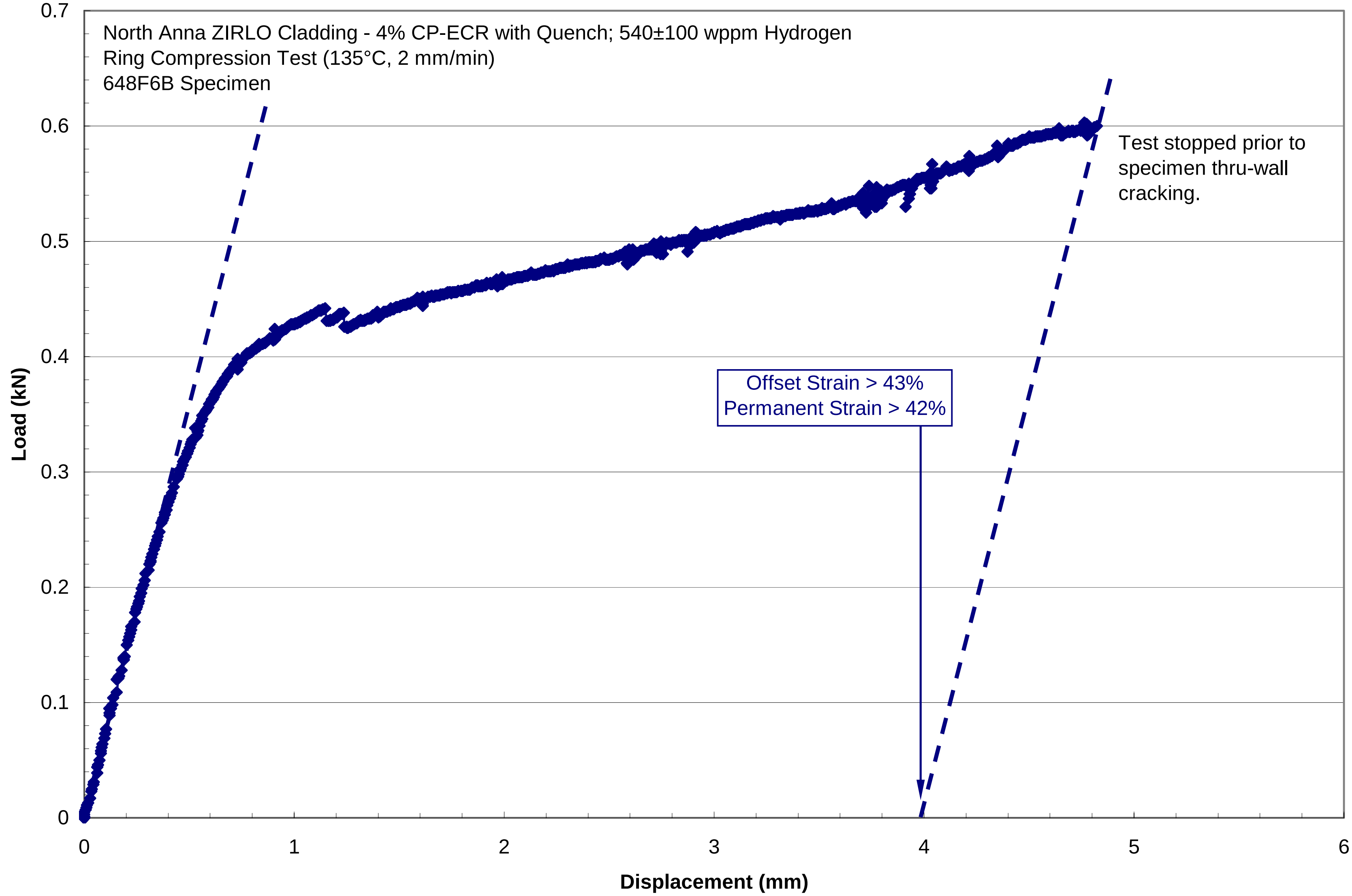

Fig. 11. Load-displacement curve for high-burnup ZIRLO oxidized to 4.0% CP-ECR and cooled with quench at 800ºC: Ring #1.

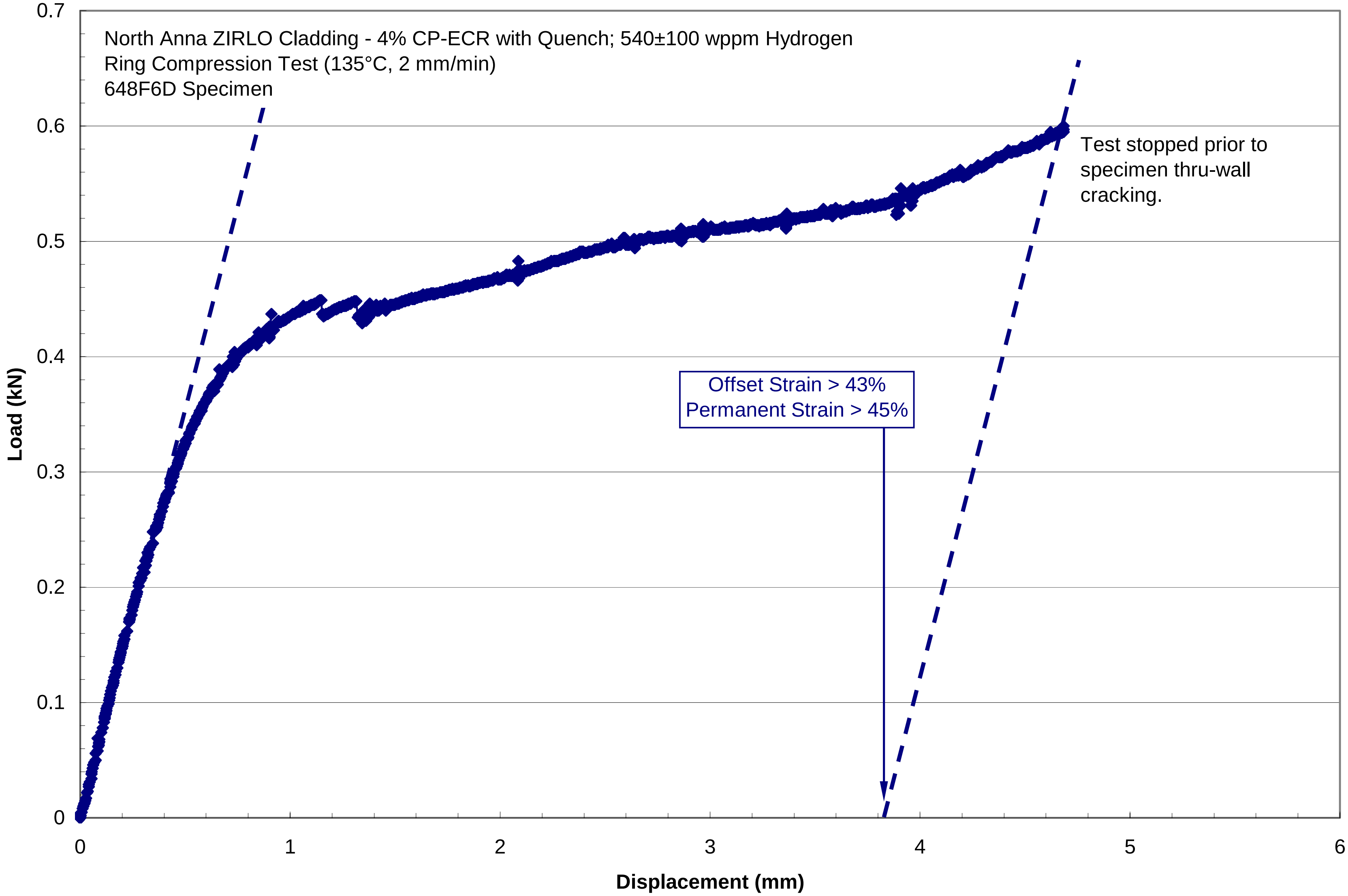

Fig. 12. Load-displacement curve for high-burnup ZIRLO oxidized to 4.0% CP-ECR and cooled with quench at 800ºC: Ring #2.

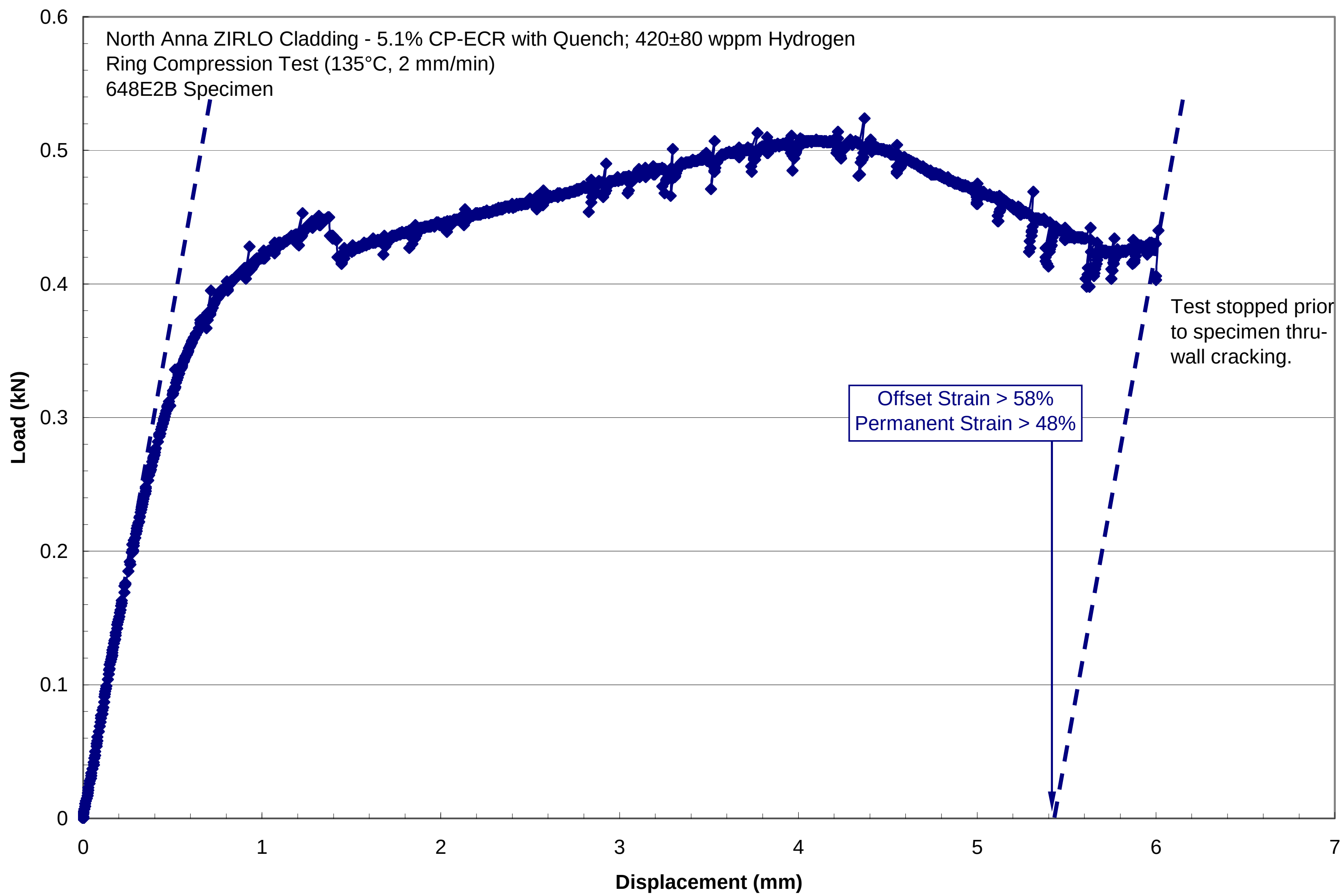

Fig. 13. Load-displacement curve for high-burnup ZIRLO oxidized to 5.1% CP-ECR and cooled with quench at 800ºC: Ring #1 (7.4-mm long). The test was stopped due to displacement limitations prior to through-wall failure.

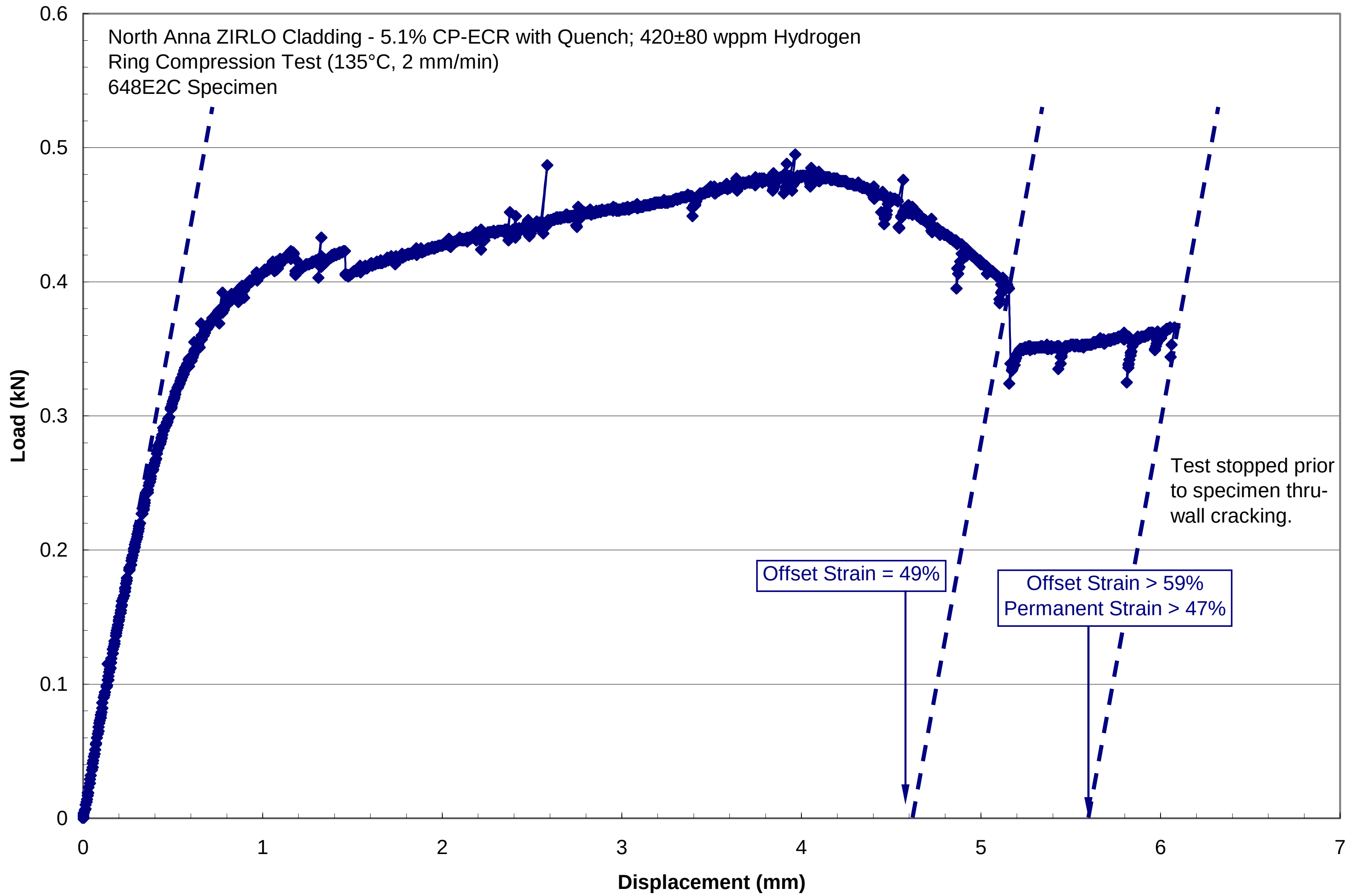

Fig. 14. Load-displacement curve for high-burnup ZIRLO oxidized to 5.1% CP-ECR and cooled with quench at 800ºC: Ring #1 (7.2-mm-long center ring). Partial through-wall side crack (90º from loading direction) observed at 49% offset strain.

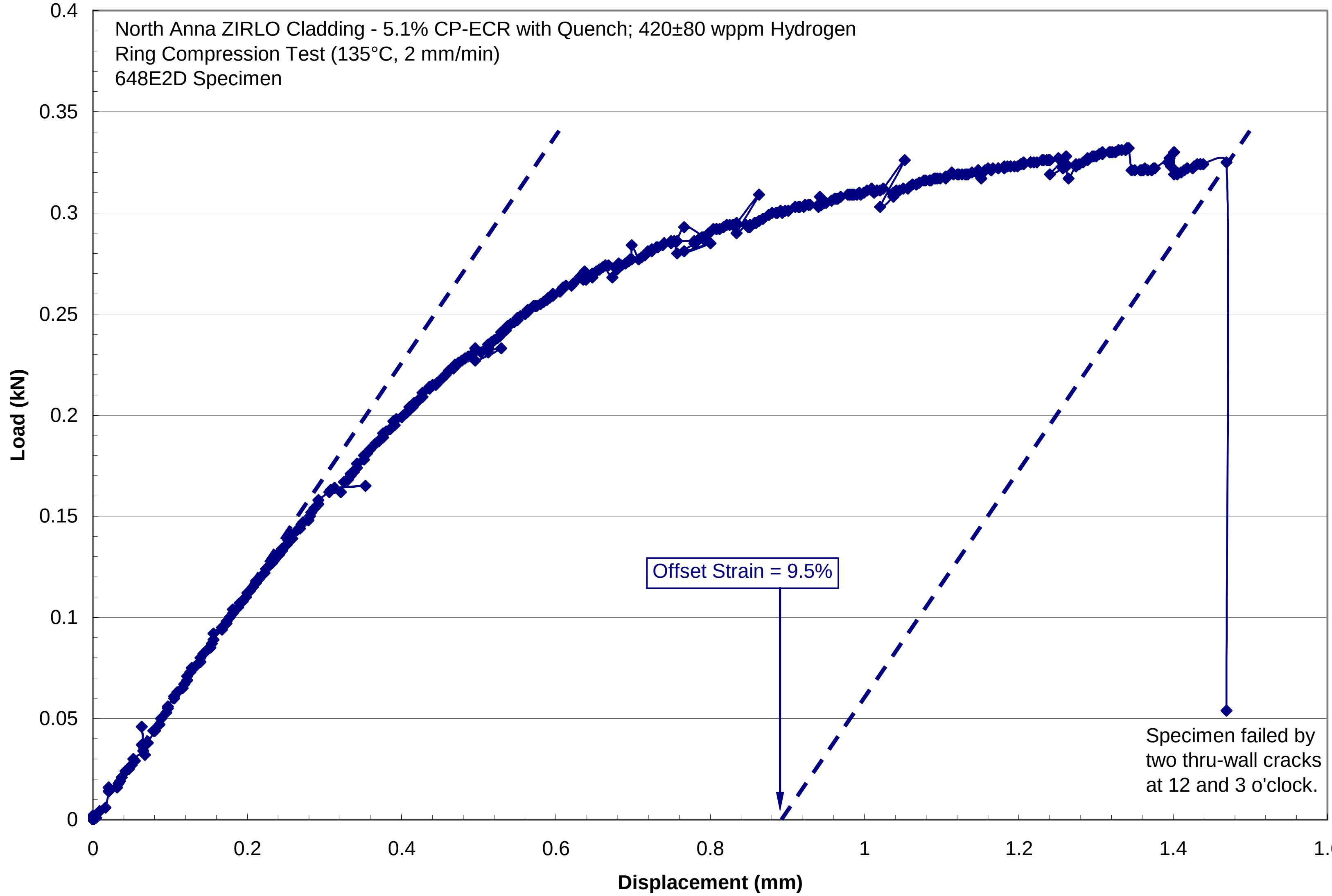

Fig. 15. Load-displacement curve for high-burnup ZIRLO oxidized to 5.1% CP-ECR and cooled with quench at 800ºC: Ring #1 (5.5-mm-long end ring). Through-wall cracks occurred at the 12 o'clock and 3 o'clock positions after 9.5% offset strain.