دانشگاه صنعتی اصفهان

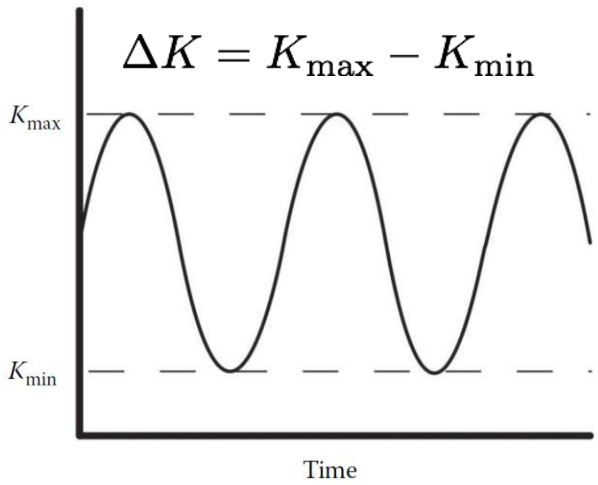
دانشکده مکانیک

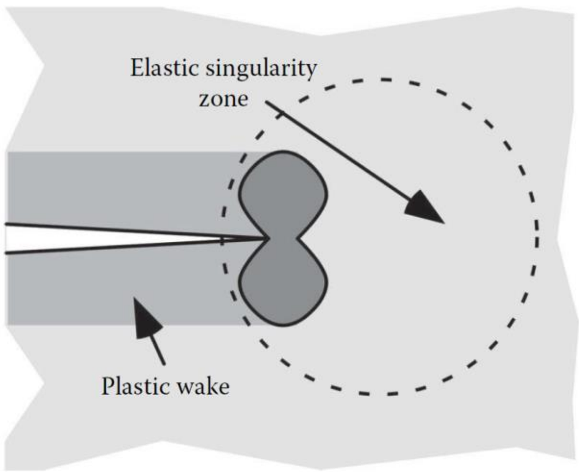
Fatigue-Crack closure effect

Fracture Mechanics Approach

Constant variable cyclic load

small-scale yielding (SSY)





$$R = K_{min}/K_{max}$$

$$\Delta K = K_{max} - K_{min}$$

$$\Delta K = K_{max} - K_{min} = K_{max}\,(1 - R)$$

crack growth rate

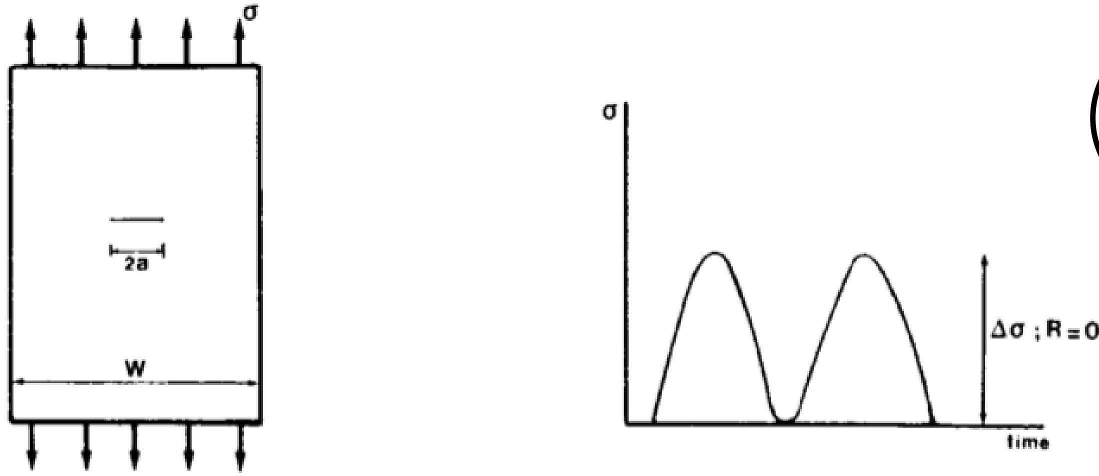
$$\frac{da}{dN} = f_1(\Delta K, R)$$

crack growth models

Crack growth data

$$K = \sigma\sqrt{\pi a}$$

1

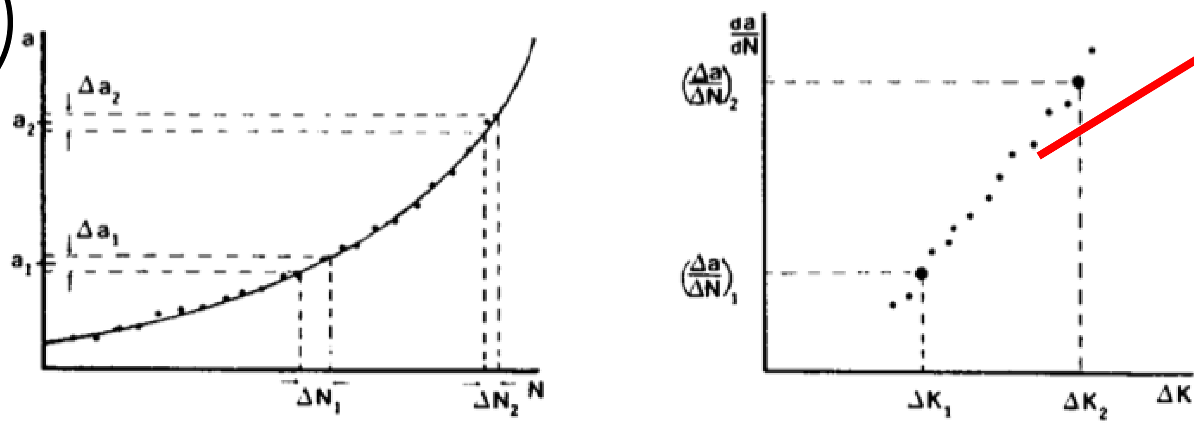


2

$$\frac{da}{dN} = f_1(\Delta K, R)$$

(a)

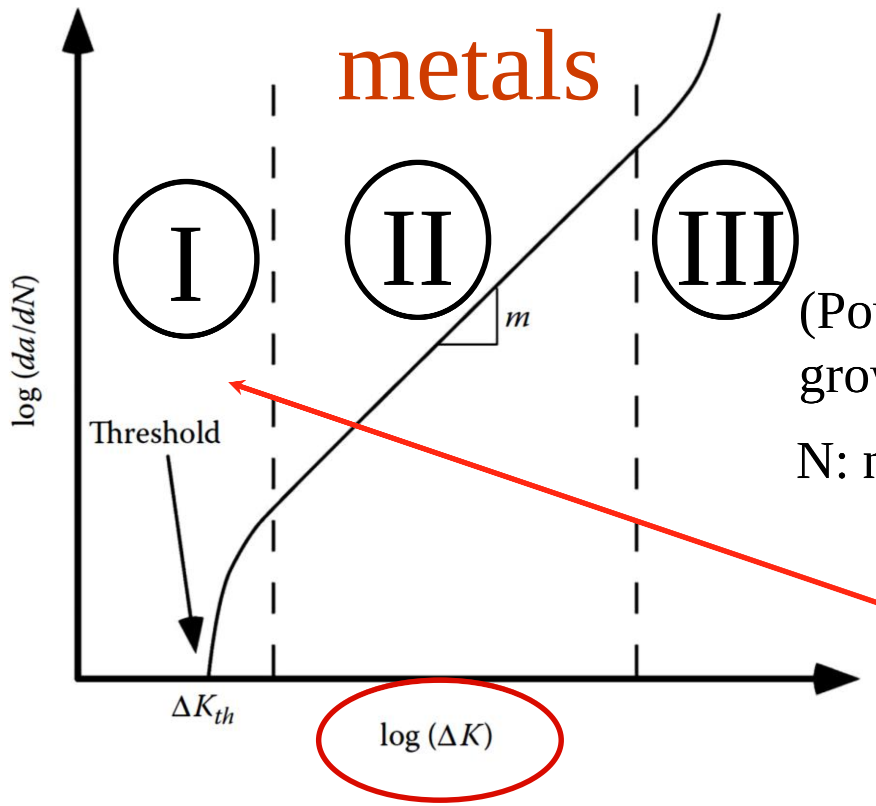
3



(b) (c)

Paris’ law (fatigue)

- Paris' law can be used to quantify the residual life (in terms of load cycles) of a specimen given a particular crack size.
- Paris’ law is the most popular fatigue crack growth model



Fatigue crack growth behavior in metals

Paris’ law $\frac{da}{dN} = C(\Delta K)^m, \ \Delta K = K_{\max} - K_{\min}$

$2 \leq m \leq 7$

(Power law relationship for fatigue crack growth in region II)

N: number of load cycles

For region I:

$\Delta K \leq \Delta K_{\text{th}}$: no crack growth

(dormant period) 10^{-8} mm/cycle

Paris' law

$$\frac{da}{dN} = C(\Delta K)^m, \quad \Delta K = K_{\max} - K_{\min}$$

not depends on load ratio R

Table 1: Numerical parameters in the Paris equation.

alloy	m	C
Steel	3	10^{-11}
Aluminum	3	10^{-12}
Nickel	3.3	4×10^{-12}
Titanium	5	10^{-11}

C and *m* are material properties that must be determined experimentally from a log(ΔK)-log(da/dN) plot.

m=2-4 for metal and m= 4-100 for ceramics/ polymers.

Other fatigue models

Forman's model (stage II-III)

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{C(\Delta K)^n}{(1-R)K_c - \Delta K}$$

Paris' model

$$\frac{da}{dN} = C(\Delta K)^m$$

$$(R = K_{min} / K_{max})$$

$$\frac{K_{\max} - K_{\min}}{K_{\max}} K_c - (K_{\max} - K_{\min}) \qquad \text{If} \quad K_{\max} = K_c : \frac{da}{dN} = \infty$$

Other fatigue models

Nasgro's Model

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{\max}}{K_C}\right)^q}$$

Paris' model

$$\frac{da}{dN} = C(\Delta K)^m$$

where N is the number of applied fatigue cycles, a is the crack length, R is the stress ratio, ΔK is the stress intensity factor range, $f=K_{op}/K_{max}$ and C, n, p, and q are empirically derived constants.

Crack closure

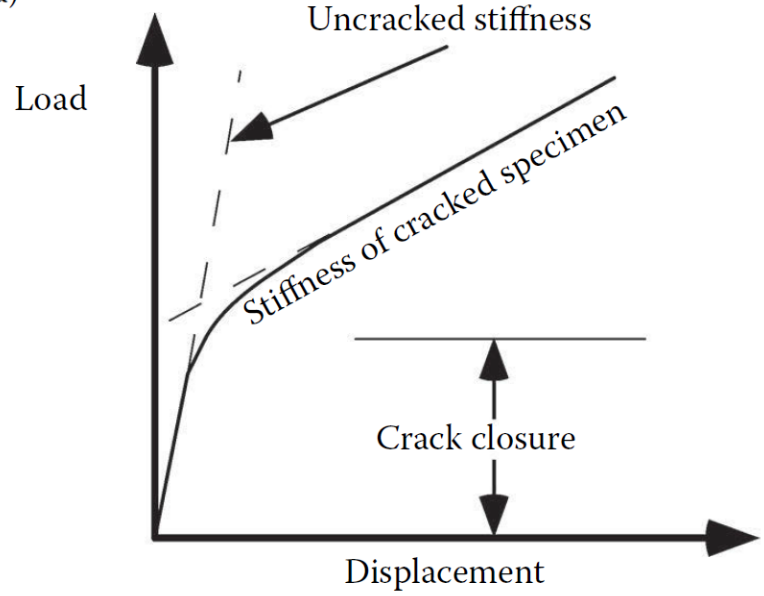
Elber

- At low loads, the compliance of cracked specimens are closed to that of un-cracked specimens.

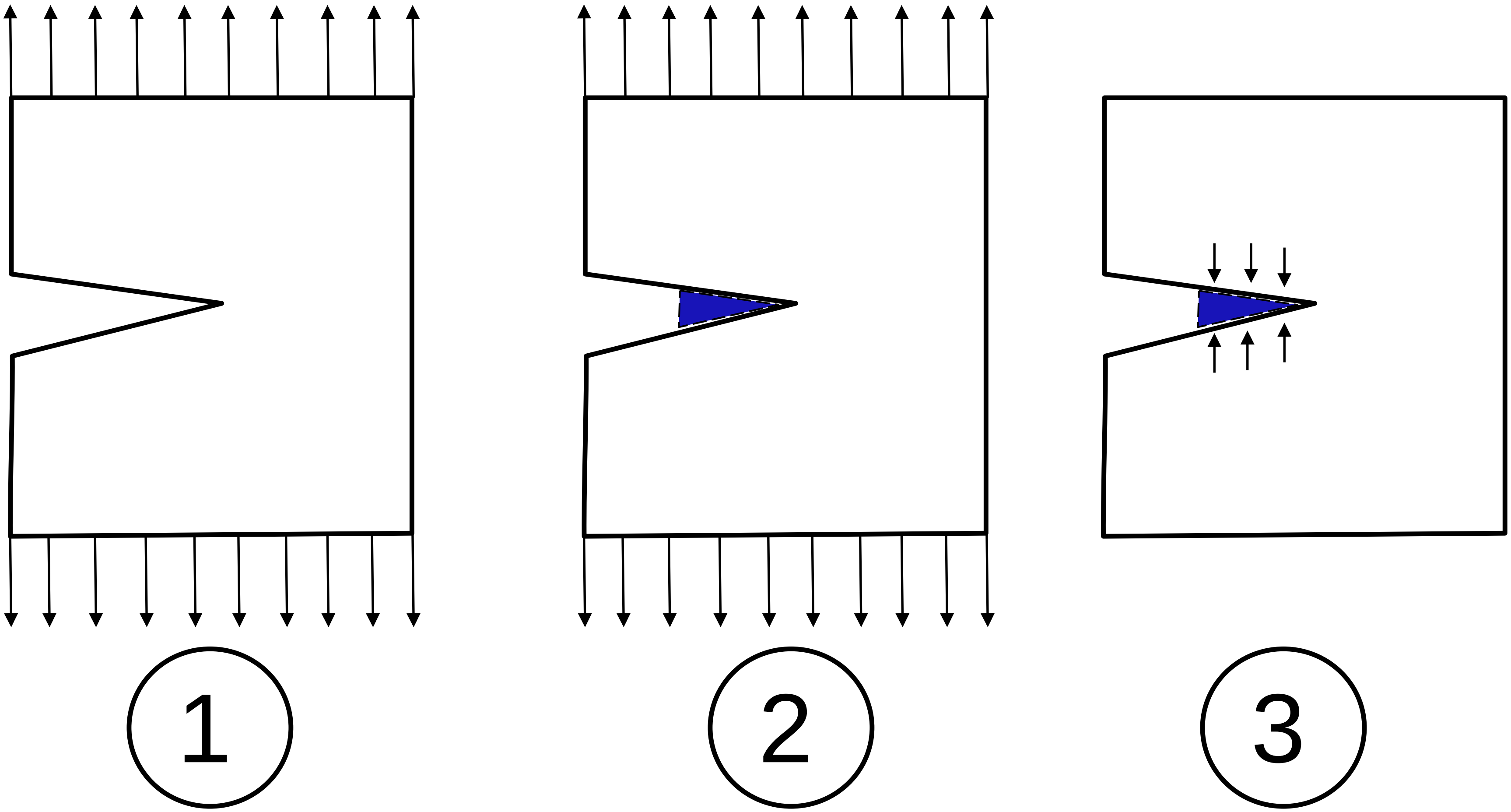
- Contact of crack faces: **crack closure**

- Fatigue crack growth occurs only when crack is fully open.

(a)



Crack closure



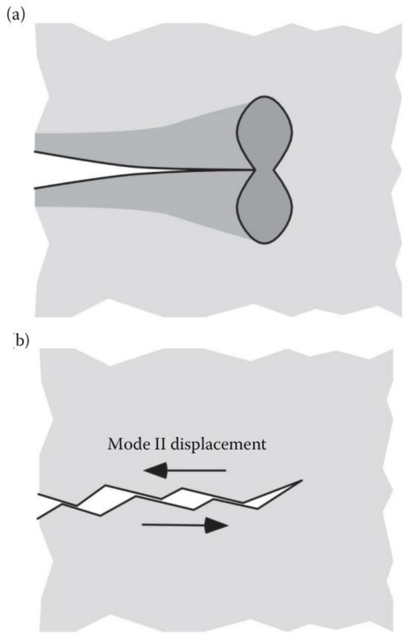
Crack closure

Effect of $R=K_{min}/K_{max}$: crack closure

- Suresh and Ritchie [16] identified five mechanisms for fatigue crack closure.

- During loading phases at maximum stress
  - There is an active plastic zone (phase transformation can happen)
  - The crack opening allows fluid or products to enter

- If R is low (< 0.7) or negative the crack lips can enter into contact at low stress values due to:



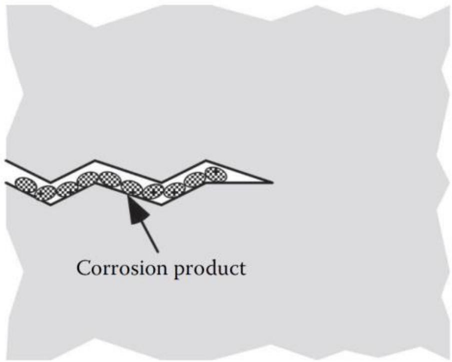
- Plasticity
  - –Residual plastic strain resulting from plastic wake will close the crack

- Roughness
  - –Non flat lips prevent sliding (mode II)

Crack closure

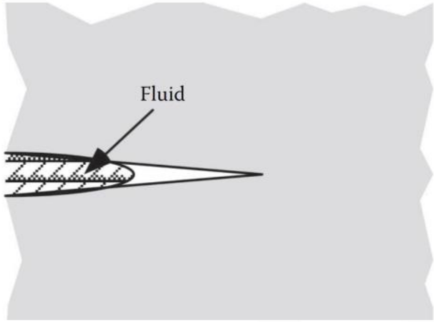
- Corrosion
  - Corrosion products fill the opening

(c)



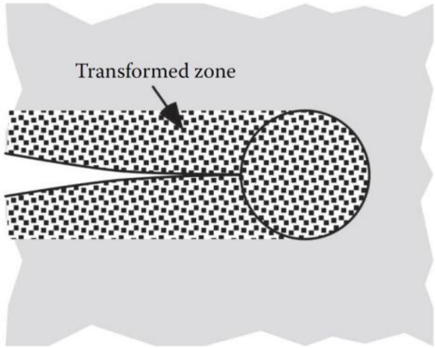
- Viscous fluid
  - Lubricant fluids fill the opening

(d)



- Phase transformation
  - Phase transformation at crack tip can put material in compression

(e)



Crack closure

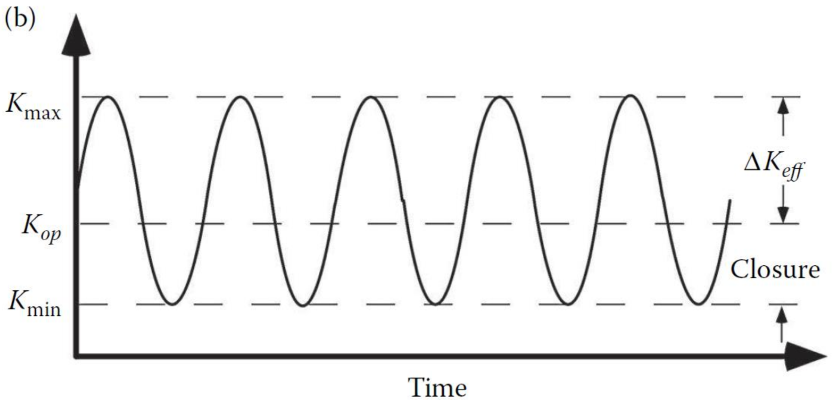
- Effect of crack closure on fatigue

–When the loading decreases ----> local compressive effects ----> parts of the cracks are kept opened.
–The stress intensity factor at the minimum of the cycle is more important than predicted ----> the effective ΔK is actually reduced.

$$\Delta K_{\mathrm{eff}} = K_{\mathrm{max}} - K_{\mathrm{op}}$$

K_{op}: opening SIF

$$\frac{da}{dN} = C \Delta K_{\mathrm{eff}}^{m}$$



Empirical relation: $K_{op} = \varphi(R) K_{\max}$

$$\varphi(R) = 0.25 + 0.5R + 0.25R^{2} \qquad -1 \le R \le 1$$

❖ *The crack closure effect is therefore beneficial to structure life.*

Crack arrestment

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\Delta K_{\mathrm{eff}}^{m} = C\left(\frac{\Delta K_{\mathrm{eff}}}{\Delta K}\Delta K\right)^{m}$$

$$= C\left(\frac{K_{\max} - K_{\mathrm{op}}}{\Delta K}\Delta K\right)^{m}$$

$$= C\left(\left(\frac{K_{\max}}{K_{\max} - K_{\min}} - \frac{K_{\mathrm{op}}}{\Delta K}\right)\Delta K\right)^{m}$$

$$= C\left(\left(\frac{1}{\frac{K_{\max}}{K_{\max}} - \frac{K_{\min}}{K_{\max}}} - \frac{K_{\mathrm{op}}}{\Delta K}\right)\Delta K\right)^{m}$$

$$= C\left(\left(\frac{1}{1-R} - \frac{K_{\mathrm{op}}}{\Delta K}\right)\Delta K\right)^{m}$$

- For

$$\frac{1}{1-R} - \frac{K_{\mathrm{op}}}{\Delta K} = 0$$

we get

$$\Delta K = K_{\mathrm{op}}(1-R) = \Delta K_{\mathrm{th}}$$

and

$$\frac{\mathrm{d}a}{\mathrm{d}N} = 0$$

- For

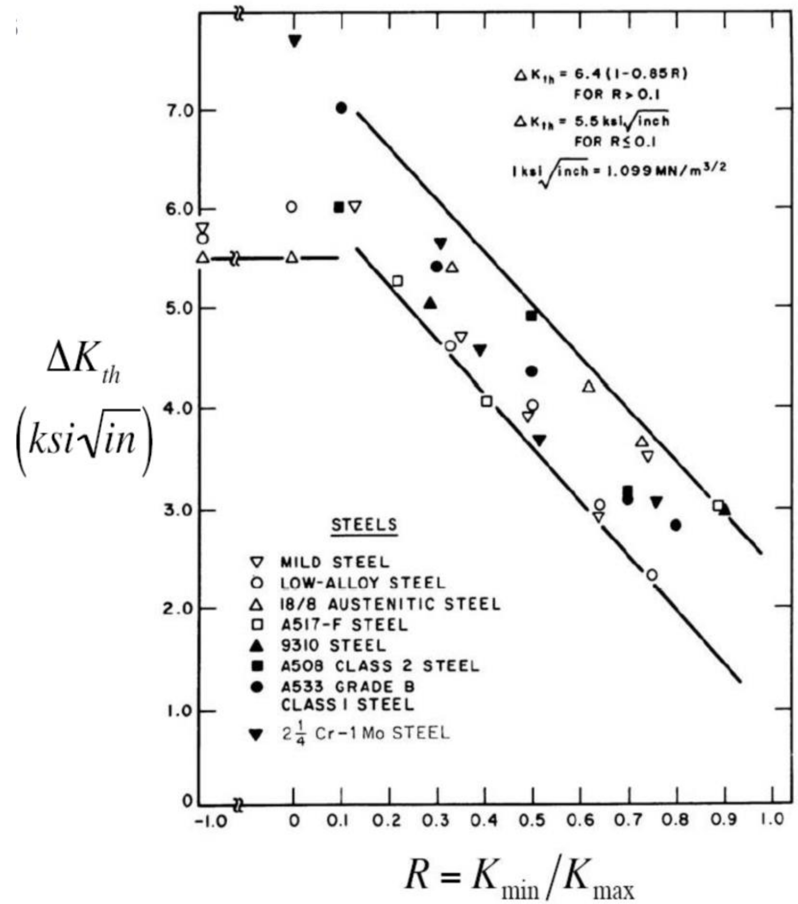
$$\frac{1}{1-R} - \frac{K_{\mathrm{op}}}{\Delta K} = 1$$

we get

$$\Delta K = K_{\mathrm{op}}\left(\frac{1}{R} - 1\right)$$

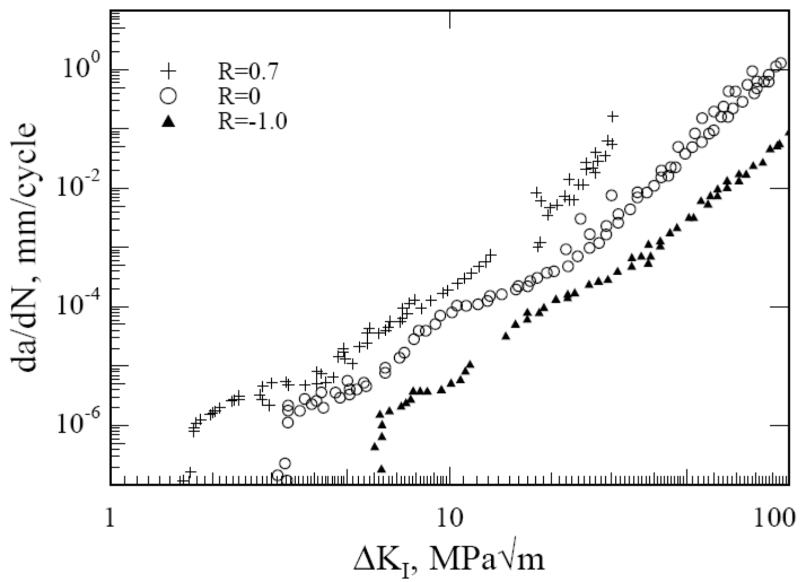
Crack closure

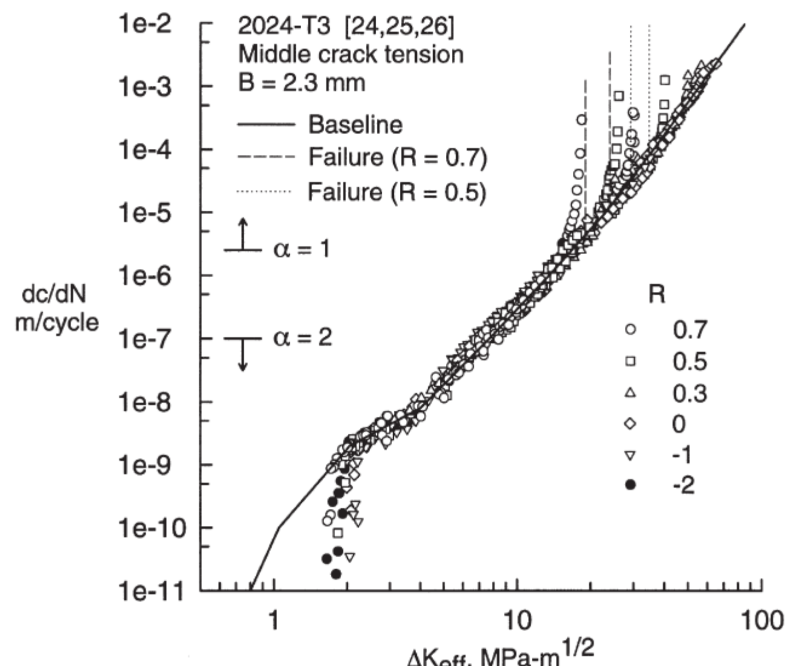
- Effect of $R=K_{min}/K_{max}$ on threshold (Zone I)
  - Due to Plasticity Induced Crack Closure
  - ΔK_{th} decreases when R increases



Crack closure

- Effect of $R=K_{min}/K_{max}$ on crack growth rate (Zone II)
  - Due to crack closure life of structure is improved for low R
- Example of 2024-T3 aluminum alloy



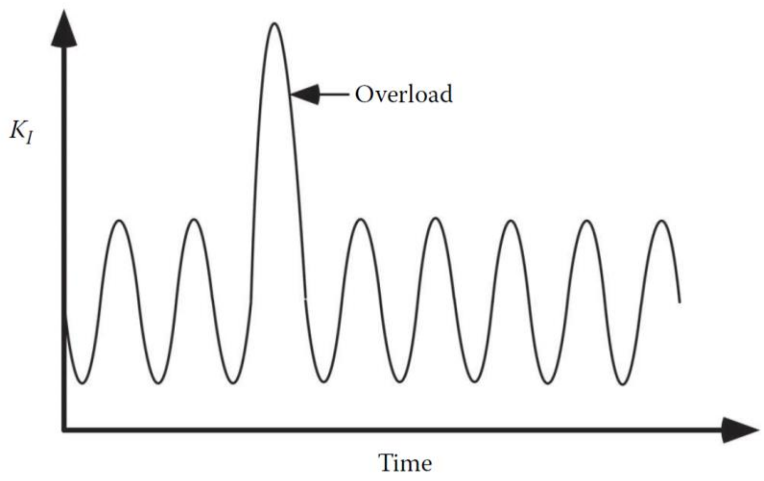


  - ΔK_{eff} depends on many parameters (loading, environment, …)
    - Example: model of Elber & Schijve for Al. 2024-T3
    – $\Delta K_{eff} = (0.55 + 0.33\,R + 0.12\,R^2)\,\Delta K$ for $-1<R<0.54$
    - Models can be inaccurate in non-adequate circumstances

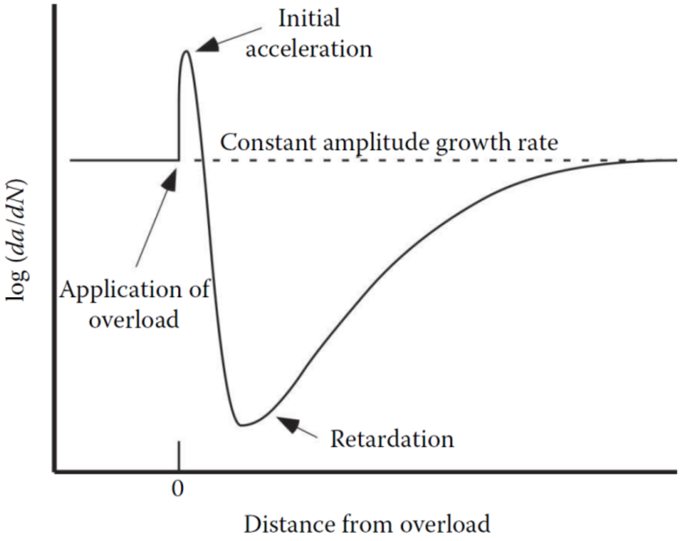
Crack closure

- Overload effect

➢ Constant-amplitude loading is interrupted by a single overload, after which the K amplitude resumes its previous value. Prior to the overload, the plastic zone would have reached a steady-state size, but the overload cycle produces a significantly larger plastic zone.



A single overload during cyclic loading.



Typical crack growth behavior following the application of a single overload.

Crack closure

- Overload effect

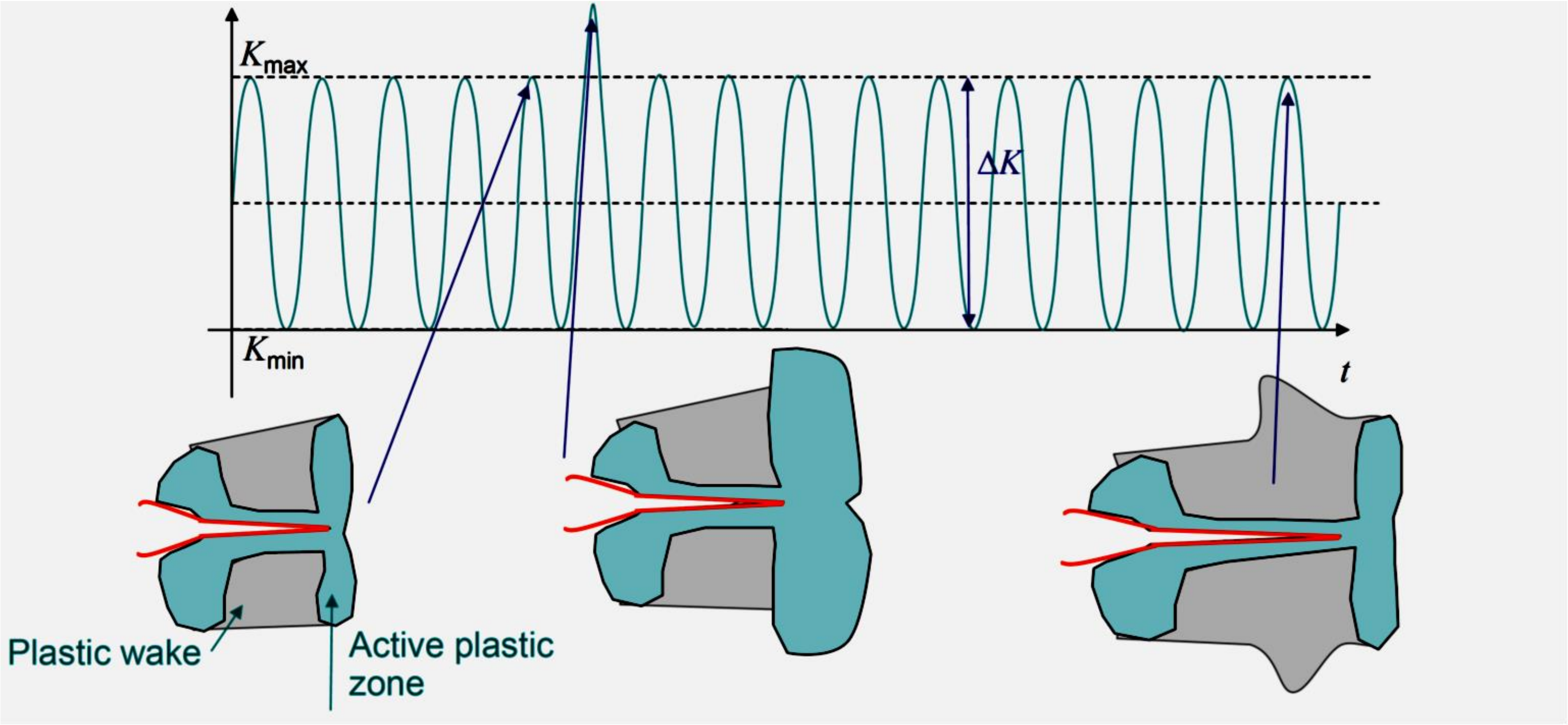
➢ Three possible mechanisms have been proposed to explain retardation following an overload:

1. The crack blunts following an overload, and crack growth is delayed while the crack tip re-sharpens.
2. The compressive residual stresses in front of the crack tip retard the crack growth rate.
3. As the crack grows into the overload zone, residual stresses behind the crack tip result in plasticity-induced closure.

Crack closure

- Overload effect

➢ What happens if there is a few (or a moderate) number of overloads ?



➢ Plastic wake is temporarily increased, until the active plastic zone at crack tip passed the plastic zone created by the overload

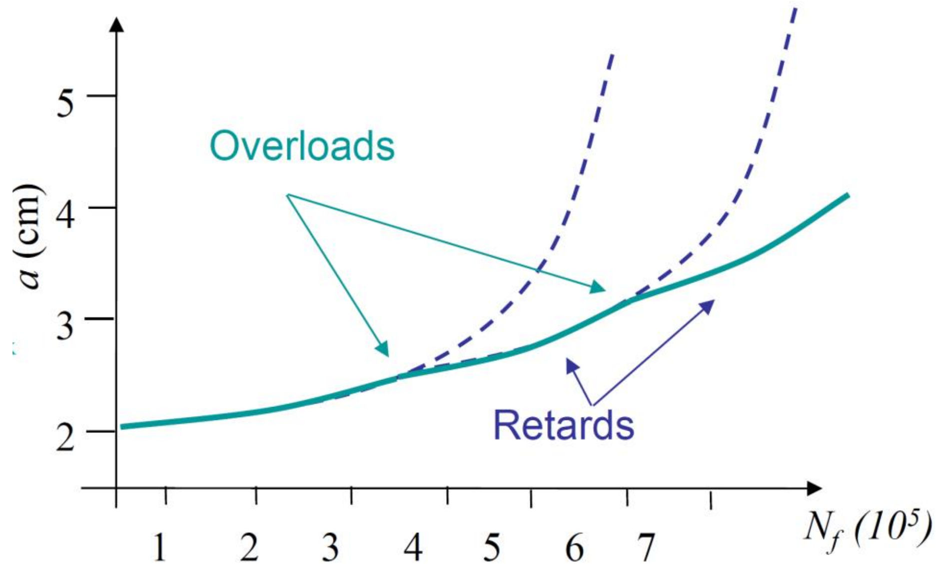
➢ So which effect ?

Crack closure

- Overload effect

➢ As the plastic wake is temporarily increased, ΔK_{eff} is reduced due to Plasticity Induced Crack Closure ----> there is a retard effect in the crack propagation

- Infrequent overloads help
- Frequent overloads may help
- Too frequent overloads are damaging, as it actually corresponds to increasing K_{max}

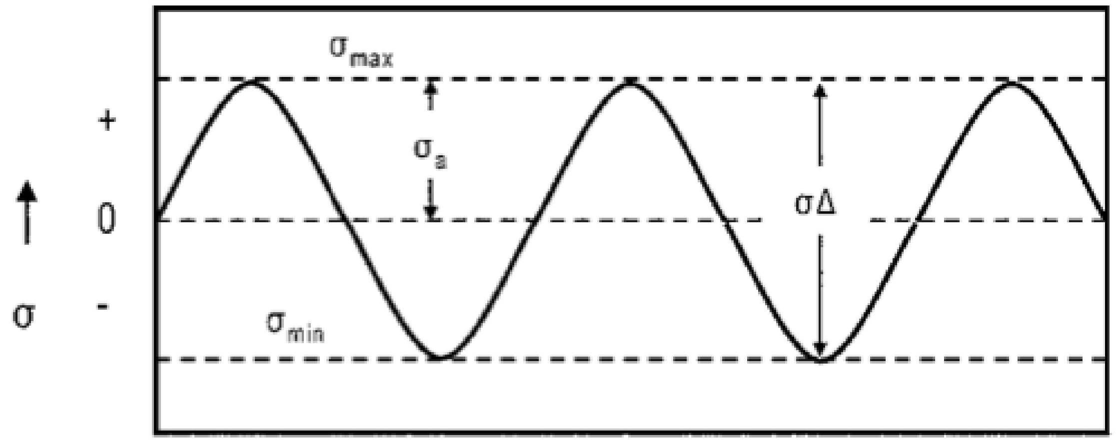


Tension/compression cyclic loads

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} < 0$$

$$\frac{da}{dN} = C(\Delta K)^m, \quad \Delta K = K_{\max} - \cancel{K_{\min}}$$

$$\boxed{\frac{da}{dN} = C(K_{\max})^m}$$

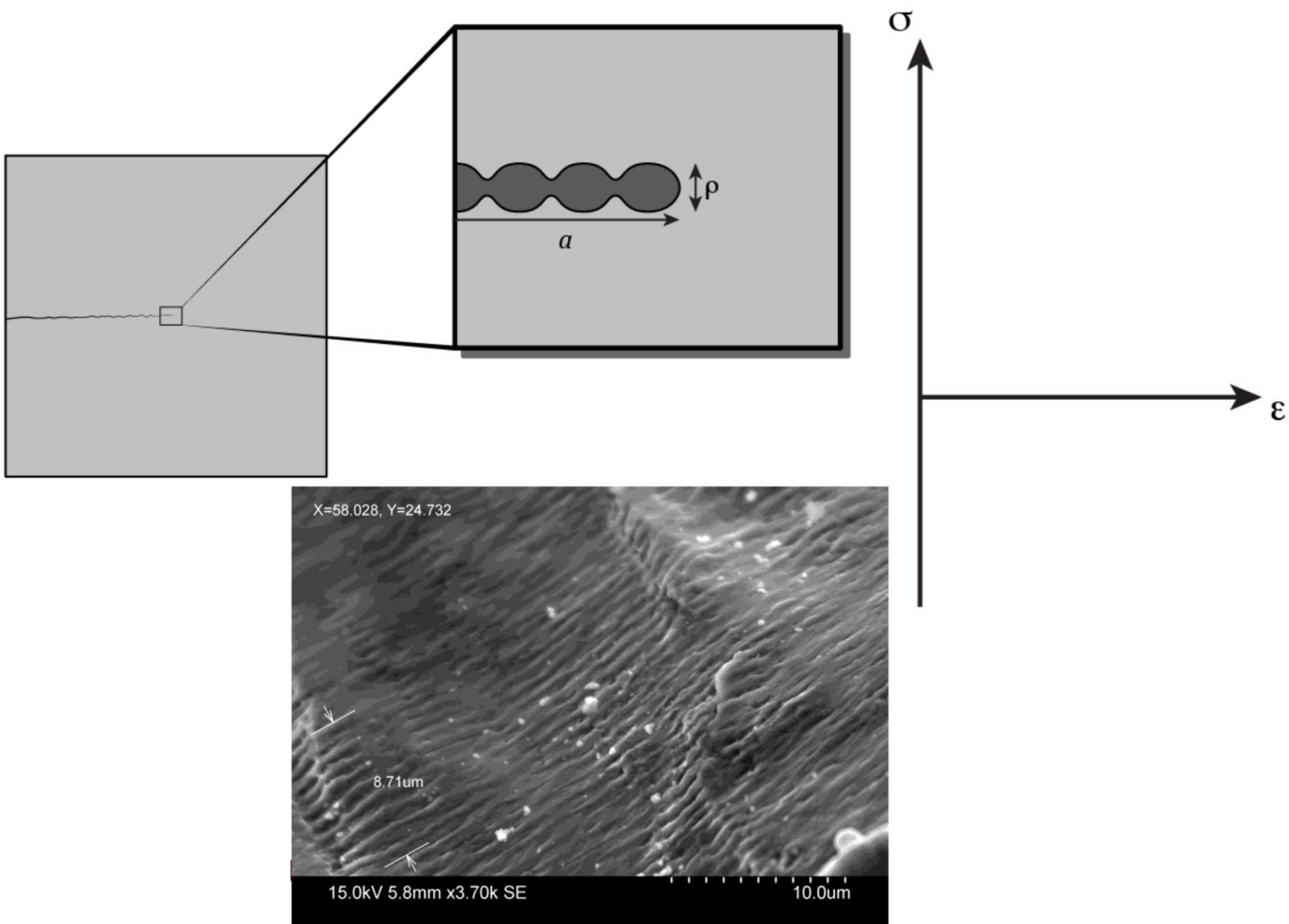


Fully Reversed Loading

Fatigue – Three Stages

region	I	II	III
Terminology	Slow-growth rate (near-threshold)	Slow-growth rate (Paris law)	High-growth rate
Microscopic failure mode	Single shear	Striations, duplex slip	Additional static modes
Fracture surface features	Faceted or serrated	Planar with ripples	Additional cleavage or microvoid coalescence
Crack closure levels	High	Low	—
Microstructural effects	Large	Small	Large
Load ratio effects	Large	Small	Large
Environmental effects	Large		Small
Stress state effects	—	Large	Large

Crack growth is governed by crack tip plasticity



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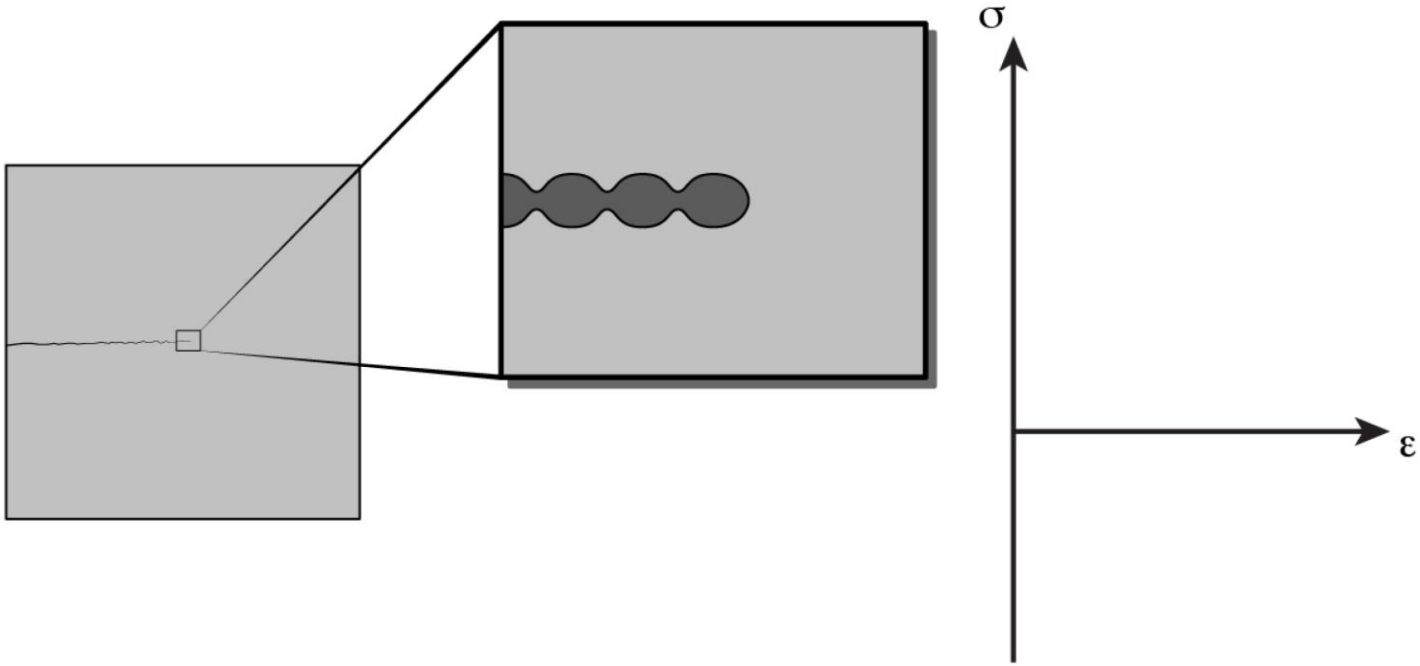

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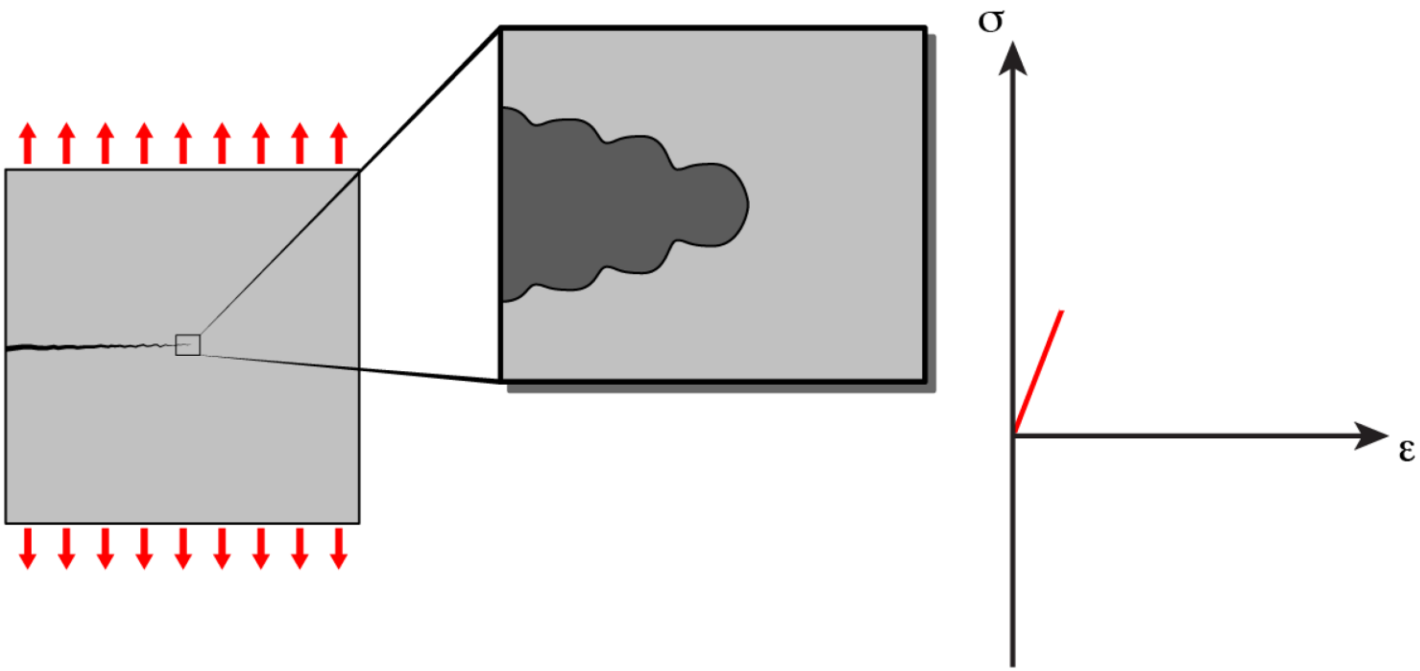

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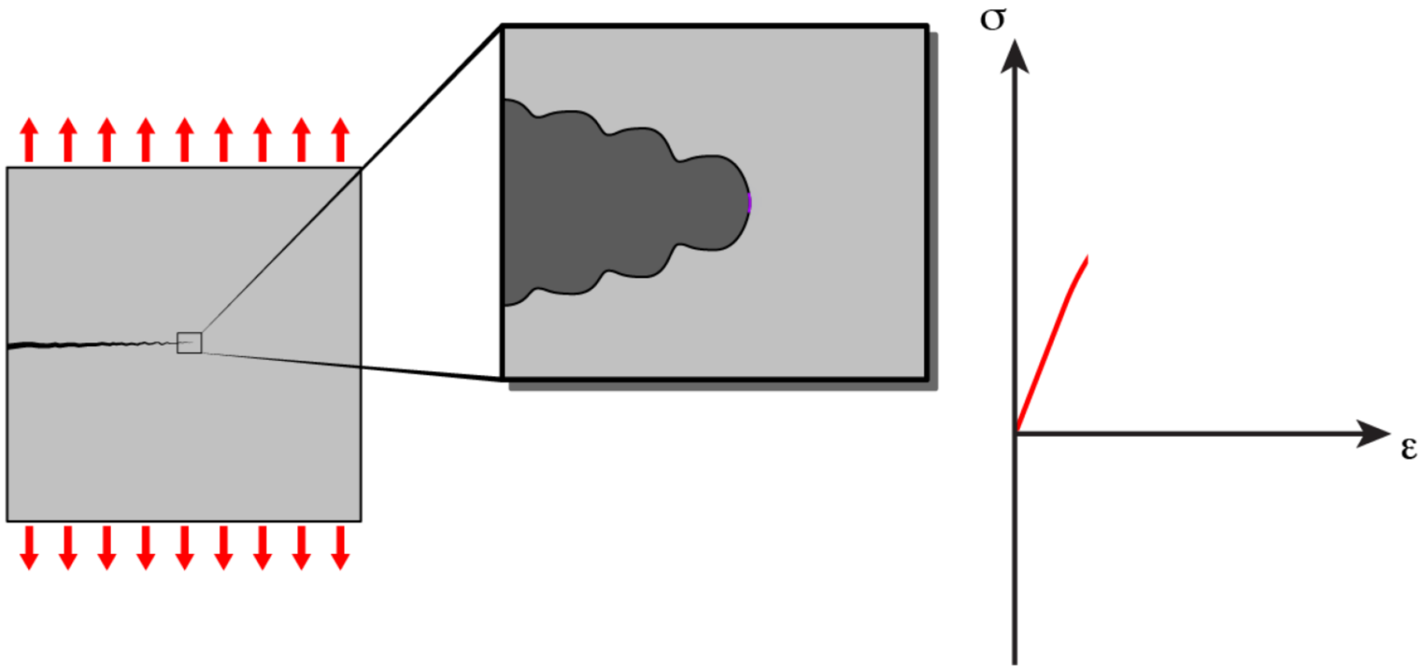

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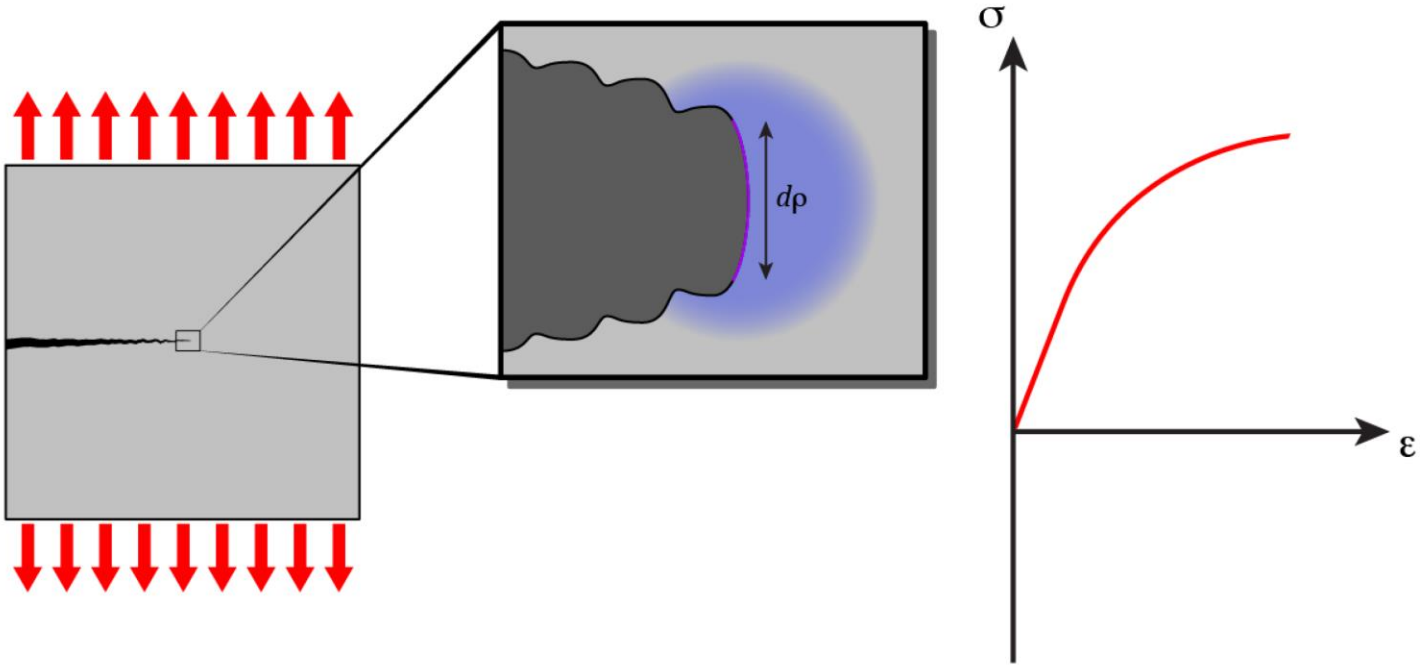

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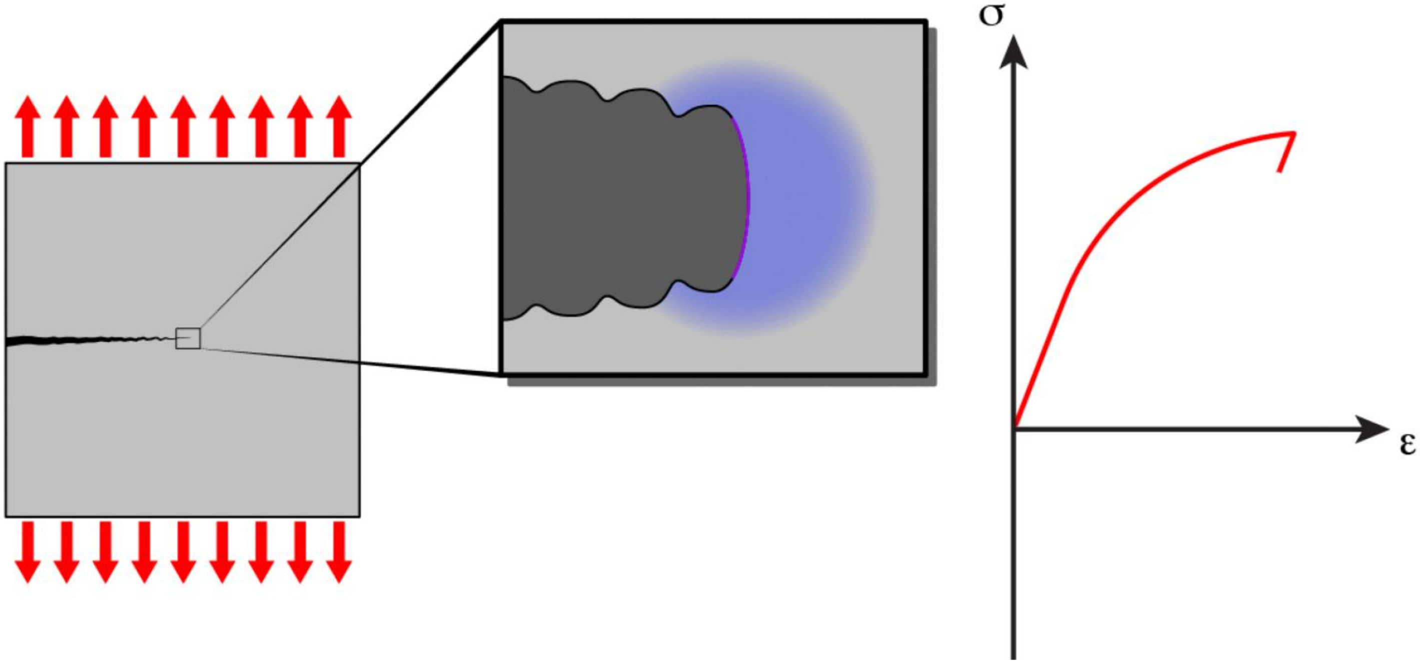

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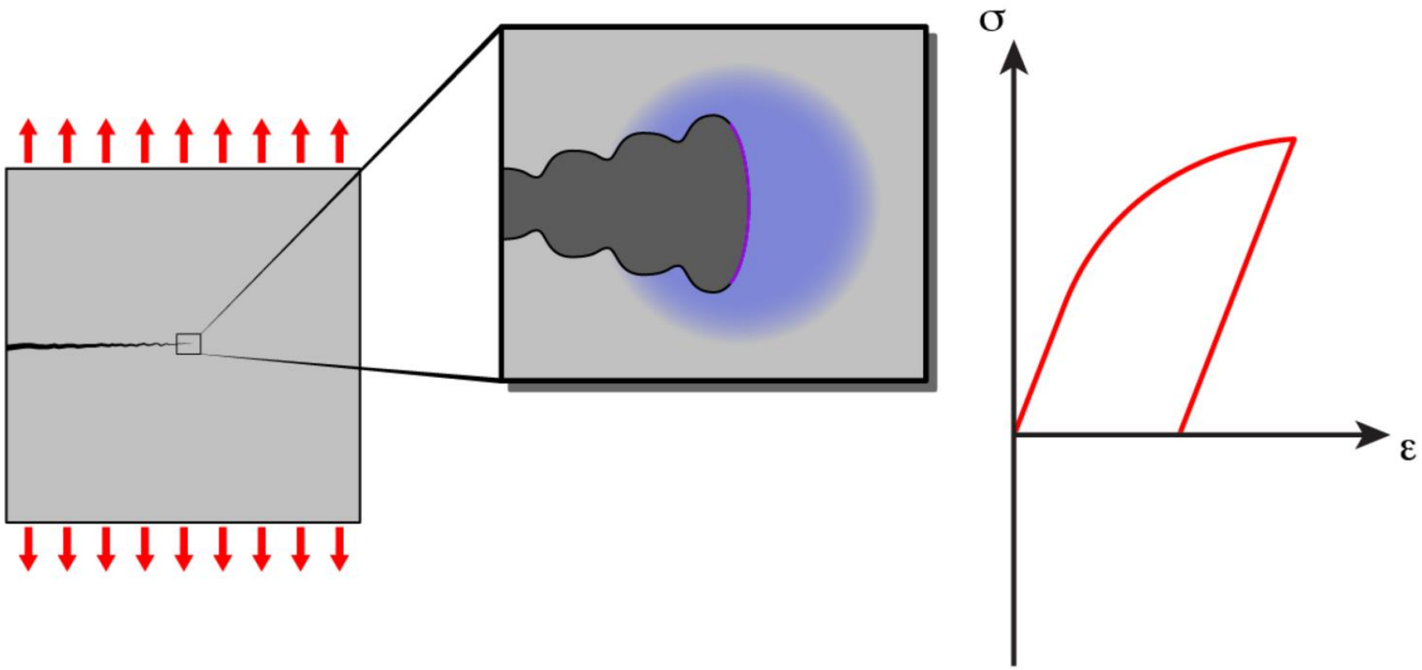

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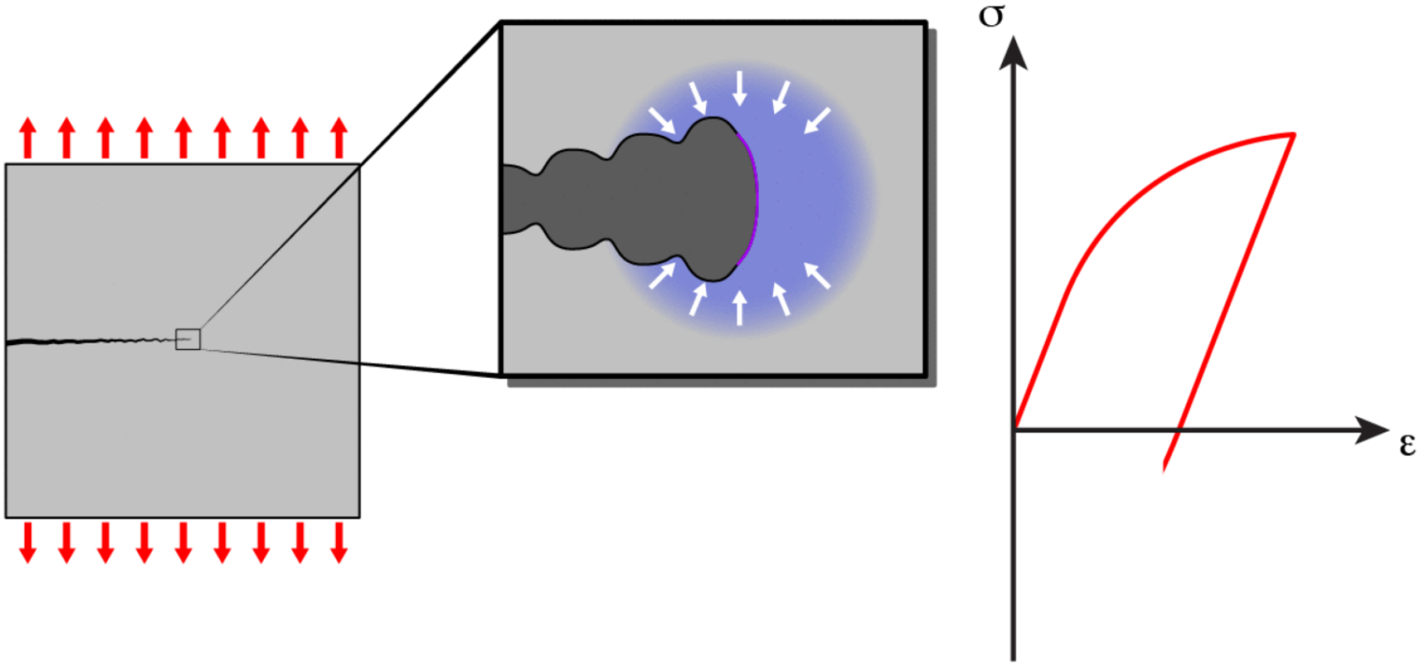
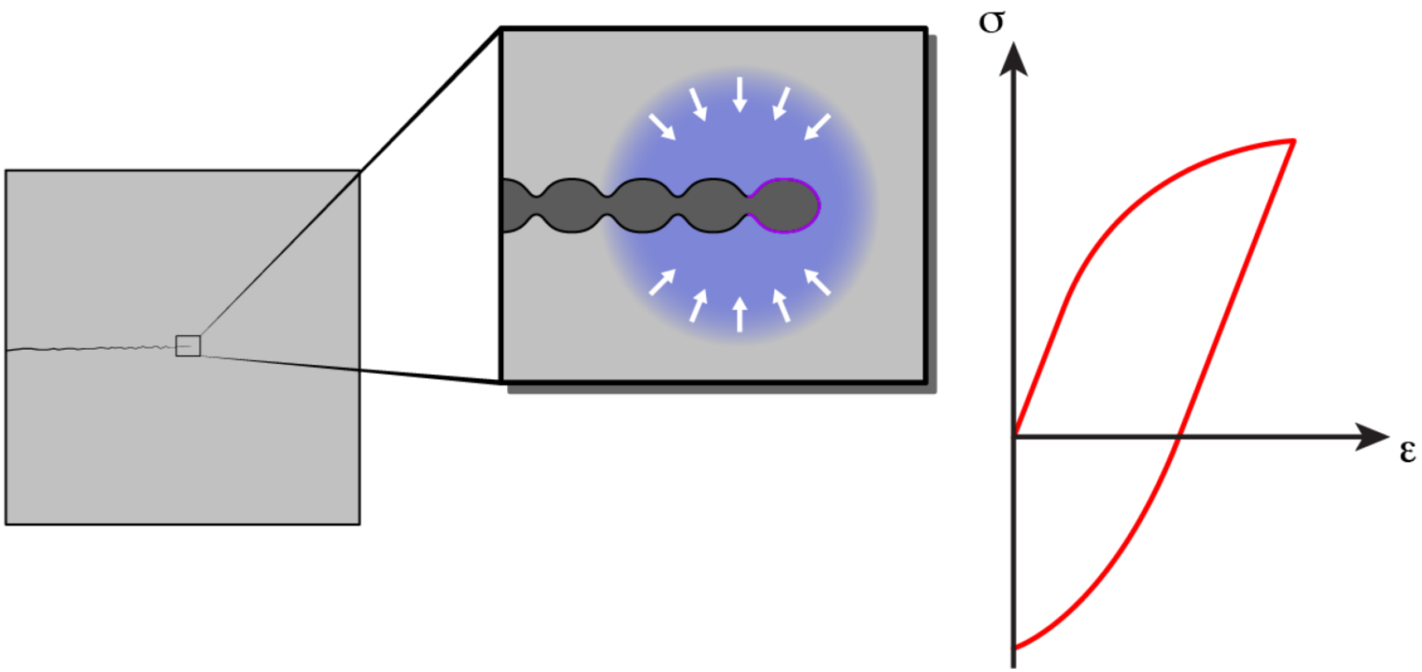


Crack growth is governed by crack tip plasticity



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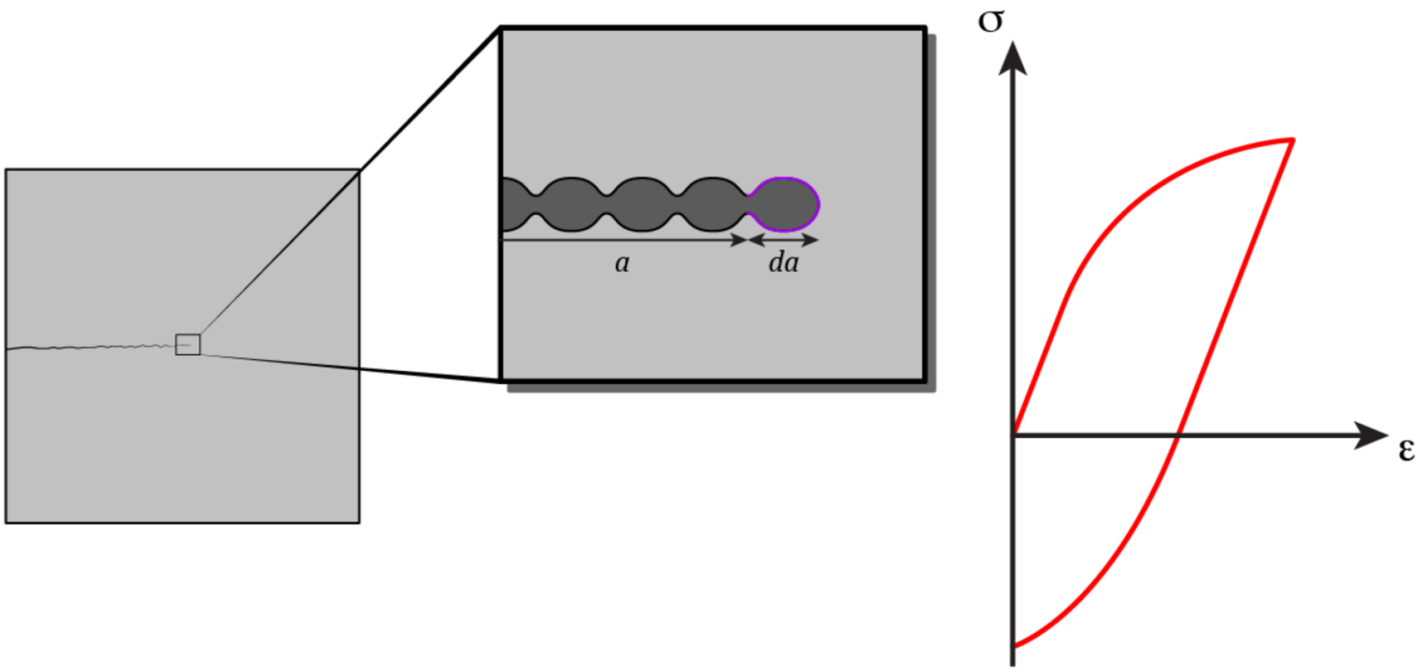

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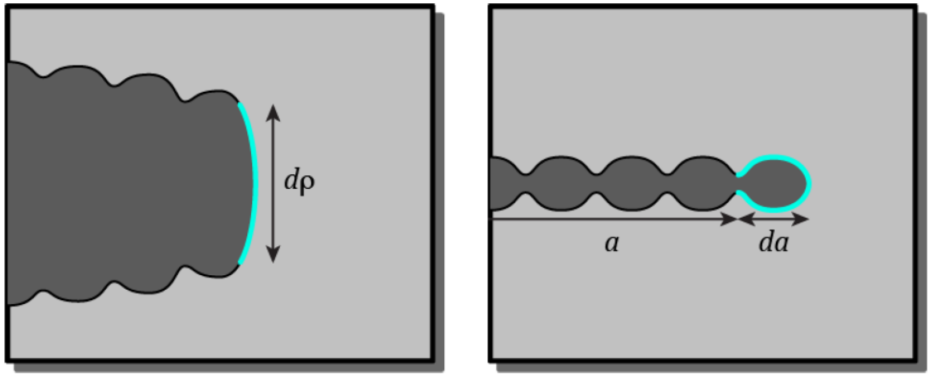

$$\frac{da}{dN} = \alpha \frac{d\rho}{dN}$$