Understanding Fretting fatigue – an extreme condition

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- Grid-to-rod fretting failure due to fuel rod vibration remains as a significant cause of nuclear fuel failure in pressurized water reactors (PWRs)

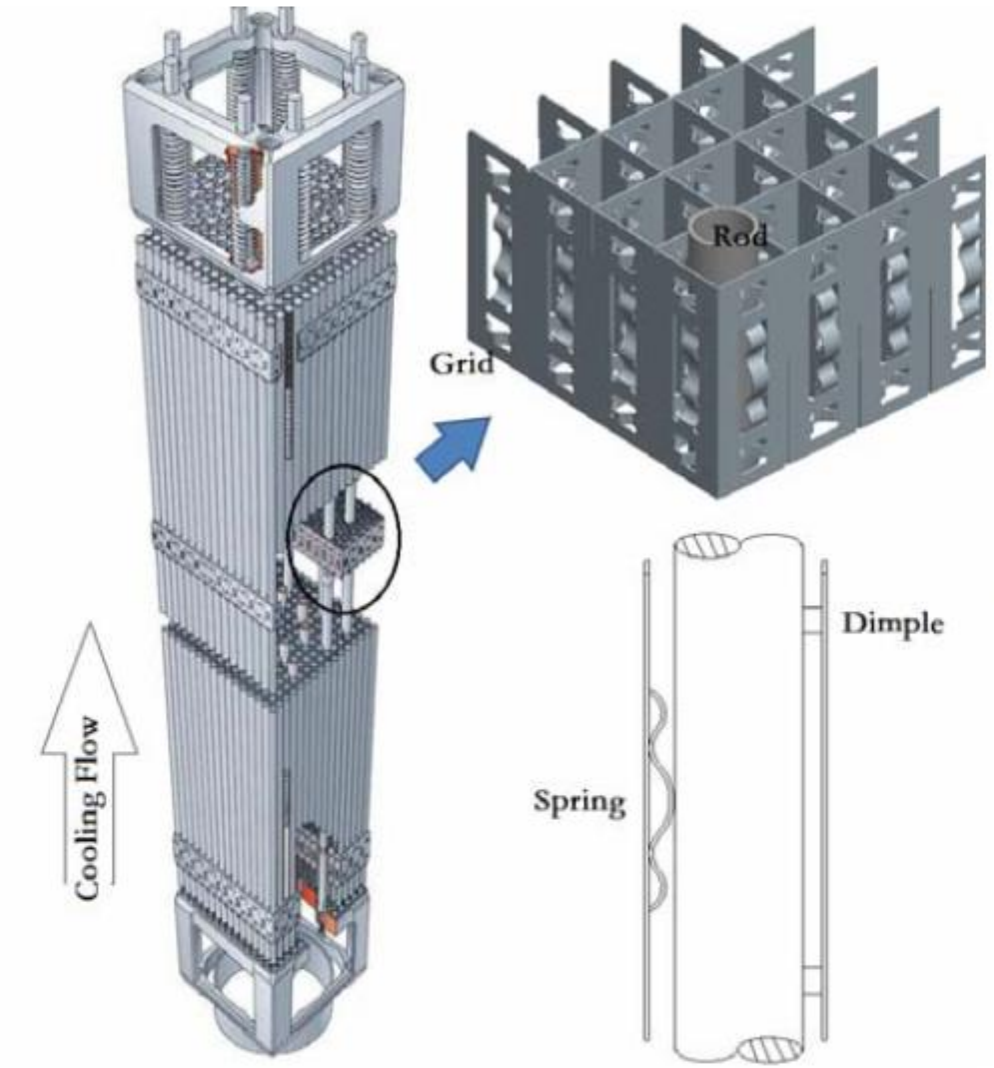


Figure 1. Grid-to-rod assembly

- Significant numbers of failure in turbine engine components are attributed to fretting fatigue-related damage (see Figure 1a). Examples of these are routinely seen damage in dovetail joints of turbine engine blades including their press-fit or interlocking connections to the disk, which are subjected to surface wear and fretting fatigue.

Figure-1a Bladed disk dovetail attachment region and its associated damage.

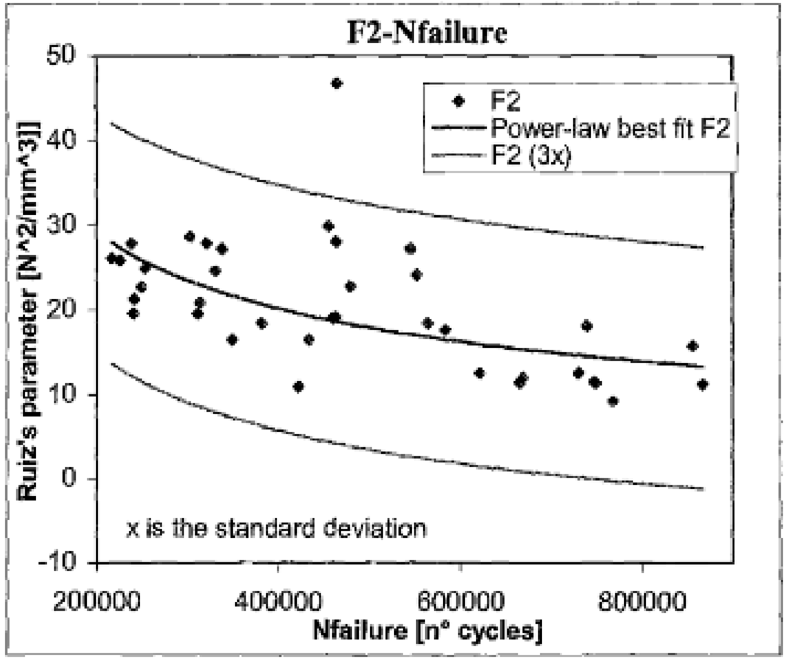
Typical literature

- *The literature on fretting corrosion clearly shows that the endurance limit values of metals with fretted or corroded surfaces decrease to as little as 25% of their uncorroded values…*
- *The rate of fretting is influenced by the magnitude of the microscopic relative motions between the mating parts, ..*
- *..research work is ongoing to establish a mathematical relationship to allow the accurate prediction of the loss of fatigue life as a function of fretting severity. The fact remains that there is a plentiful supply of empirical data showing this loss of fatigue strength.*

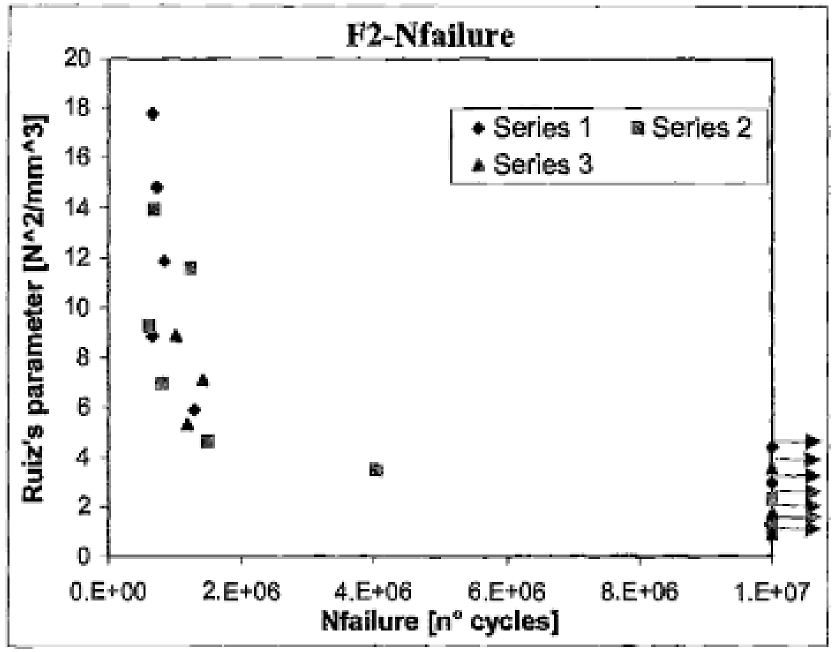
Source http://www.epi-eng.com/mechanical_engineering_basics/fretting_corrosion.htm

Ruiz parameter R=δτ σ proposed in the '80s

Nowell & Hills [11]). Further, the Oxford group (Ruiz et al. 1984, 1986 [12,13]) suggested a "Ruiz's composite surface damage parameter," $R=F_2=(\sigma\tau\delta)_{max}$, which ta empirically into account the evidence that cracks are more likely to develop in a regior tension rather than compression, therefore accounting also for the early stages propagation. Nowell & Hills [11] obtained a value of $R \quad 4N^2/mm^3$ as the lower bound initiation and failure within 10^7 cycles for the particular material examined (the 4% (Al alloy known as HE15-TF) and for a Hertzian 2D plane fretting contact.



a)

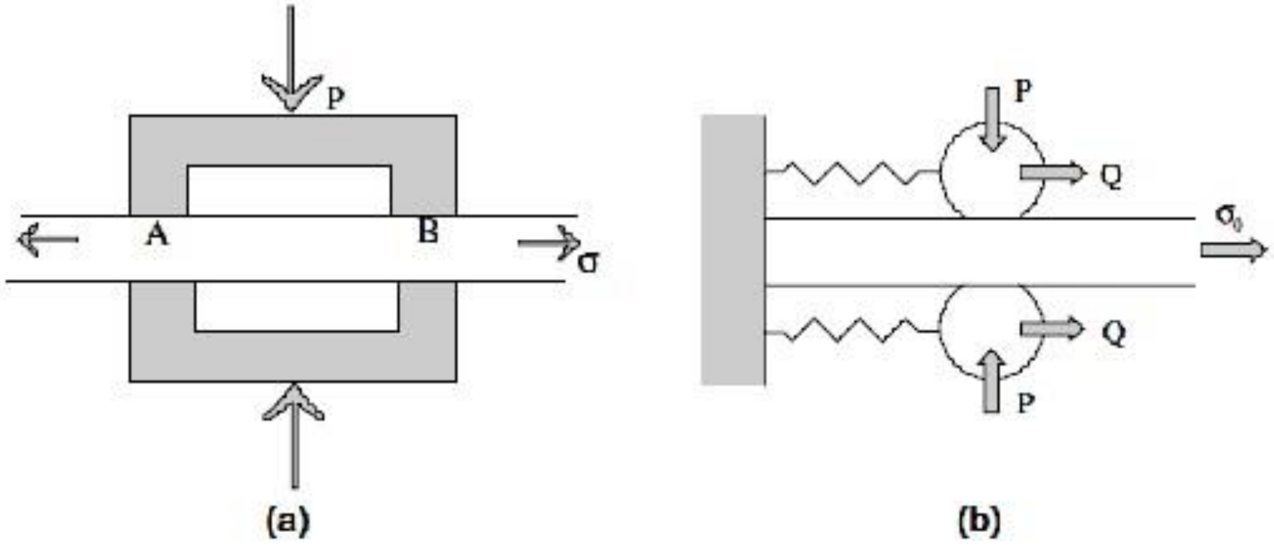


b)

FIG. 1— *F2 against fretting fatigue life of specimens: a) experimental data [14]; b) experimental data [15].*

An overall correlation was found, in Oxford (a), Purdue (b) data, but no model was ever attempted similar to what Kapoor has done in RCF, with wear accelerating and removing cracks at the same time (with some exception from Fouvry in Lyon)

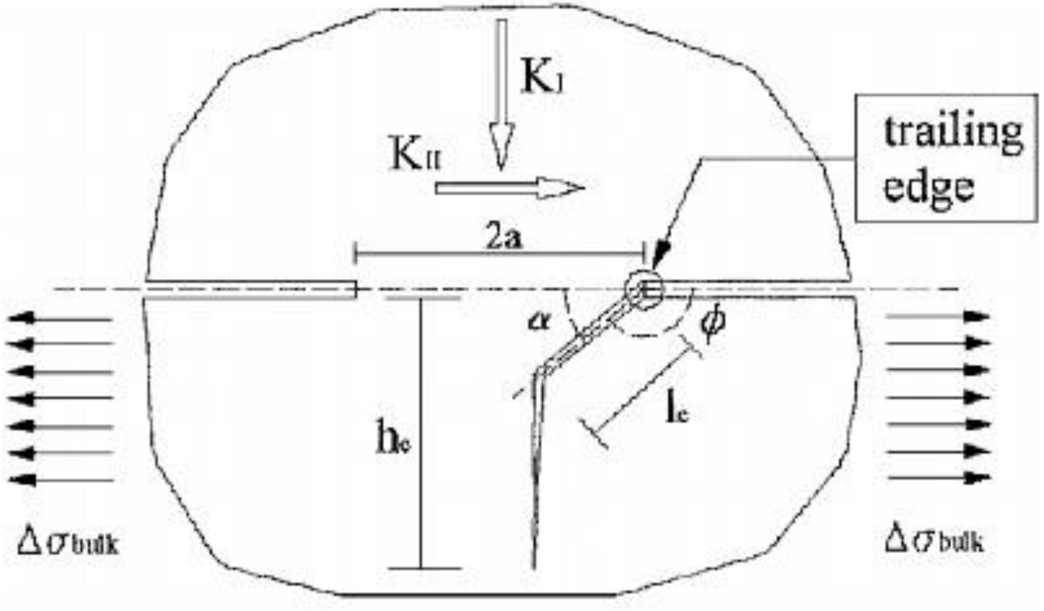
Trouble is...



…that generally in typical testing, when we increase loads, we increase both displacements and stress concentrations…….   So how to distinguish if fretting fatigue is really due to «corrosion», or more simply fatigue from stress concentration?

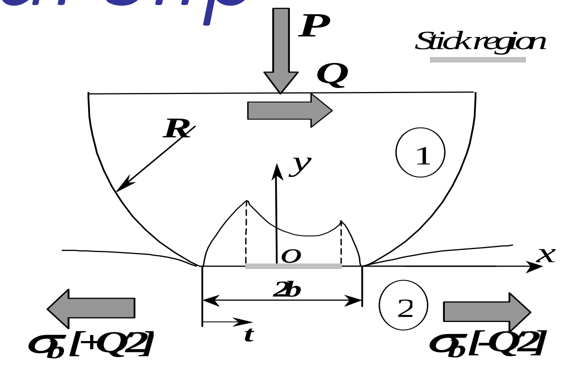
Is it purely fatigue from stress raisers?

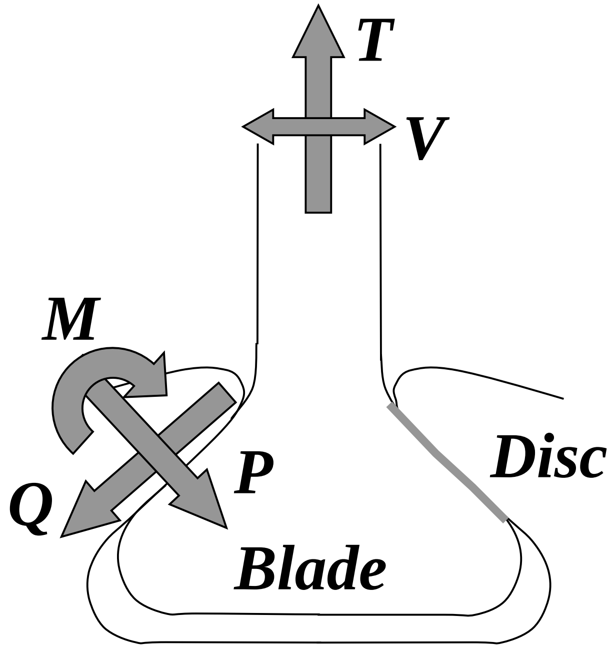
- MIT introduced in the late 90’s an interesting “crack analogue” model, whose original paper contains (qualitative) experimental validations: this seems to suggest that the effect of slip is not fundamental. As of today, not clear if fretting accelerates fatigue other than this factor



Contact mech. of partial slip

- Phd work with David Hills @ Oxford
- Cattaneo & Mindlin generalized partial slip problems
- This has opened the way for more accurate and more general solutions of contact problems, but has this helped in understanding fretting? Probably not much..





Dovetail joint

«Crack-like» and «blunt» notches

Atzori, B., P. Lazzarin, and G. Meneghetti. "Fracture mechanics and notch sensitivity." *Fatigue & Fracture of Engineering Materials & Structures* 26, no. 3 (2003): 257-267.

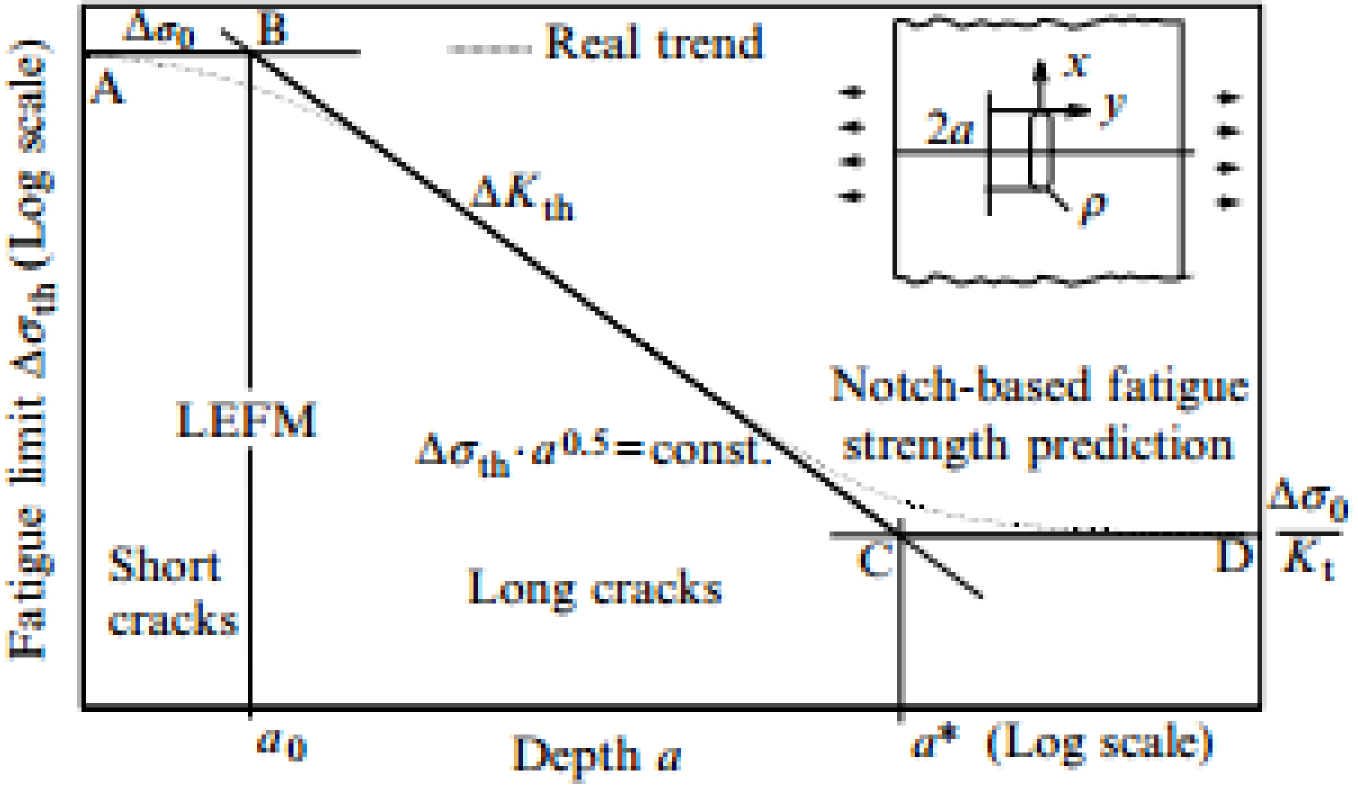
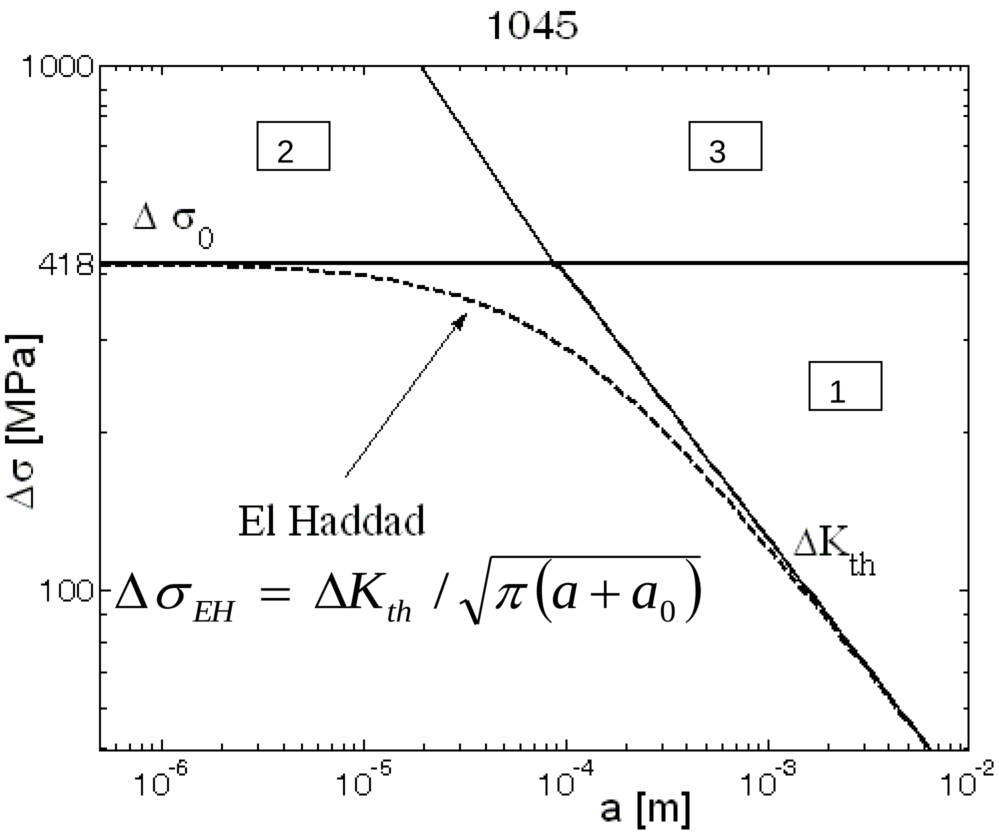


Fig. 4 Fatigue behavior for a crack and a notch centred on an infinite plate (the separation between short cracks and long cracks based on a_0 has to be considered as a simplified rule).

El Haddad eqt & Kitagawa-Takahashi diagram



1. Region above the threshold but below fat limit
2. Region above fat limit but below fat threshold
3. Region above both, fat limit and fat threshold

EH beatifully expresses the condition for non propagation of cracks or crack self-arrest

The CLNA model: an improved CA solution +..

'CRACK-LIKE' NOTCH ANALOGUE 1161

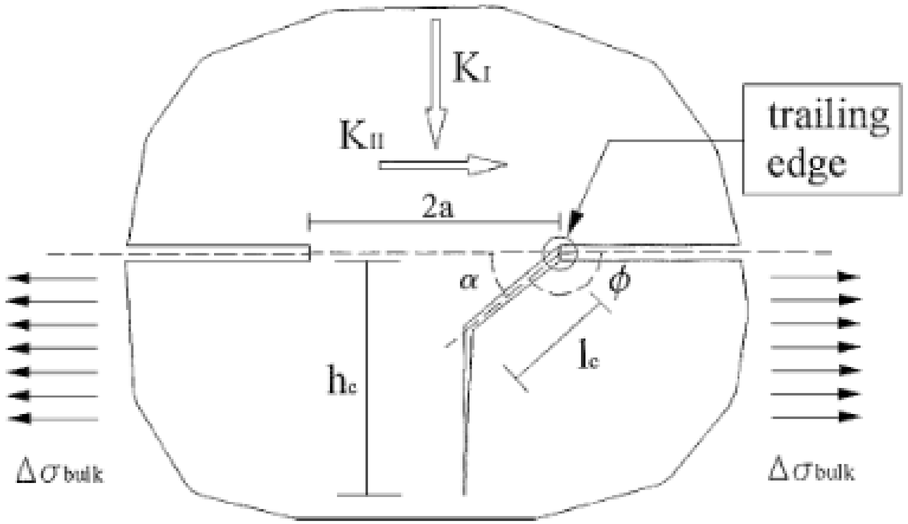


Fig. 1 The CA model a flat punch under normal load.

$$K_I = -\left(\frac{P}{\sqrt{\pi a}}\right) = -\left(\frac{2}{\pi}\bar{p}\sqrt{a}\right),$$
$$\Delta K_{II} = 2\left(\frac{Q}{\sqrt{\pi a}}\right) = 2\left(\frac{2}{\pi}\bar{q}\sqrt{a}\right), \quad (4)$$

$$(K_{II})_{\text{stick}} = \left(\frac{Q}{\sqrt{\pi a}}\right) + \frac{1}{2\gamma}\sigma_b\sqrt{\pi a},$$
$$\sigma_b \le \frac{4}{\pi}\gamma f \bar{p}\left(1 - \frac{Q}{fP}\right)$$
$$(K_{II})_{\text{slip}} = f K_I, \quad \sigma_b > \frac{4}{\pi}\gamma f \bar{p}\left(1 - \frac{Q}{fP}\right). \quad (6$$

Correcting for the presence of bulk stress makes the CA much simpler than original MIT model, and also more complete and immediate

.. + a good Notch analogue peak stress

456 *M. Ciavarella, G. Macina / International Journal of Mechanical Sciences 45 (2003) 449–467*

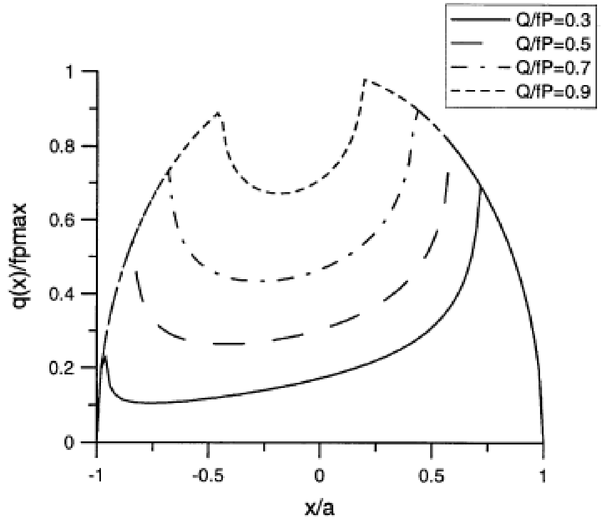


Fig. 5. Hertzian contact with tangential load and moderate bulk stress: shear tractions $q(x)/fp_{max}$ for $\sigma_b/fp_{max}=0$ various levels of Q/fP.

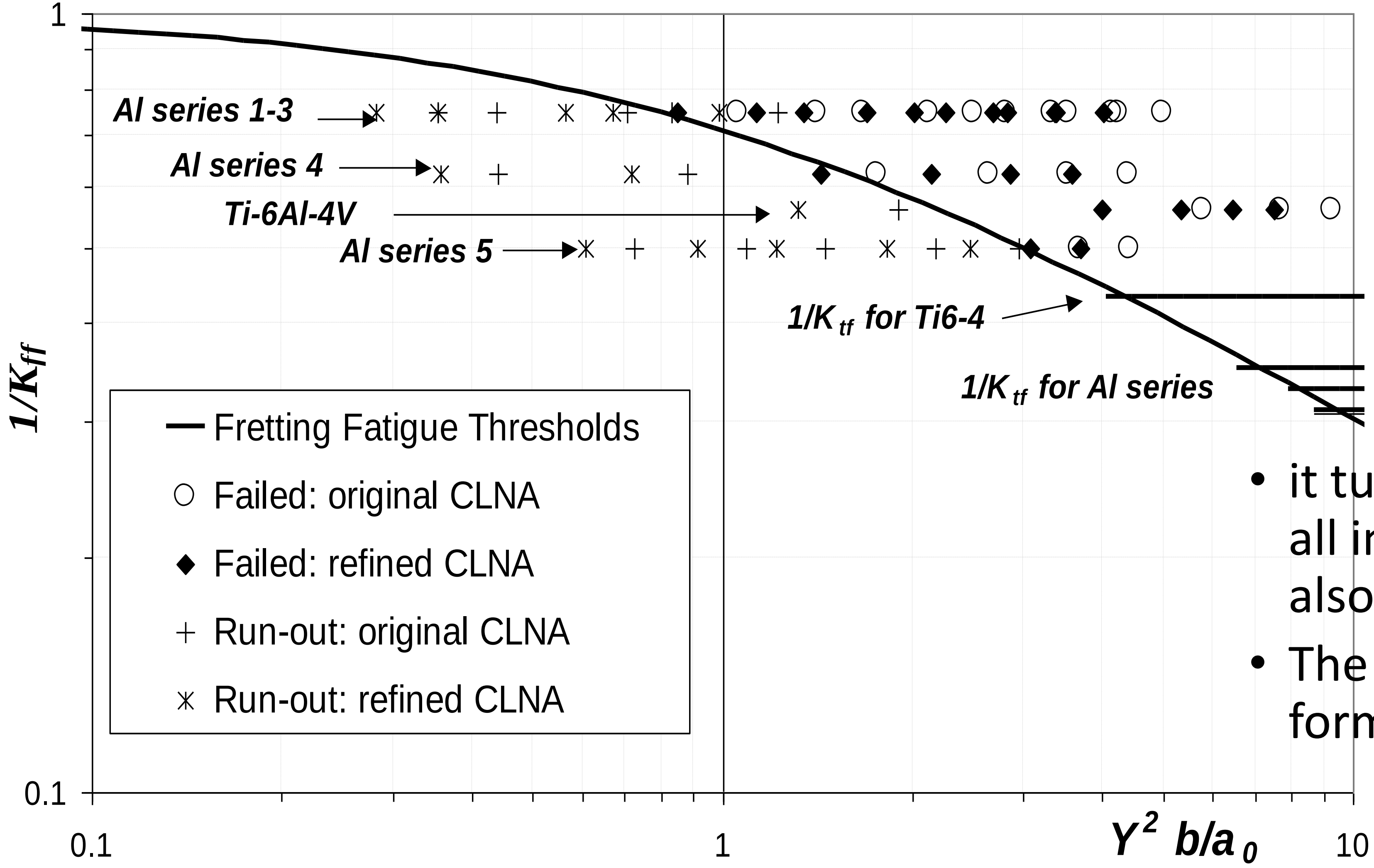
accurate formula for Hertzian, or rounded flat geometry, subject to constant pressure and oscillating tangential load is given by Ciavarella *et al.*[32,33] neglecting the effect of bulk stress on shear tractions,

$$\sigma_{\text{cont}} = \frac{8}{\pi}\bar{p}k\sqrt{fQ/P}, \tag{7}$$

where k is a contact geometrical factor equal to 1 in the Hertz contact case, and increasingly greater for rounded flat geometries towards the flat indenter case (d is the half-width of the flat part of the punch and a the half-width of contact)

$$k = \sqrt{\frac{1-\frac{2}{\pi}\arcsin\left(\frac{d}{a}\right)}{1-\frac{2}{\pi}\arcsin\left(\frac{d}{a}\right)-\frac{2}{\pi}\left(\frac{d}{a}\right)\sqrt{1-\left(\frac{d}{a}\right)^2}}}. \tag{8}$$

CLNA on Nowell's phd experiments



- it turns out that Nowell's data are all in the "crack-like" regime (and also Farris and Araujo)
- The CLNA model is entirely closed form

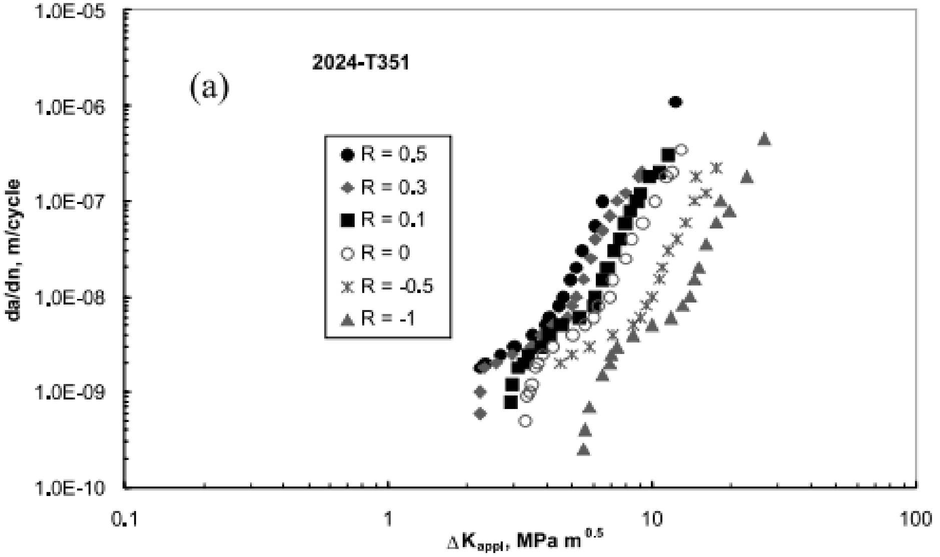
CLNA diagram with Y factor: Nowell data on Al2024 have been cited largely because they introduced clearly size effects by changing the radius of Hertzian pads. However, unfortunately no DKth data

Comments on Nowell’s data

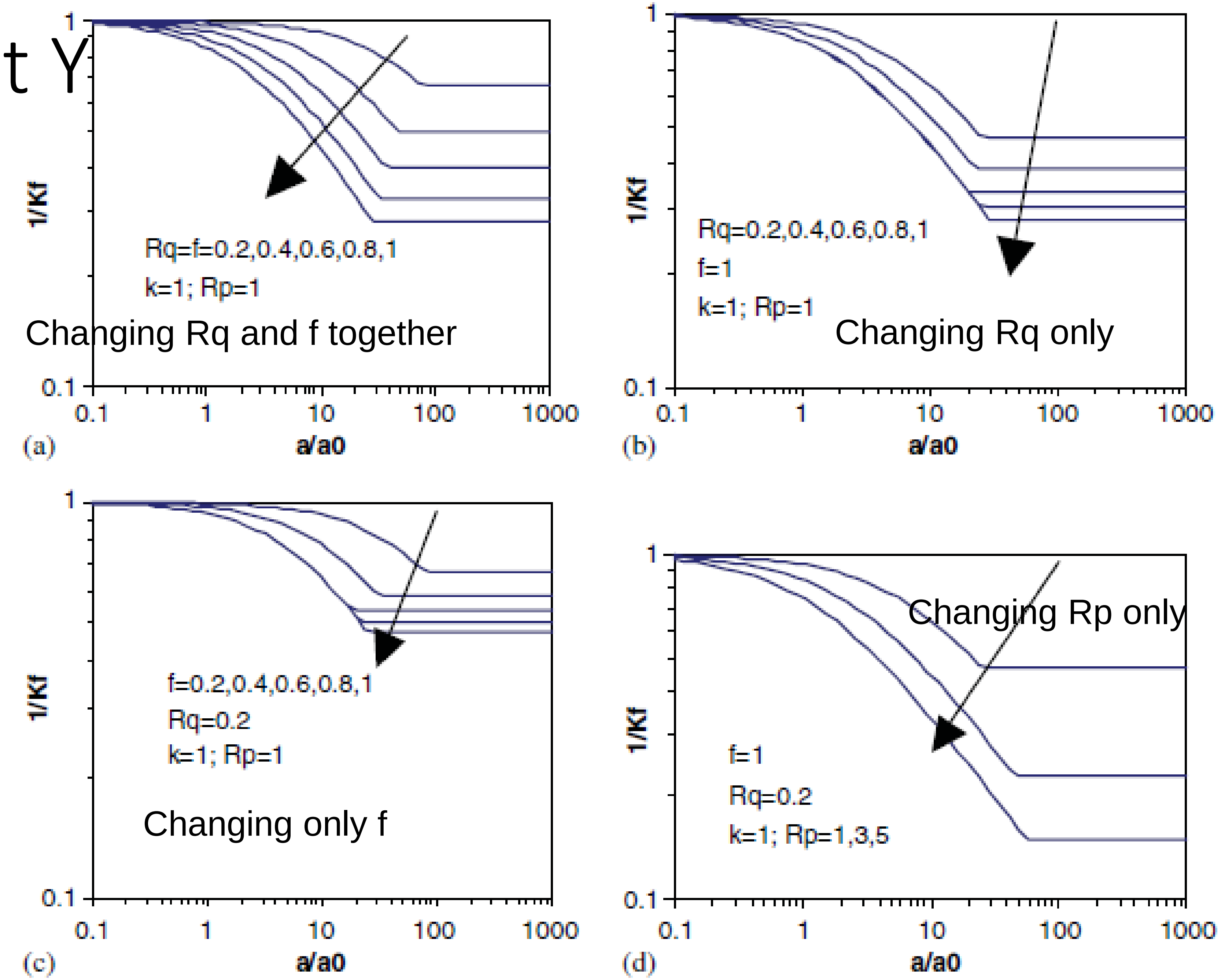
- Nowell data on Al2024 have been cited largely because they introduced clearly size effects by changing the radius of Hertzian pads, and hence contact area, without changing the peak pressure.
- This is ideal to show indeed the “crack analogue” nature of the stress concentration effect, and only recently Oxford-Imperial group is eventually reaching the same conclusion [*Hills, D. A., A. Thaitirarot, J. R. Barber, and D. Dini. Int J of Fatigue 43 (2012): 62-75 contains the same equations of CLNA 2003 paper!],* with many alternative procedures which produce the same
- However, unfortunately no accurate DKth data exist for the Al2024 used in those experiments (no interest then), and the devil is in details!

- If we beleive Kujawski2001 on similar material, at R=-1 dKth could be even higher than 4MPa√m which I considered in CLNA paper, so this could be a “fretting” degradation effect

D. Kujawski / Engineering Fracture Mechanics 68 (2001) 1357–1369

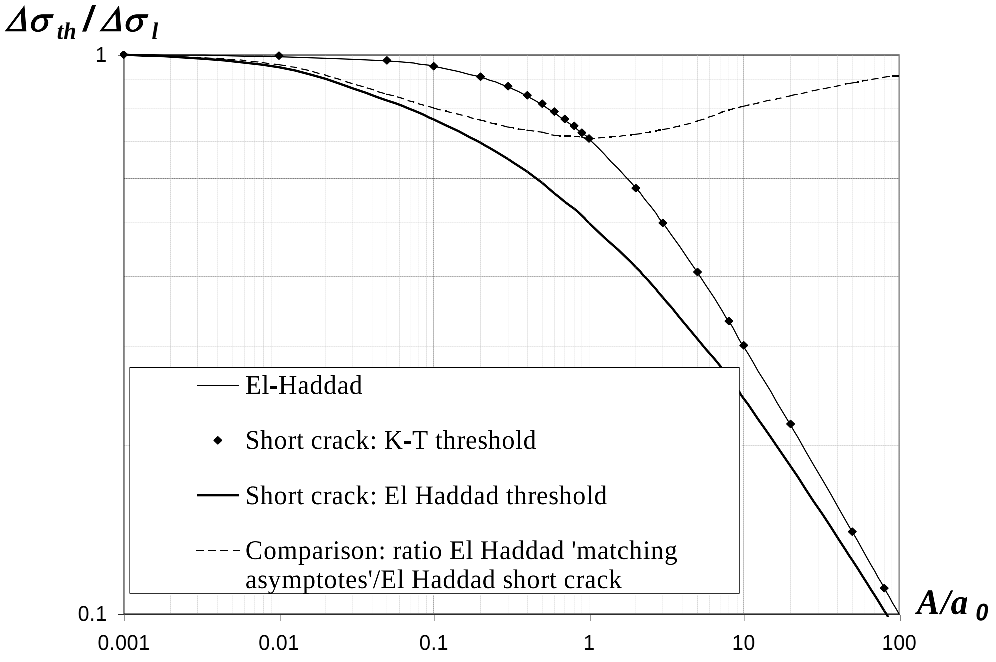


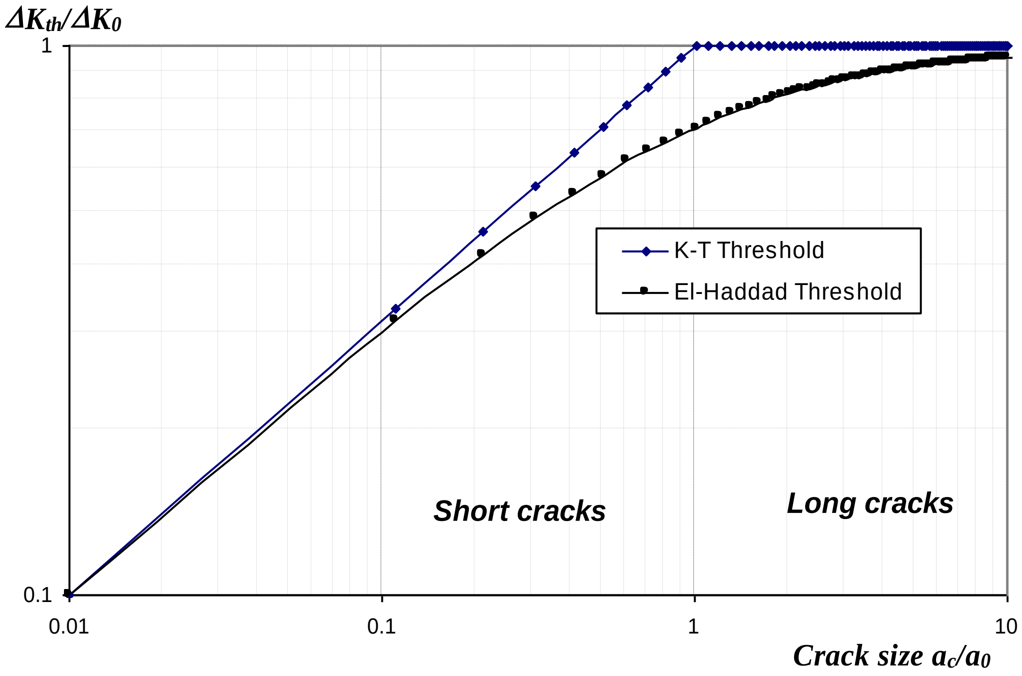
CLNA without Y



Equivalence with short-crack KT threshold

- Some authors define a reduced threshold for short cracks based on KT diagram or ElHaddad equation. This however requires solution of a full stress field and of the crack problem, should be used only when no full analytical solution is possible, like in CA or CLNA model





Comparison CLNA – KT short-crack arrest

- Despite much larger complexity of the short crack arrest methodology proposed by JA Araújo, D **Nowell** - Int J of Fatigue, 1999, or D Dini, D **Nowell**, IN Dyson – Trib int, 2006, the results are extremely similar, and therefore bring no new insight with respect to the CLNA model

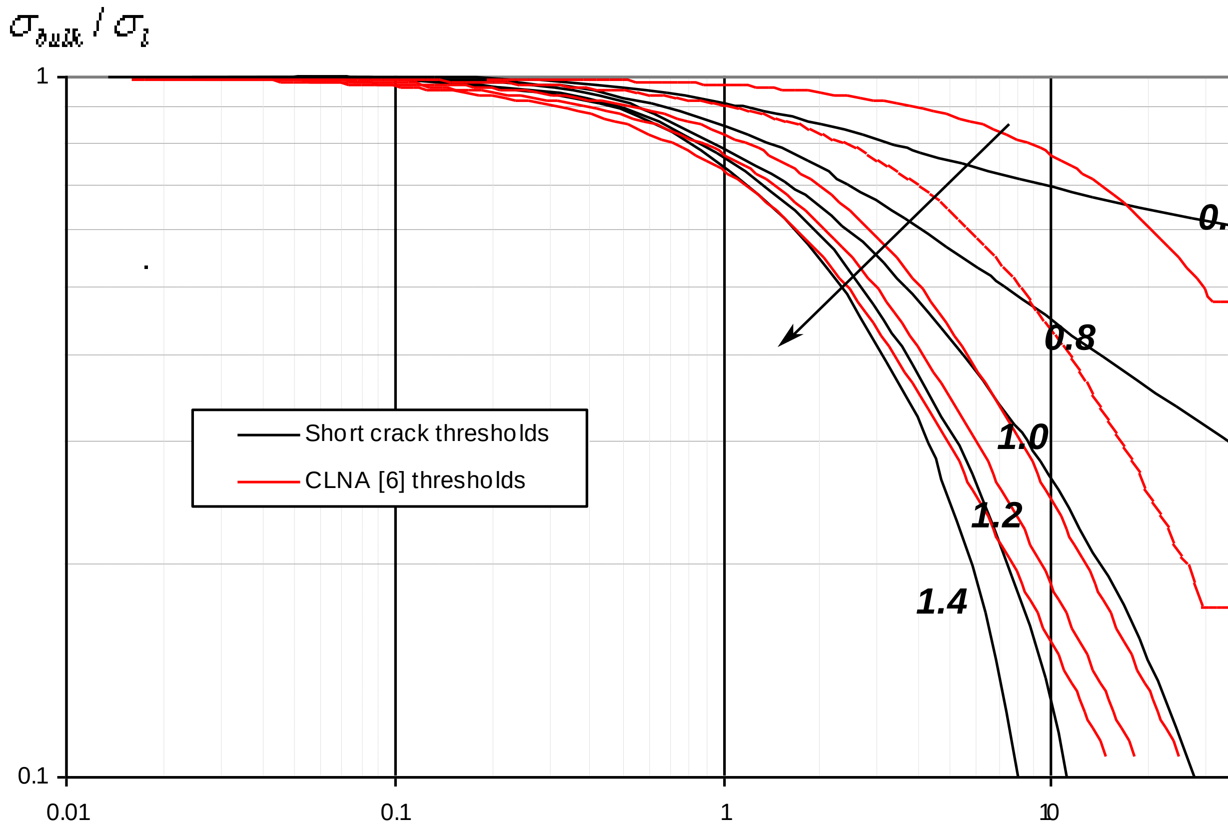
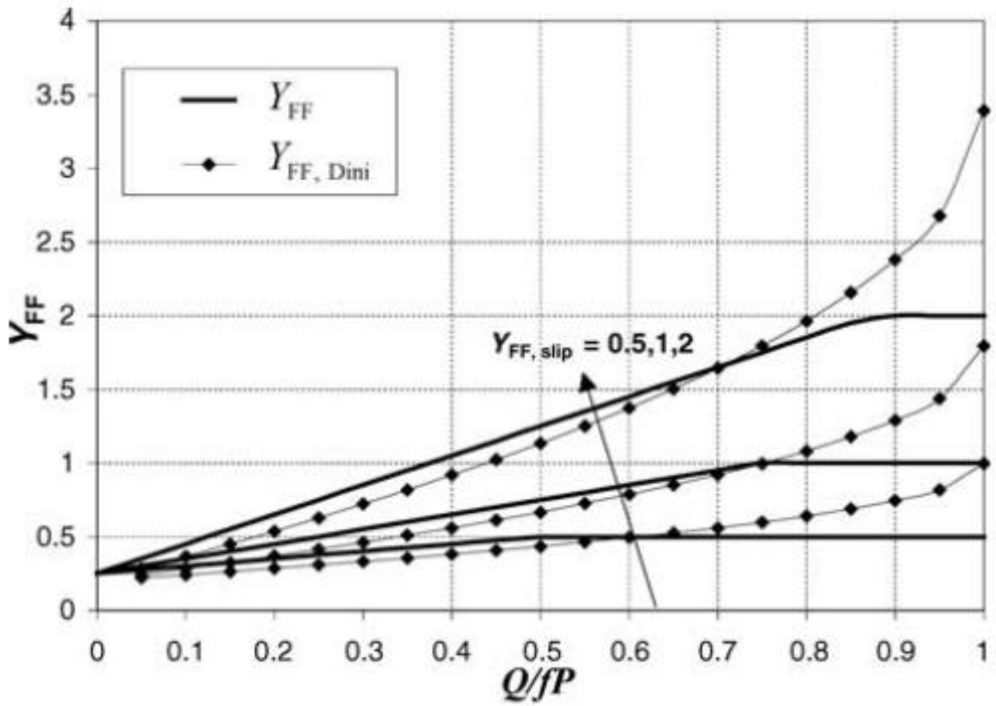


Figure 8. Prediction and comparison with CLNA[6] for different values of

p_0 / σ_l

Comparison CLNA-Dini-Hills asymptotics



(a)

Similarly, D Dini, DA **Hills** - IJSS, 2004 technique to extract bounded and so unbounded asymptotic stress field has been compared to CLNA in M **Ciavarella**, D **Dini** - FFEMS 2005 finding very small differences

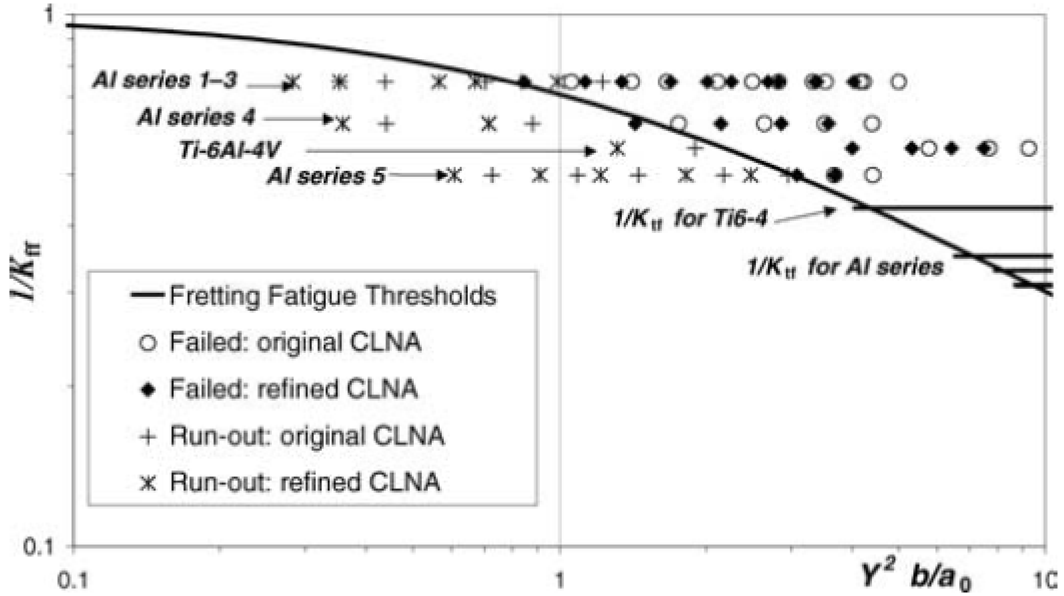


Fig. 10 Comparison of Nowell co-workers' experiments[13,14] ($a_0 = 91\ \mu$m, 25 μm for Al- and Ti-alloys, respectively, with predictions of both the original and the refined CLNA model.

An idea to study effect of slip: remove it!

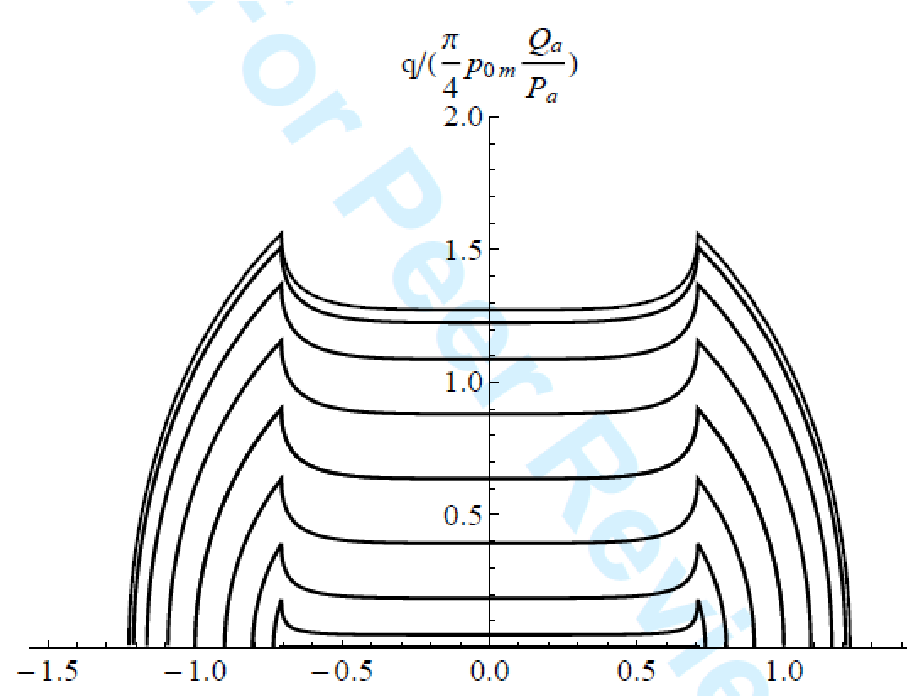
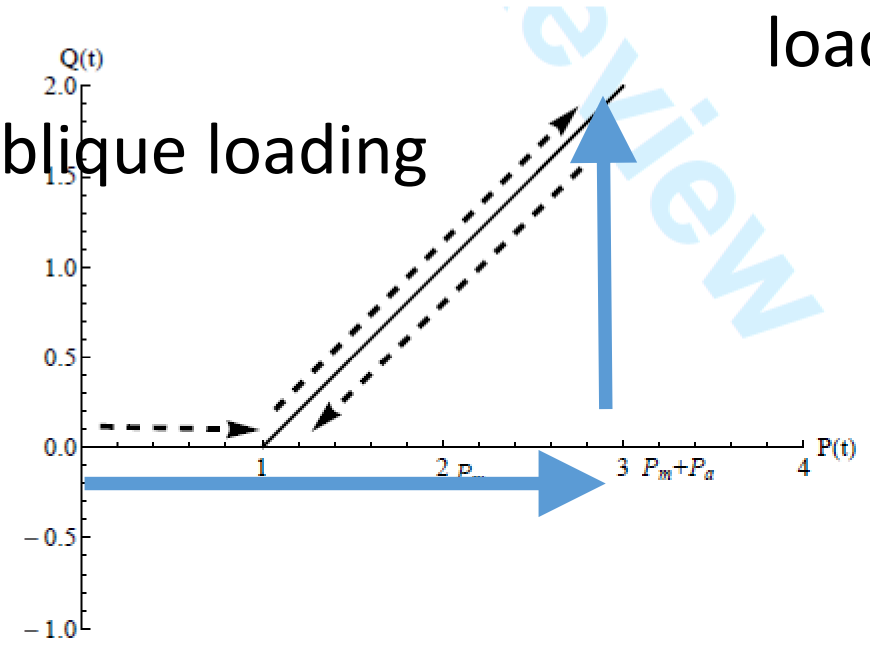


Fig. 2 - Loading cycle for the shear tractions $q(x,t)$ in (6) (inte



Old papers K Nishioka et al Bull of JSME, 1968

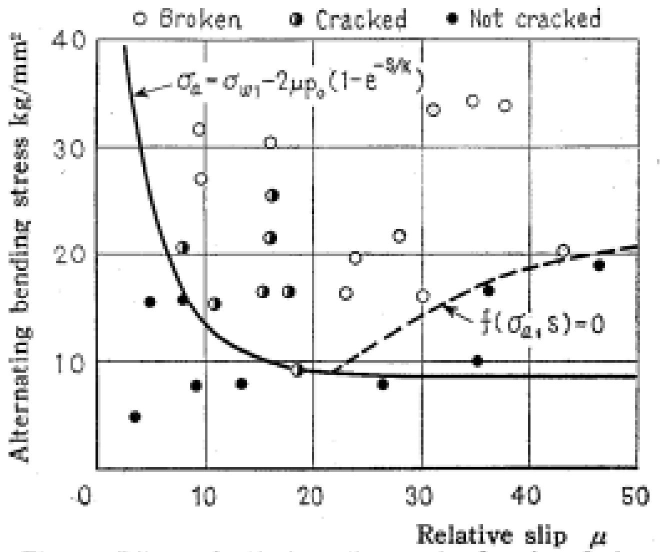


Fig. 6 Effect of relative slip on the fretting fatigue strength of induction hardend carbon steel specimens

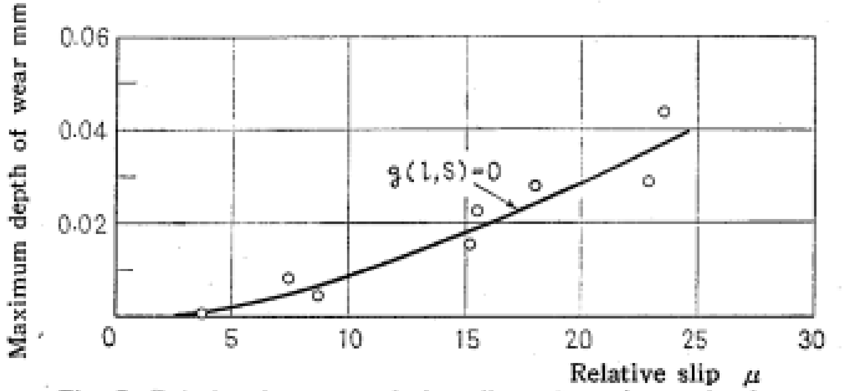


Fig. 7 Relation between relative slip and maximum depth of wear, obtained by induction hardened carbon steel specimens

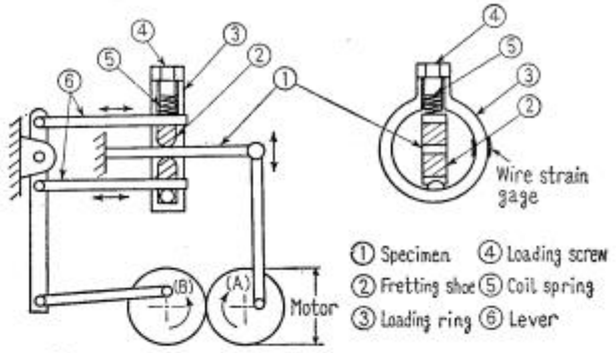


Fig. 1 Fretting fatigue testing machine

Above a certain level of loading, there is evidence of wear, but taking this into account is quite Empirical and rarely done

conclusions

- Fretting fatigue has been studied for a long time, and there has been considerable progress in understanding the contact problem and stress induced up to very small details, does this count on fatigue?
- As fatigue from stress raiser also there has been tremendous progress, mainly thanks to crack and notch analogues, many of the proposed methodologies are similar, and variants of the CA MIT model
- Many authors continue to propose methodologies which are already known in fatigue (for either initiation or propagation) and normally these work also for fretting. Not enough attention to the question: do material properties degrade because of fretting?
- This is because the effect of wear is generally mild in partial slip, and can be neglected. Maybe more specific tests could be defined
- An idea has been put forward to separate the effect of slip in a new type of experiments