Friction, Fracture, Fatigue, Fractals … and the Future

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ITALY

Early research areas

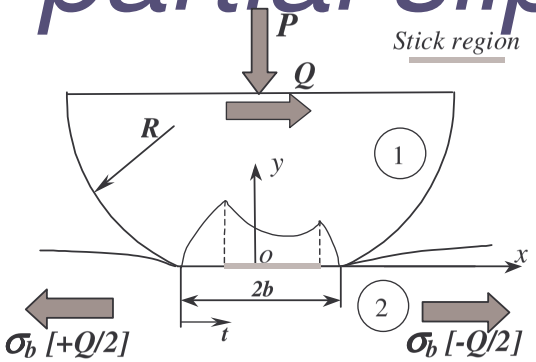
- 1 – Contact mechanics of partial slip
- 2 – Fretting Fatigue
- 3 – Rolling Contact Fatigue
- 4 – Fracture & Fatigue: unified laws
- 5 – Rough contact
- 6 – Thermo-Elastic Instabilities (TEI)

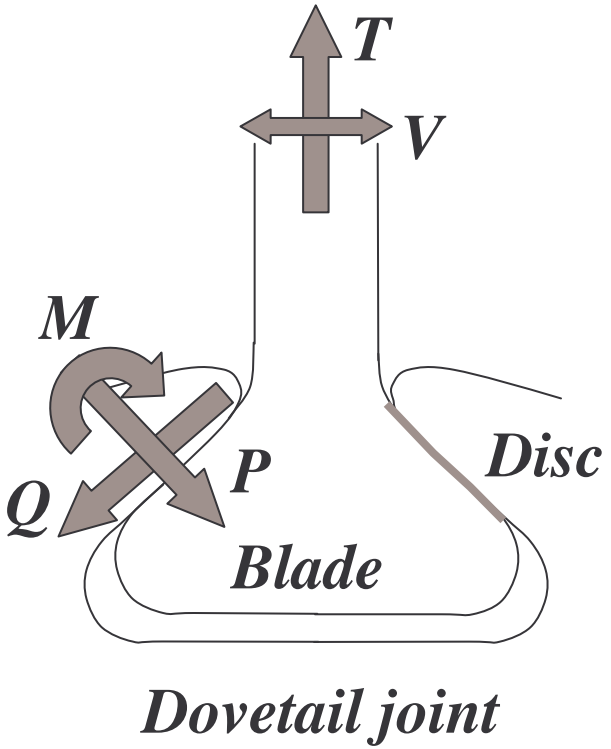
More recent research areas

- 7 – Frictional Instabilities (DI & TEDI)
- 8 – Friction shakedown plast. theorems
- 9 – Conformal contacts
- 10 – Bio, AFM & rough adhesion
- 11 – Corrugation & wear instabilities

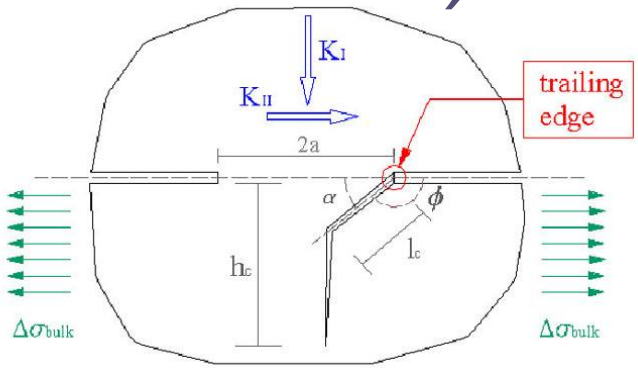
1) Contact mech. of partial slip

- Phd work with David Hills @ Oxford
- Cattaneo & Mindlin generalized partial slip problems
- 12 journal papers [2,3,5,7,8,9,12,13,14, 21, 30, 31] in 1997-2000
- Appl. in jet engines, but also in science for incipient slip
- Used now by USAF, RR, GE, SWRI, and many universities





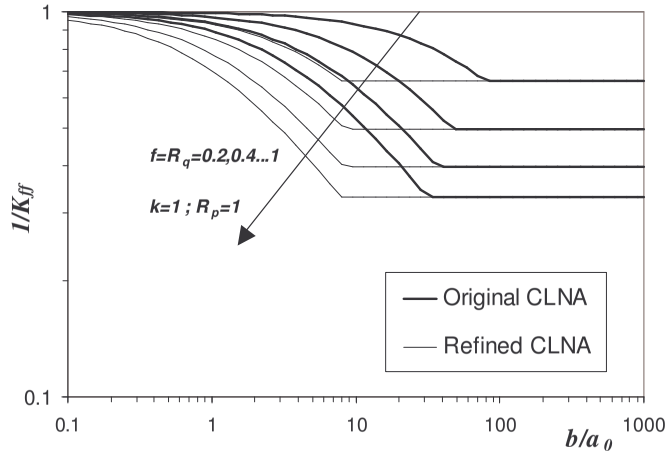
2) Fretting Fatigue



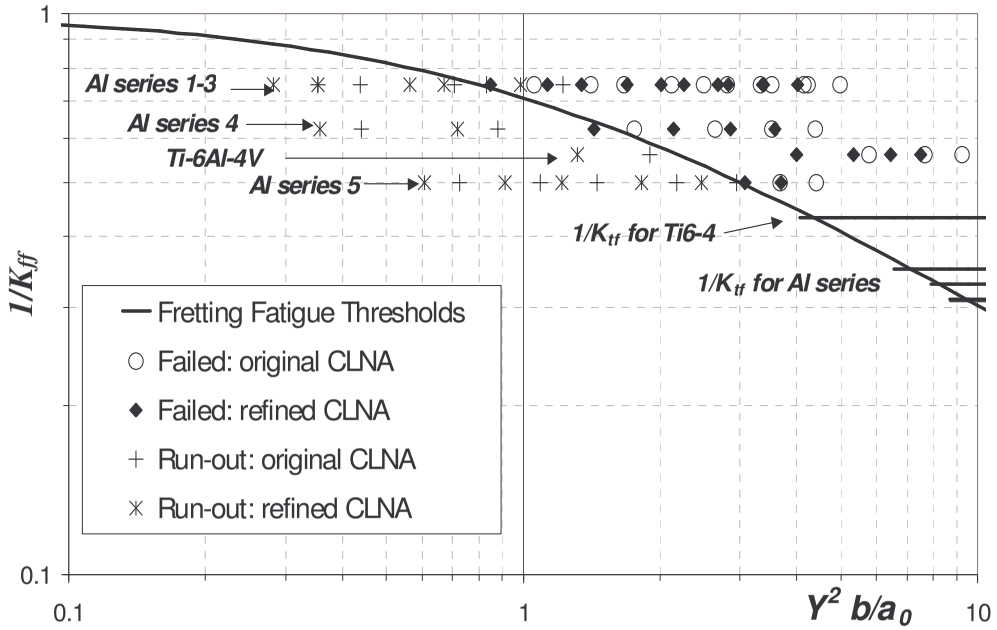
MIT crack analogue

- "crack-like notch analogue" CLNA model, merging of MIT crack analogue and notch analogues
- CLNA Fretting fatigue diagram
- 6 journal papers [34, 37, 42,44, 59,67] in 2003-2006

MIT notch analogue



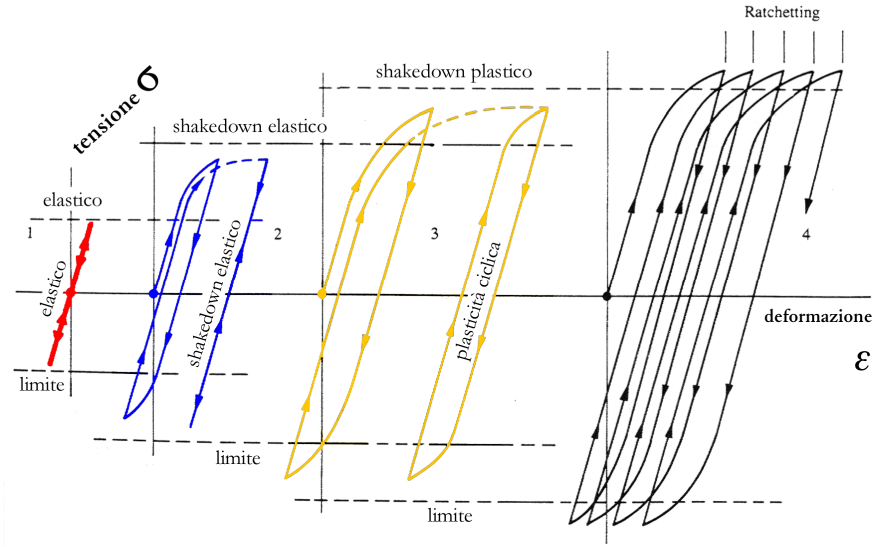
CLNA diagram without Y factor



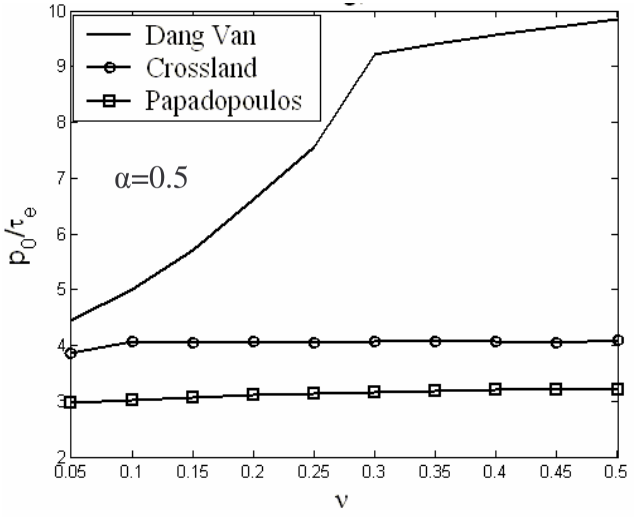
CLNA diagram with Y factor

3) Rolling Contact Fatigue

- Shakedown maps (41), re-examination of classical ratchetting experiments by Merwin and K.L. Johnson (49), Su and Clayton (50), multiaxial criteria (DangVan, Papadopoulos)
- 6 papers [41,49,50,57,62,71] in 2004-in progress
- Future work: extension of CLNA to RCF
- Application in railways, bearings, gears



KL Johnson's plastic ratchetting approach



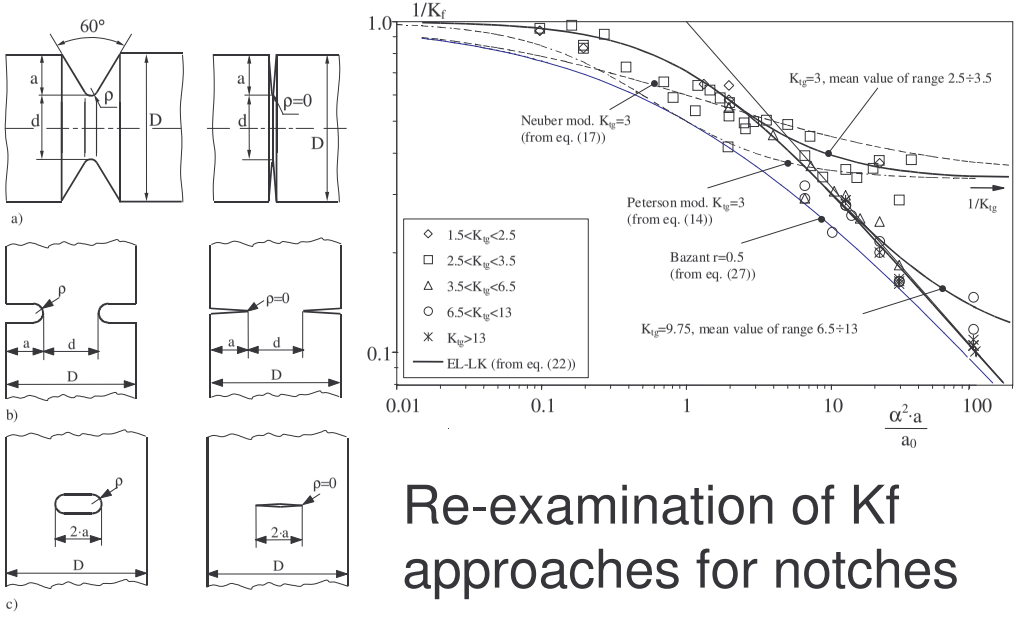
Ratchetting or LCF-HCF?

4) Fracture & Fatigue unified laws

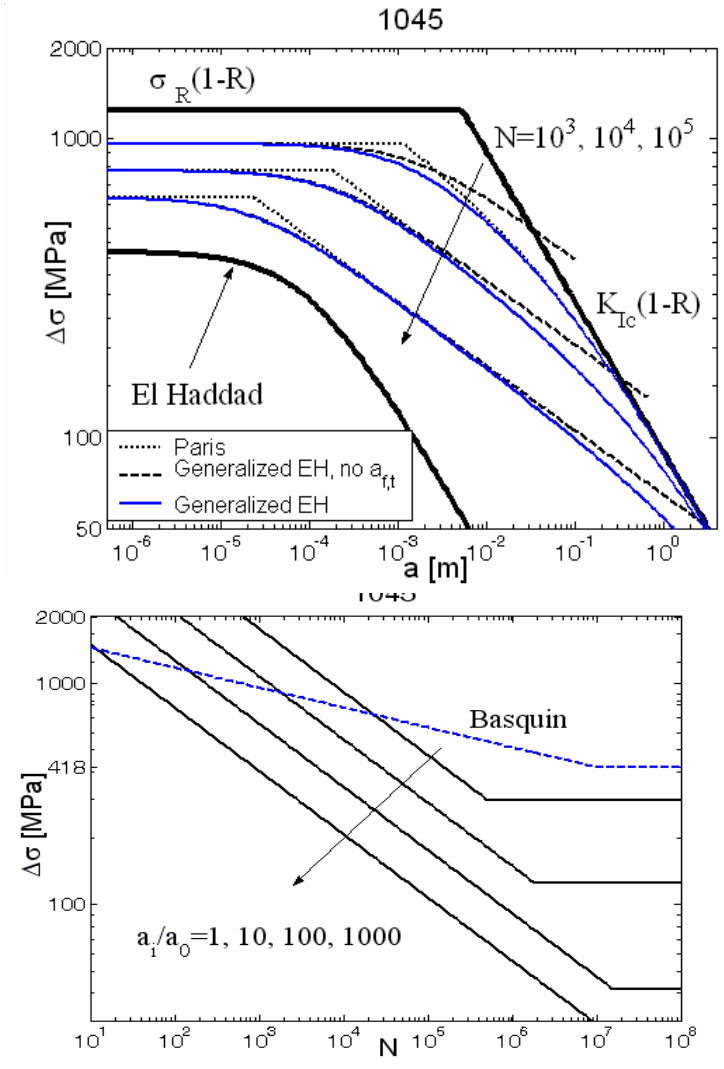
- HRR solution for sharp notches (39)
- Re-examination of Kf classical criteria

in the light of Fracture Mechanics (43)

- Extension of Kitagawa diagrams (65)
- Generalized Paris-Wöhler laws (72)
- 4 papers [39,43,65,72] in 2002-in progress



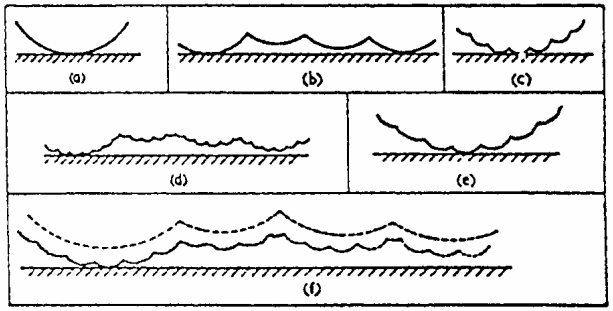
Re-examination of Kf approaches for notches



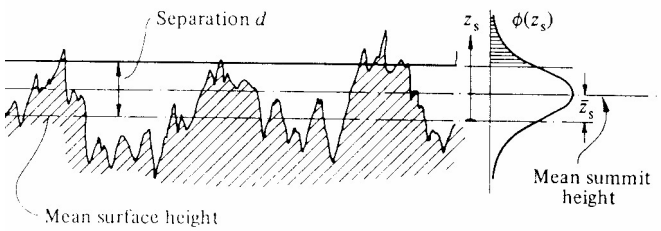
Extensions of Kitagawa and generalized Paris-Wöhler laws

5) Rough contacts

- Real Contact area is a fractal (19,29),
- Elastic contact stiffness and contact resistance depend mostly on the largest scales (55,63,64).
- GW and re-vitalized discrete GW (63) better than Persson' s theory (80)
- 11 papers in 2000-present [19,29,33,55,61,63,64,68,73,79,80]

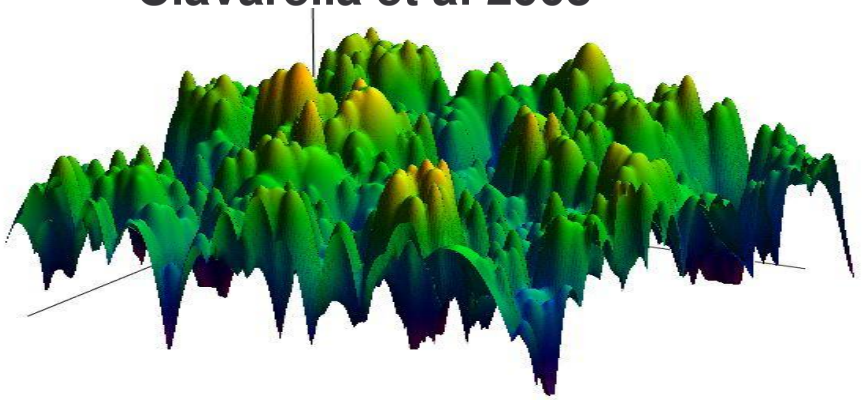


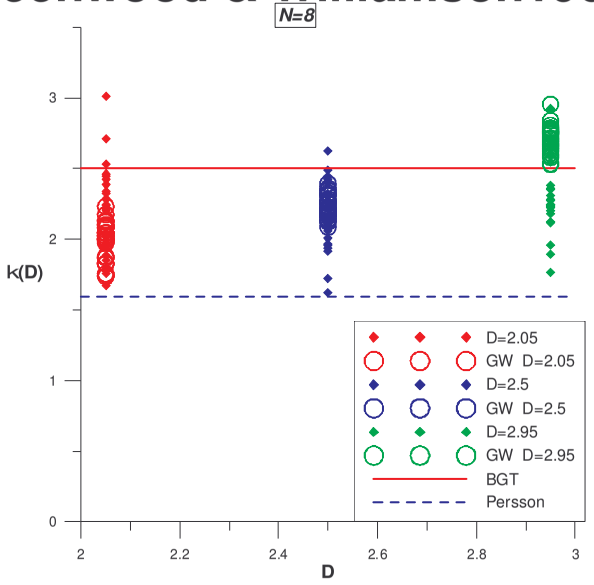
J.F.Archard PRS (1957)



Greenwood & Williamson1966

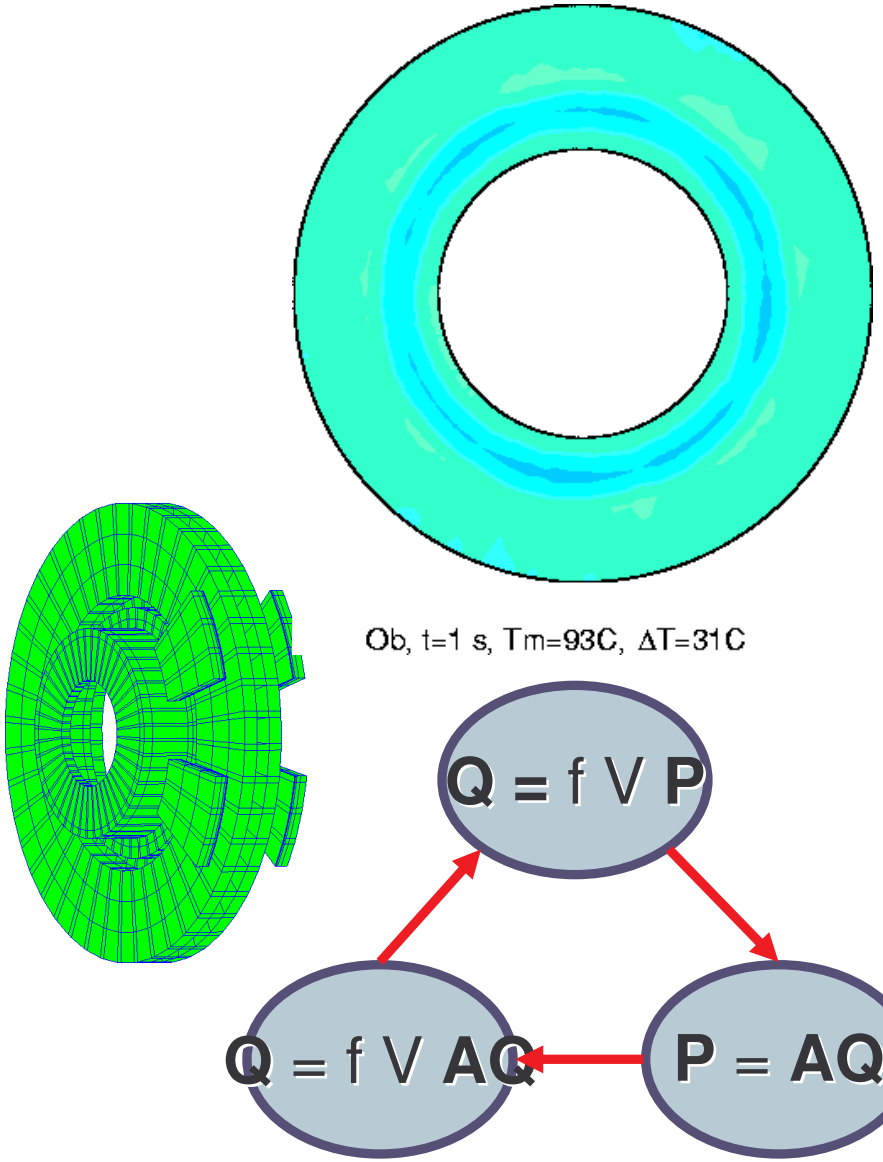
Ciavarella et al 2005





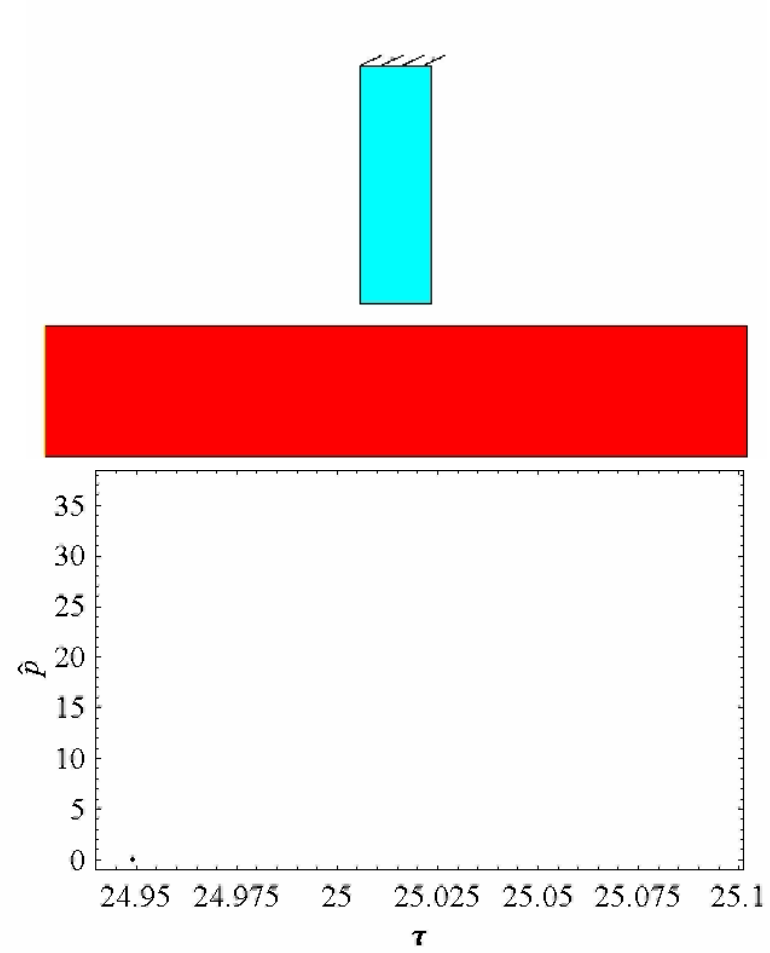
6) Thermo-Elastic Instab. (TEI)

- **Solutions of TEI problems, steady-state, existence and uniqueness, stability analysis, interaction of thermal contact resistance, simple models, transient simulations**
- **11 papers in 2000-2005 [23,27, 35, 36,46,48,51,52, 53,56, 60]**
- **Develp/consultancy with industries (Ferrari, Bosch, etc.)**
- **Collaboration with J Barber @ UMich USA since 1997!**

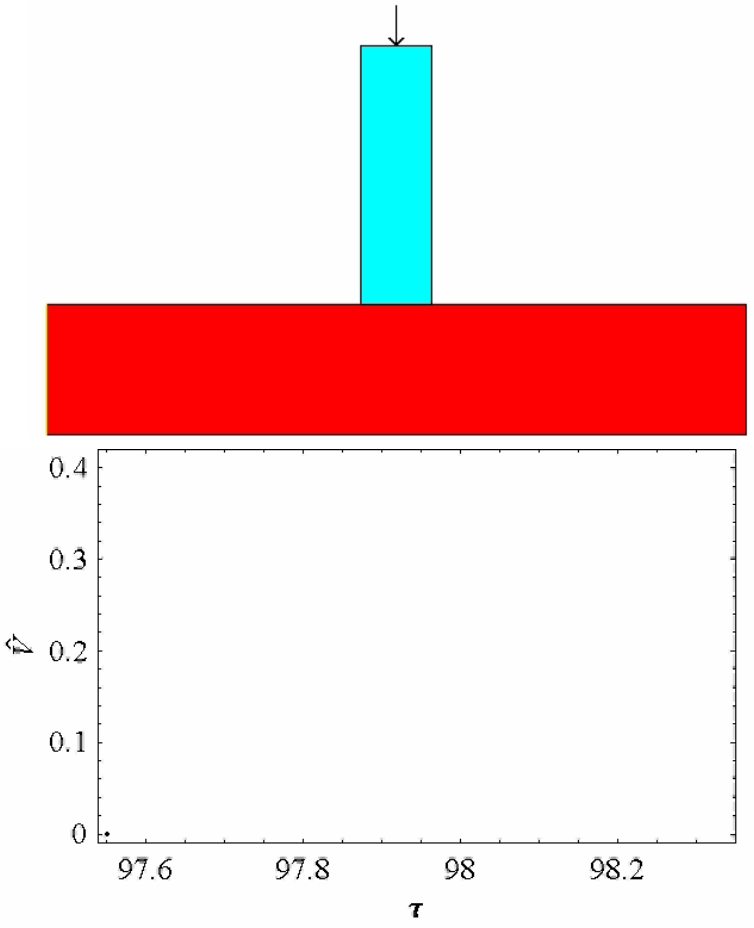


7) Friction Instab. (DI & TEDI)

- **New form of coupled instability**
- **3 papers in 2006 [66,74,75]**



Frictionless TEDI



Frictional TEDI

8) Friction shakedown

- **res. stresses reduce frict. slip? friction hardening, separation**
- **conditions for Melan's theorem 3 papers in 2007 [76,78,81] in press**
- **Future res. multi-DOF models, appl. to geo- & granular materials**

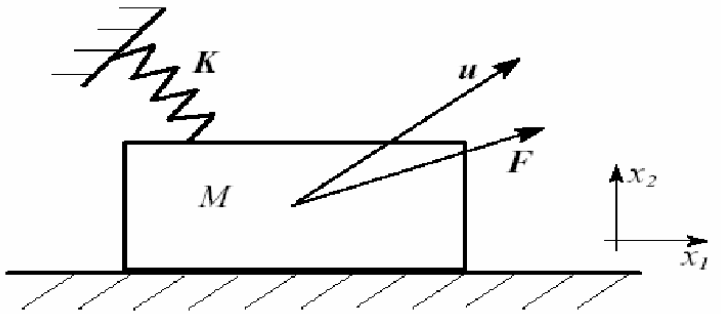
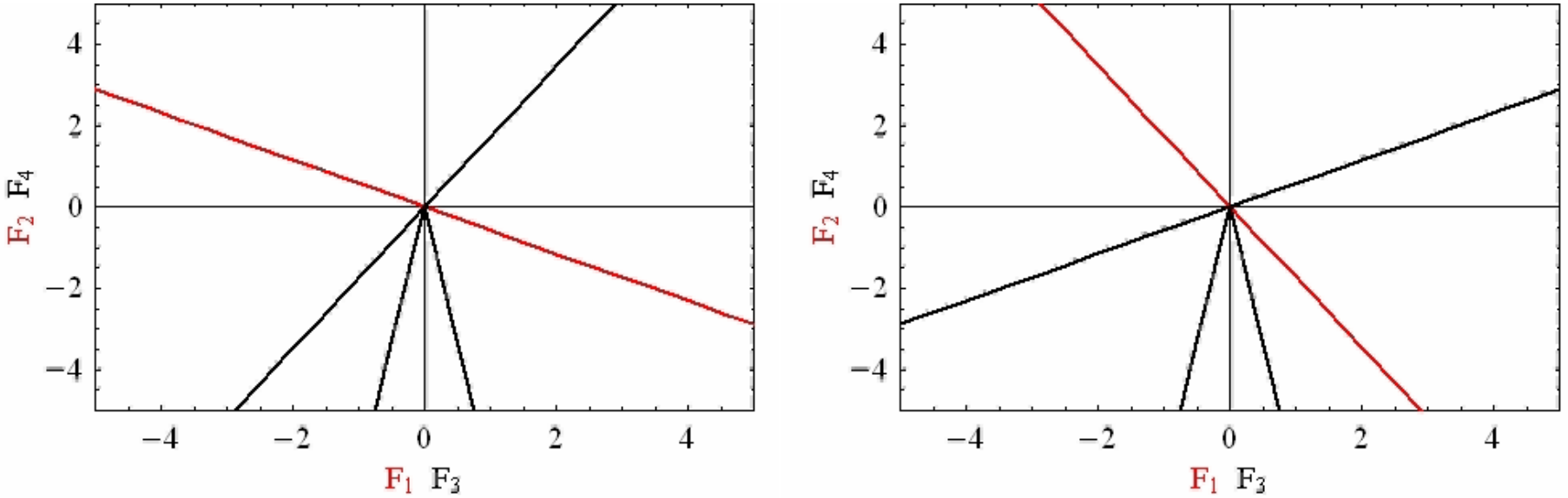
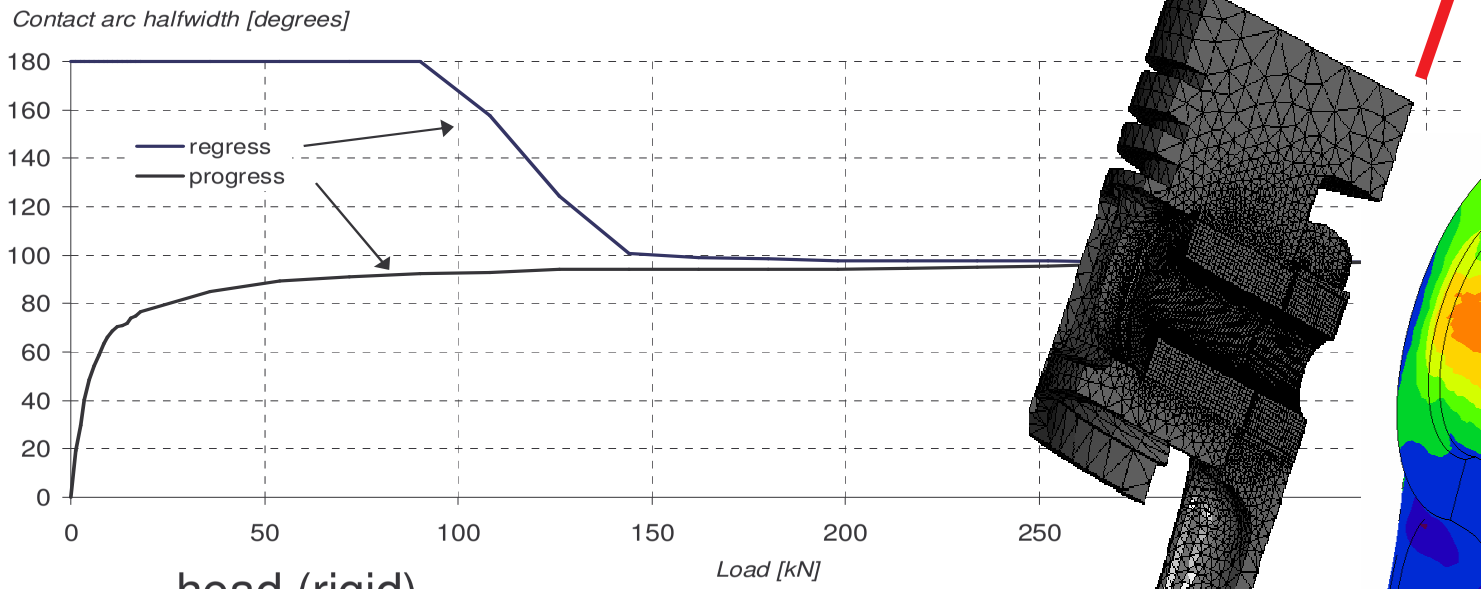


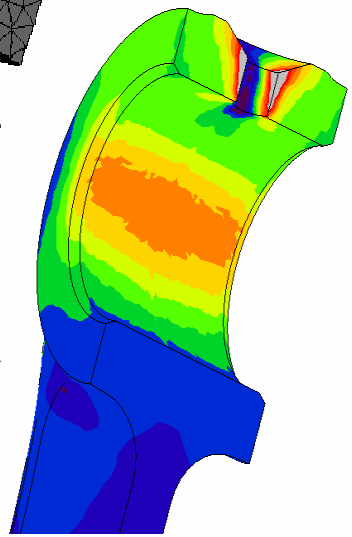
Figure 1: The one-point model.

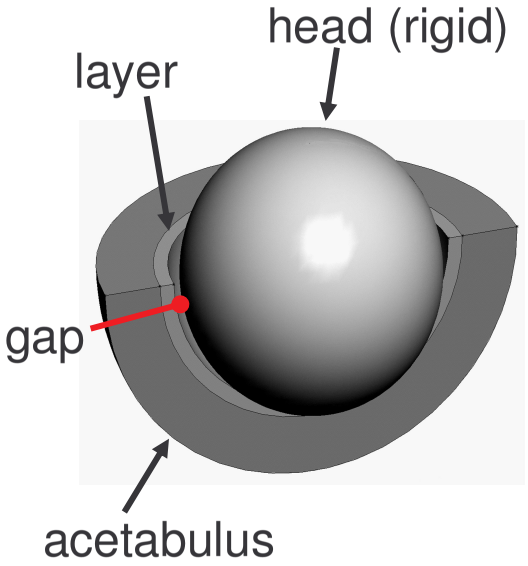


2-DOF model, proportional transient loading (a), non-proportional (b)

9) Conformal contact

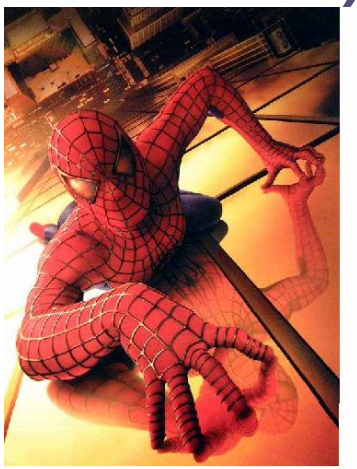


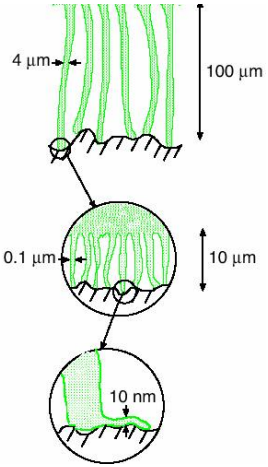




- **Quasi-conformal contacts are non-linear but ..**
- **2 papers in 2006-7 [72,82]**
- **Future res. appl. to biomech. conrod geometries, etc.**
- **Collaborations with U Modena, Rizzoli, Ferrari, etc.**

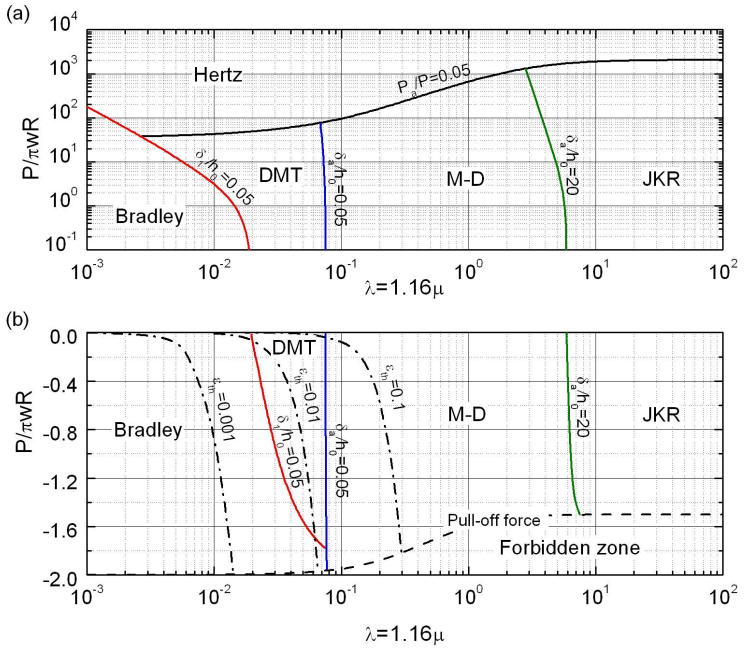
10) Adhesion at nanoscale



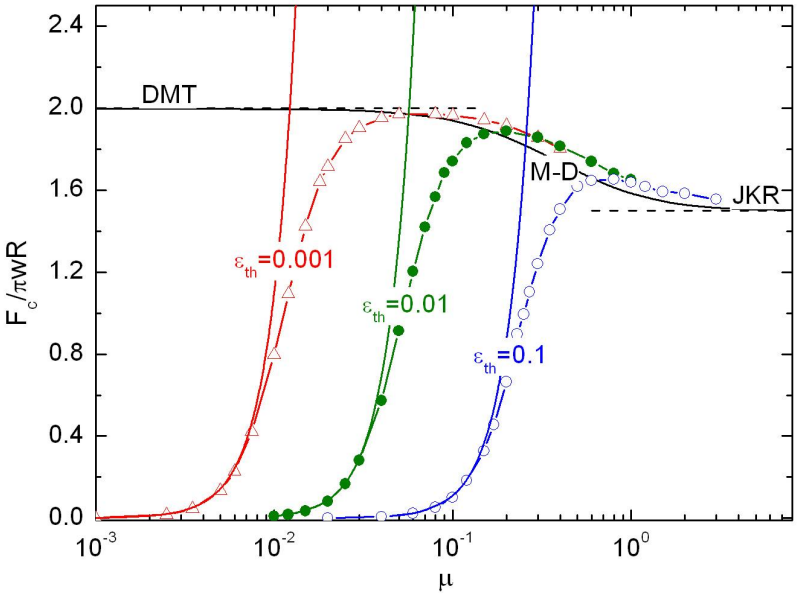


Work in progress in collaboration with Huajian Gao @ Brown U. and Singapore

1) **Correction of adhesion maps at nanoscale**
2) **New models for AFM adhesion**
3) **New multiscale models for rough adhesion**
4) **Applications in new areas of technology**



Adhesion map for sphere as a function of Tabor parameter



Pull-off for sphere as a function of Tabor parameter

11) Corrugation & wear-dynamic instabilities

Figure 1 Corrugation in three places on the London Underground, occurring as a result of four different mechanisms

Work in progress in collaboration with Paul Meehan at Brisbane (Australia), Norbert Hoffmann @ Hamburg, and others

1) **Explanation of "roaring rail" enigma**
2) **New models with simple wheel dynamics (2 DOF) and Carter's solution perturbation, to find effect of tangential vs. creepage control**
3) **re-interpretation of old models**
4) **Manufacturing (rolling, etc.)**

Main int.l collaborations

- U Michigan (Barber) – contact mech
- Cambridge (KLJ, JAG, JAW, JWi, JWo, ..)
- Ecole Polytechnique Paris – instab., plast.
- Imperial College (Dini, ..) – RCF, fatigue
- Hamburg – instab., squeal, friction control
- Valencia – fretting fatigue
- Newcastle (Kapoor) -- railways
- Brown U (Gao, Bower,) – nano adhesion
- Singapore – computat. Nano
- Italy: Modena, Torino, Milano, Padova

Some measure of Impact

Some "example" statistics on published papers (total=79)

Journal	**# of papers**
International Journal of Solids and Structures	**15**
Journal of the Mechanics and Physics of Solids	**8**
Int Journal of Mechanical Science	**6**
Wear	**5**
J. of Appl. Mech Trans ASME	**4**
Proc. Roy. Soc. London (A)	**3**
Int. Journal of Fatigue	**3**

and others in Int. J. Fracture, Fat. Fract Eng Mat Struct., Journal Strain Analysis, etc

Number of citations of some of the journal papers (from ISI Web of Science)

Hits	Cited Author		Cited Work	Volume	Page	Year	Ref # in the list
36	...Ciavarella	M	INT J SOLIDS STRUCT	37	29	2000	18
31	CIAVARELLA	M	P I MECH ENG C-J MEC	212	319	1998	5
27	CIAVARELLA	M	INT J SOLIDS STRUCT	35	2349	1998	2
16	CIAVARELLA	M	INT J SOLIDS STRUCT	35	2363	1998	3
15	CIAVARELLA	M	P ROY SOC LOND A MAT	456	387	2000	19
12	CIAVARELLA	M	INT J SOLIDS STRUCT	36	4149	1999	14
7	...Ciavarella	M	COMPUT METHOD APPL M	190	6053	2001	33
6	CIAVARELLA	M	INT J SOLIDS STRUCT	38	1791	2001	31
5	CIAVARELLA	M	INT J MECH SCI	40	977	1998	6
5	CIAVARELLA	M	J STRAIN ANAL ENG	37	493	2002	37
5	CIAVARELLA	M	EUR J MECH A-SOLID	18	491	1999	12
4	CIAVARELLA	M	INT J MECH SCI	41	1533	1999	13

Some esteem indicators

- Invited visiting professor at Ecole Politechnique, Paris Palaiseau, Jan/Nov 2008
- Invited at NSF workshop on Friction modelling in Washington 14-15 Oct 2006
- Invited lecture at Thermo-mechanical modelling of solids – Ecole Politechnique, Paris Palaiseau 9-12 July 2007
- Invited by the US Air Force (*WOS Windows On Science* program) to a cycle of conferences on Fretting Fatigue
- Invited by the Inst. of Physics (UK) Cambridge - 22 July 2003, Bristol, march 2004
- 1998 Capocaccia National Prize of the AIAS “Stress Analysis Italian Association”,
- CNR final price 1998
- CNR “short term” fellowship Michigan, Oxford, Harvard, Oxford

Pecunia non olet!

- EU, AUTOCON FP5 Project on electrical connectors, 4 M€ (locally 100 k€) 2002-2005
- MIUR, FISR – Multiscale Material Modelling, 4.5 M € (locally 100 k€) 2002-2006
- MIUR, CEMEC – Centre for Excellence in Computational Mechanics @ PoliBA, 1 M€ 2001-2004
- CNR, COMES – network on Computational Mech. of solids, 200 k€ 1999-2001
- MIUR Programs of national interest, RCF, 100k€ 2001-2002, 80k€ 2005-2006
- British council, Egide, Crui travel grants

Are kindly acknowledged ..

References

Full list of published papers (total=79)

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13) Ciavarella M, Demelio G, *On non-symmetrical plane contacts*, **Int. J. of Mech. Sci.**, Volume 41, Issue 12, December 199, Pages 1533-1550
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