دانشگاه صنعتی اصفهان

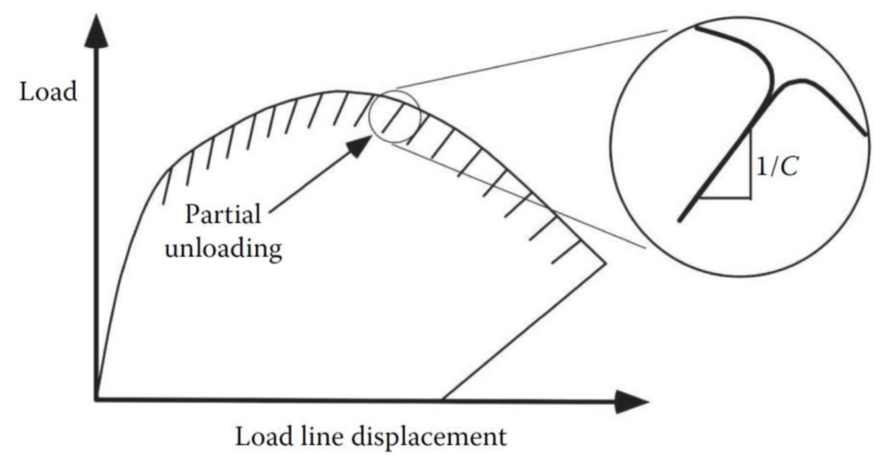
دانشکده مکانیک

# Fracture Toughness Testing (4)

# J–R Curve Testing

- The resistance curve test method in ASTM E1820 requires that the crack growth be monitored throughout the test. However, this complication is more than offset by the fact that the J–R curve can be obtained from a single specimen. Determining a J–R curve with the basic method requires tests on multiple specimens.

- The most common single-specimen test technique is the unloading compliance method. The crack length is computed at regular intervals during the test by partially unloading the specimen and measuring the compliance. As the crack grows, the specimen becomes more compliant (less stiff). The various J testing standards provide polynomial expressions that relate a/W to compliance.



# J–R Curve Testing

- Since the crack length changes continuously during a J–R curve test, the J integral must be calculated incrementally. For unloading compliance tests, the most logical time to update the J value is at each unloading point, where the crack length is also updated. Consider a J test with $n$ measuring points. For a given measuring point $i$, where $1 \le i \le n$, the elastic and plastic components of J can be estimated from the following expressions:

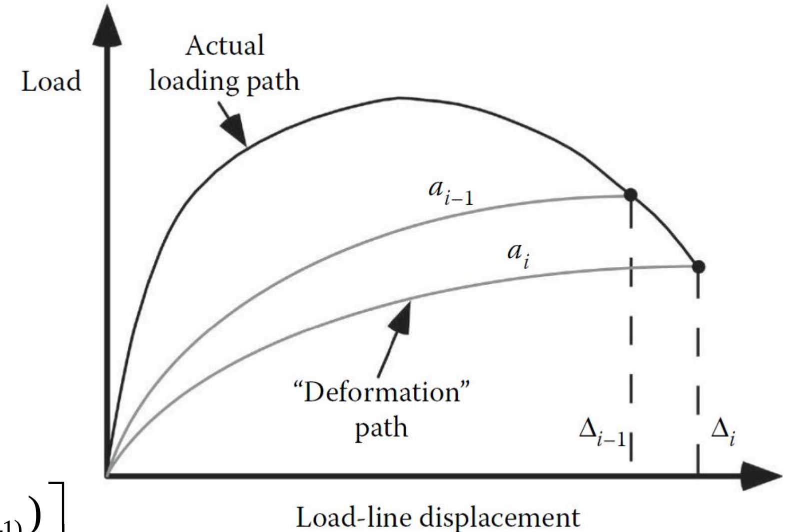
$$J_{(i)} = J_{el\,(i)} + J_{pl\,(i)}$$

That:

$$J_{el\,(i)} = \frac{K_{(i)}^{\,2}(1-\nu^2)}{E}$$

$$K_{(i)} = \frac{P_{(i)}}{B\sqrt{W}} f\,(a_{(i)}/W)$$

$$J_{pl\,(i)} = \left[J_{pl\,(i-1)} + \frac{\eta_{(i-1)}}{b_{(i-1)}} \frac{(A_{pl\,(i)} - A_{pl\,(i-1)})}{B_N}\right]\left[1 - \gamma_{(i-1)} \frac{(a_{(i)} - a_{(i-1)})}{b_{(i-1)}}\right]$$



# J–R Curve Testing

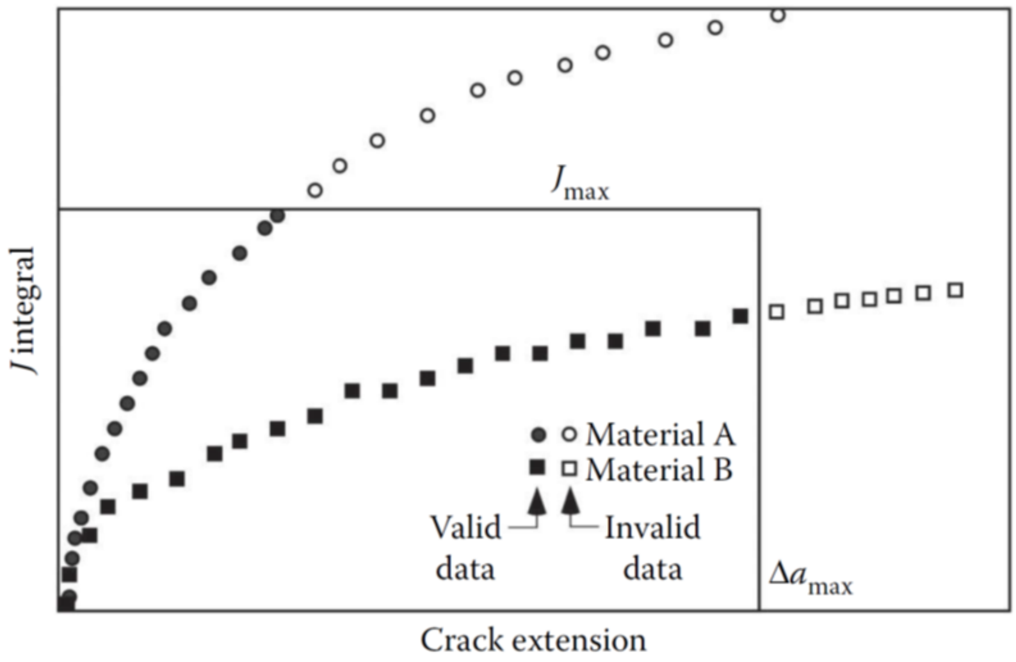
$$J_{pl(i)} = \left[ J_{pl(i-1)} + \frac{\eta_{(i-1)}}{B_N b_{(i-1)}} \frac{(P_{(i)} + P_{(i-1)})(\Delta_{pl(i)} - \Delta_{pl(i-1)})}{2} \right] \left[ 1 - \gamma_{(i-1)} \frac{(a_{(i)} - a_{(i-1)})}{b_{(i-1)}} \right]$$

For CT specimen: $\eta_{(i-1)} = 2 + \frac{0.522 b_{(i-1)}}{W}$, $\gamma_{(i-1)} = 1 + \frac{0.76 b_{(i-1)}}{W}$

- ASTM E1820 has the following limits on J and crack extension relative to specimen size:

$$B, b_0 \geq \frac{10 J_{max}}{\sigma_Y}$$

$$\Delta a_{max} \leq 0.25 b_0$$




J–R curves for two materials.

# CTOD Testing

- The ASTM published E1290, an American version of the CTOD standard. ASTM E1290 was updated multiple times, most recently in 2008. However, this standard was withdrawn in 2012.

- ASTM recently introduced a different estimation procedure that is based on a finite element study. The ASTM method entails first computing the J integral using the formulae in last slides and next, the J value is converted into a CTOD estimate as follows:

$$\delta = \frac{J}{m\sigma_Y}$$

- The m factor in this expression was inferred from finite element analysis and is a function of the yield strength/tensile strength ratio:

$$m = 3.62 - 4.21\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right) + 4.33\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^2 - 2\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^3$$

# CTOD Testing

- Both ASTM E1290 and E1820 adopted this new CTOD estimation procedure. As it turned out, however, E1290 was withdrawn a few years after this change because the revised standard fell out of favor with users.

- The majority of CTOD testing throughout the world is performed in accordance with the ISO standards 12135 and 15653.

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# Fatigue Crack Growth Experiments

# Crack Growth Rate and Threshold Measurement

- The *ASTM Standard E647* outlines a test method for fatigue crack growth measurements. ASTM E647 describes how to determine da/dN as a function of $\Delta K$ from an experiment. The crack is grown by cyclic loading, and $K_{min}$, $K_{max}$, and crack length are monitored throughout the test.

- During the test, the crack length must be measured periodically. Crack length measurement techniques include optical, compliance, and potential drop methods.

- The ASTM Standard E647 outlines two types of fatigue tests:
  - constant-load amplitude tests where K increases
  - K-decreasing tests; the load amplitude decreases during the test to achieve a negative K gradient.

# Crack Growth Rate and Threshold Measurement

- All specimens must be fatigue precracked prior to the actual test. The $K_{max}$ at the end of fatigue precracking should not exceed the initial $K_{max}$ in the fatigue test. Otherwise, retardation effects may influence the growth rate.

- The E647 standard allows tests on compact specimens and middle tension panels. The ASTM standard for fatigue crack growth measurements requires that the behavior of the specimen be predominantly elastic during the tests. This standard specifies the following requirement for the uncracked ligament of a compact specimen:

$$W - a \geq \frac{4}{\pi}\left(\frac{K_{max}}{\sigma_{YS}}\right)^2$$

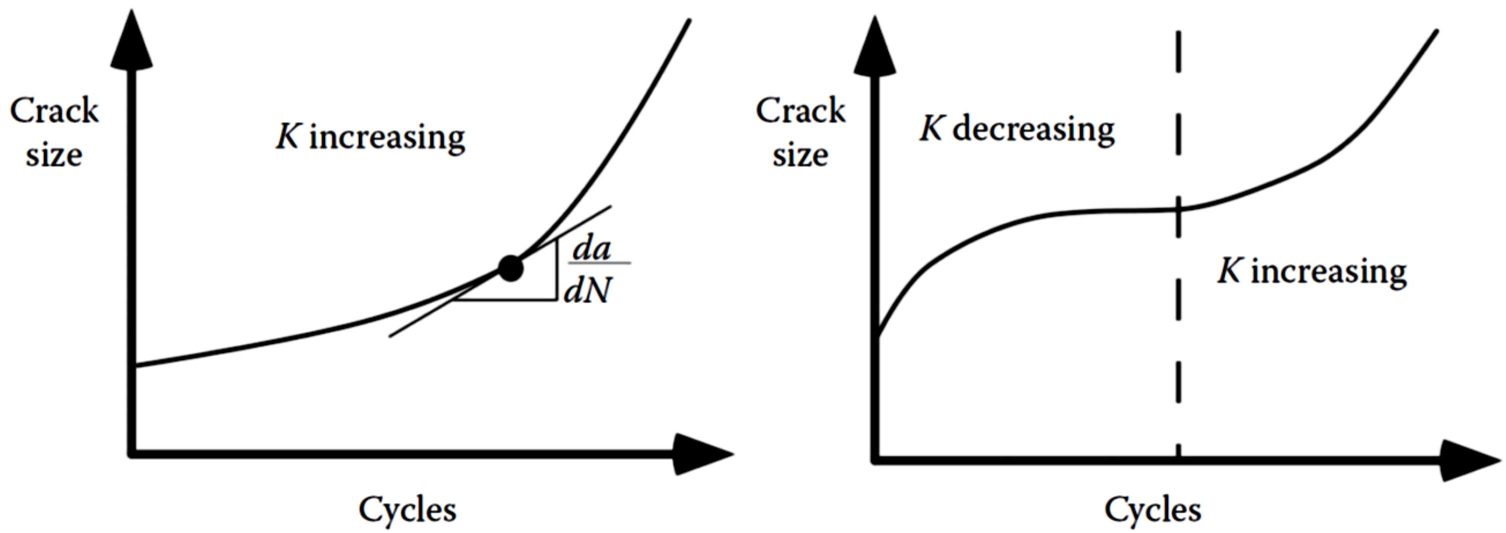
# Crack Growth Rate and Threshold Measurement

- The K-decreasing procedure is preferable when near-threshold data are required. In a typical K-decreasing test, either $K_{max}$ or the R ratio is held constant while $\Delta K$ decreases. These two approaches usually result in a different behavior in the threshold region due to the R ratio effect on $\Delta K_{th}$. Owing to the potential for history effects when the K amplitude varies, ASTM E647 requires that the normalized K gradient be computed:

$$G \equiv \frac{1}{K}\frac{dK}{da} = \frac{1}{\Delta K}\frac{d\Delta K}{da} = \frac{1}{K_{\min}}\frac{dK_{\min}}{da} = \frac{1}{K_{\max}}\frac{dK_{\max}}{da}$$

- The K-decreasing test is more likely to produce history effects, because prior cycles produce larger plastic zones, which can retard crack growth. Retardation in a rising K test is not a significant problem, since the plastic zone produced by a given cycle is slightly larger than that in the previous cycle. A K-increasing test is not immune to history effects, however; the width of the plastic wake increases with crack growth, which may result in a different closure behavior than in a constant K amplitude test.

# Crack Growth Rate and Threshold Measurement




- The figure schematically illustrates typical crack length versus N curves. These curves must be differentiated to infer da/dN. The ASTM standard E647 suggests two alternative numerical methods to compute the derivatives. A linear differentiation approach is the simplest, but it is subject to scatter. The derivative at a given point on the curve can also be obtained by fitting several neighboring points to a quadratic polynomial.

# Crack Growth Rate and Threshold Measurement

- The linear method computes the slope from two neighboring data points: $(a_i, N_i)$ and $(a_{i+1}, N_{i+1})$. The crack growth rate for $a = \bar{a}$ is given by:

$$\left(\frac{da}{dN}\right)_{\bar{a}} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i}$$

That: $\bar{a} = \dfrac{a_{i+1} + a_i}{2}$

- The incremental polynomial approach involves fitting a quadratic equation to a local region of the crack length versus N curve, and solving for the derivative mathematically.

# fatigue crack growth experiment according to ASTM E647

1- Test a compact tension (CT) specimen according to ASTM E647. Calculate (if necessary) and include the raw $a$ vs. $N$ data in your report.

2- Create a plot showing $a$ vs. $N$.

3- Calculate da/dN and ΔK values from the a and N data collected above. Calculate da/dN using the forward difference approximation:

$$\left(\frac{da}{dN}\right)_{\bar{a}} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i}$$

This value of d$a$/d$N$ is equal to the average crack growth between stages $i$ and $i$+1. Since d$a$/d$N$ is an average computed over the $a_{i+1} - a_i$ increment, use the average crack length over the region when calculating Δ$K$. The average crack length, $a_{avg}$, can be determined from: $a_{avg} = \bar{a} = \dfrac{a_{i+1} + a_i}{2}$

# fatigue crack growth experiment according to ASTM E647

For the CT specimen:

$$\Delta K_{eff} = \frac{\Delta P_{eff}}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.56\alpha^4)$$

where: $\alpha = a_{avg}/W$

$\Delta P_{eff} = P_{max} - P_{op}$ (see next slide)

B = specimen thickness

W = specimen length:

4. Plot log da/dN vs. log $\Delta K_{eff}$. Note any trends.

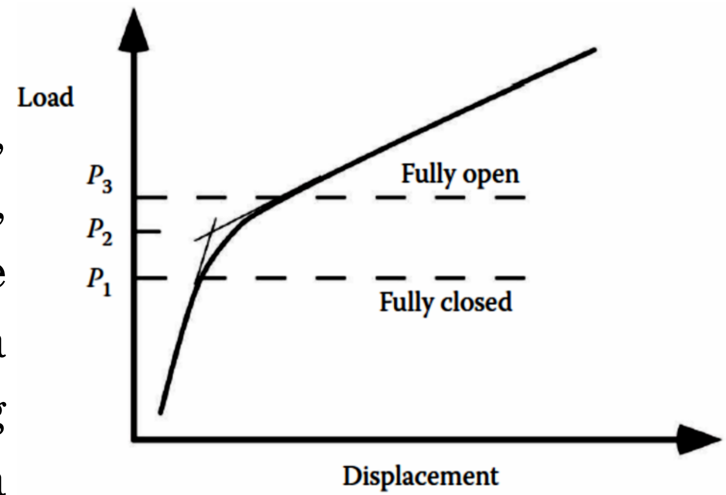
5. Perform a linear least squares cure fit on your data to determine the Parameters C and n for Paris law.

$$\frac{da}{dN} = C(\Delta K_{eff})^n$$

# A Proposed Experimental Definition of $\Delta K_{eff}$

- crack closure measurements tend to be highly subjective because closure is a gradual process that occurs over a finite load range. The important point to keep in mind is that closure is of practical concern because of its effect on the fatigue driving force. Therefore, the goal of any closure measurement should be the determination of the true $\Delta K_{eff}$.

- When the fatigue crack faces are in contact, the notch faces are separated. In such cases, the slope of the load versus clip gage displacement curve reflects compliance of a notched but uncracked specimen. Removing this contribution to compliance should have a beneficial effect on the sensitivity of closure measurements. Therefore, let us define an adjusted clip gage displacement as follows: $V^* = V - C(a_N)P$

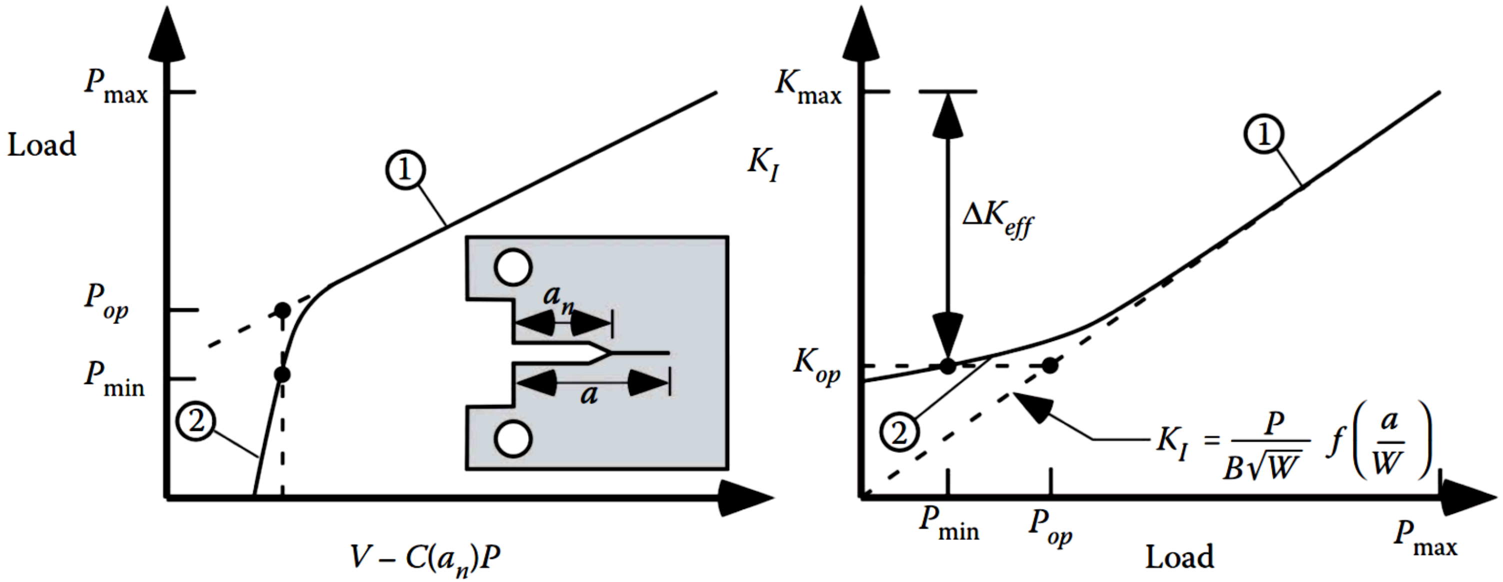



*Alternative definitions of the closure load.*

where $C(a_N)$ is the compliance of an uncracked specimen with notch depth $a_N$.

# A Proposed Experimental Definition of $\Delta K_{eff}$

Region 1: K is driven by applied load, Region 2: K is driven by crack face displacements.




➢ Proposed definition of $P_{op}$ , designed to give a true indication of $\Delta K_{eff}$ :

1. Determine the adjusted clip gage displacement at $P_{min}$.
2. Construct a vertical line at the $V^*$ value from Step 1.
3. Extrapolate the load–displacement curve for the fully open condition (Region 1) down to lower load levels. The opening load, $P_{op}$, is defined at the point where the extrapolated load-displacement curve for Region 1 intersects the vertical line constructed in Step 2.
4. Compute $K_{op}$ from $P_{op}$ using the standard relationship for the test specimen.