FACULTY OF MECHANICAL ENGINEERING CTU IN PRAGUE

Reasons for FABER

Why maintaining the status quo is limiting us

Jan Papuga

jan.papuga@fs.cvut.cz, papuga@pragtic.com

An example

The practical example
of disproportions between research outcome
and its implementation in engineering
is prepared on the topic of
multiaxial fatigue strength criteria

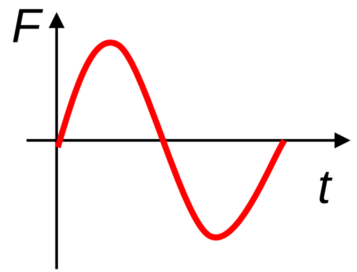
Multiaxial fatigue problem

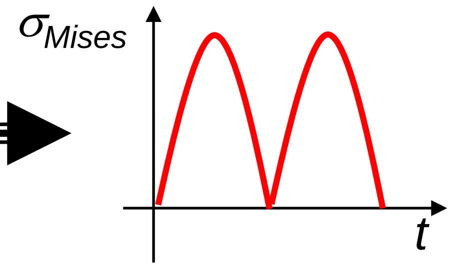
- If more load channels interact, a phase shift among their periodical loadings can occur
- The non-zero phase shift between them can improve the fatigue properties (the maximums of the load are not concurrent)
- Also the combination of one static and one variable load channels – the common stress tensor reduction hypotheses fail

One of the Simplest Solutions

- Signed von Mises stress
  - Can be used also for loading with non-constant amplitude

Why signing?





$$\sigma(t) = \sqrt{\frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + \left(\sigma_z - \sigma_x\right)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)\right]}$$

PragTic

$$\sigma^*(t) = \sigma(t) \cdot sign\left(I_1(t)\right)$$

MSC.Nastran (and PragTic)

$$\sigma^*(t) = \sigma(t) \cdot sign\left(\max(|\sigma_1|, |\sigma_3|)\right)$$

⇛ σ_a, σ_m ⇛ Walker

Criteria for Fatigue Limit Estimation

How to check them?

- All fatigue criteria converted to the standard:

$$D_p \le f_{-1}$$

D_p – damage parameter ~ local stresses

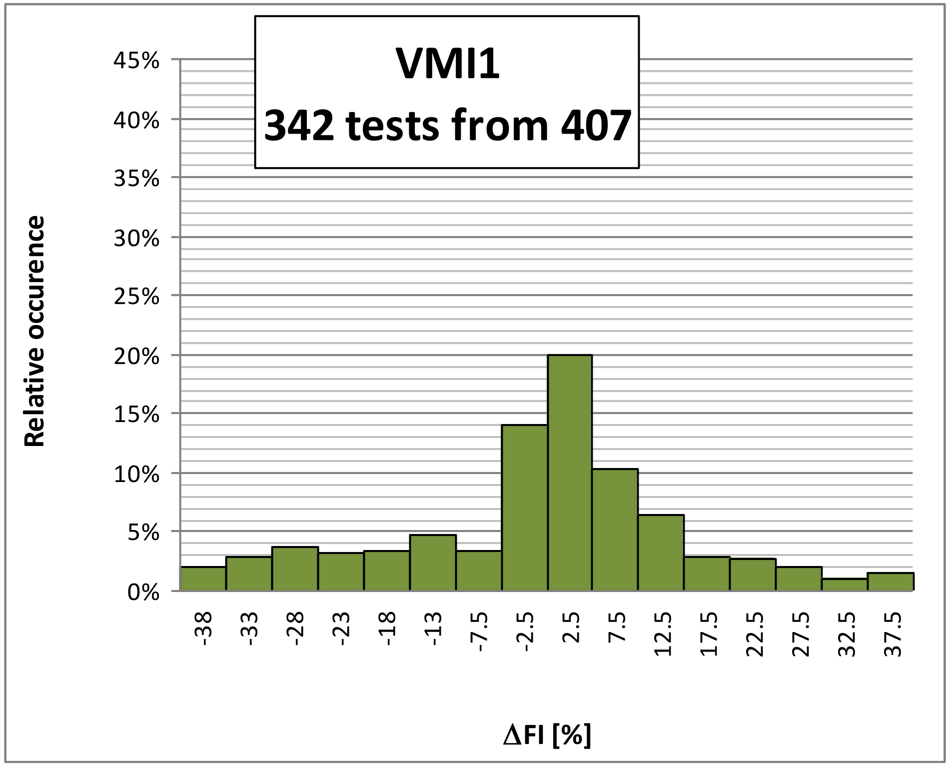
f_{-1}- fatigue limit in fully reversed axial loading

- For an experimentally set multiaxial fatigue limit: $$D_p = f_{-1}$$

- Fatigue index error: $$\Delta FI = \left(\frac{D_P - f_{-1}}{f_{-1}} \right) \cdot 100\%$$

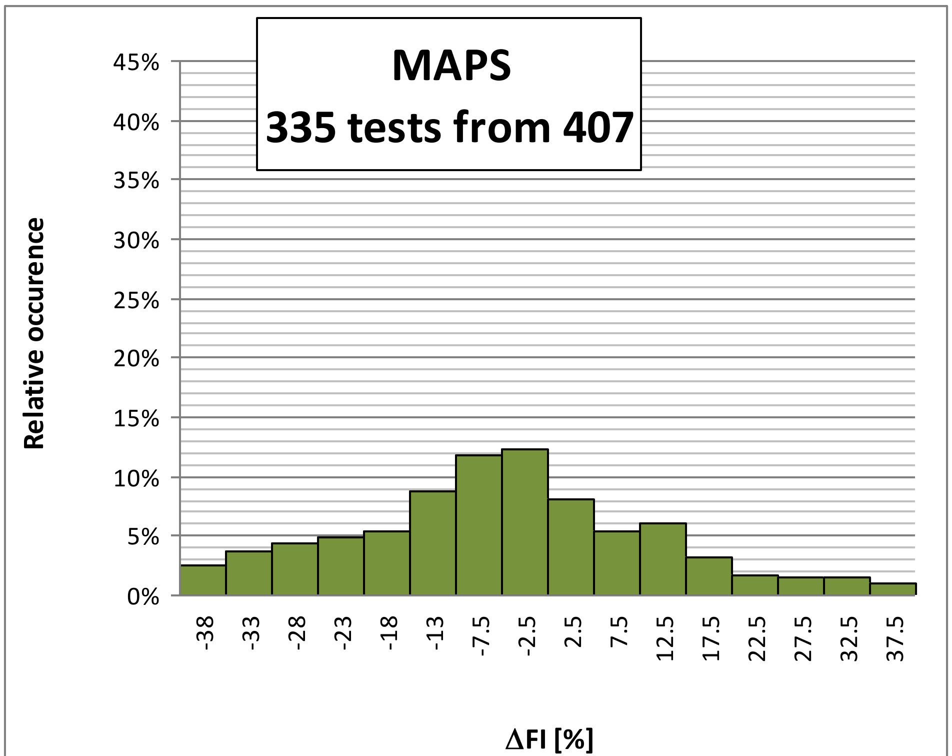
..But the Results…

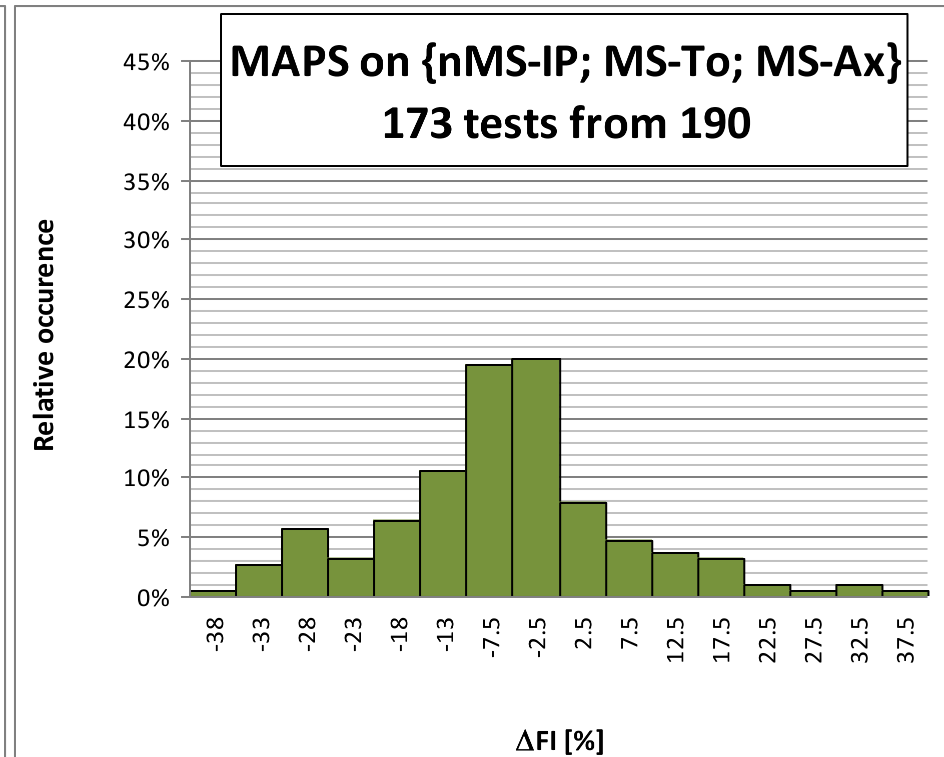
- Signed von Mises
  - The difference between both signing variants is negligible overall
  - Optimum variant only for ductile materials and in-phase loading with zero mean stress
  - Problems
    - Mean axial stress within multiaxial loading
    - Mean torsion stress within multiaxial loading



MSC.Fatigue - MAPS

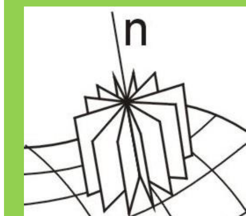
- Maximum Absolute Principal Stress
- Provides the best overall results, though they are not very good





Multiaxial fatigue assessment criteria

Critical plane methods



Compute X_i on all planes

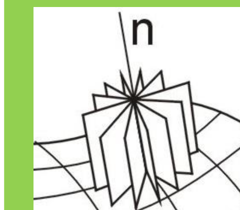
$$CP = P(\max_i(x_i))$$

$$D = D_{CP}$$

Mc Diarmid, Wang & Brown, Dang Van

- Critical plane according to:
  - Maximum Shear Stress/Strain Range (MSSR)
  - Maximum Damage (MD)
  - Critical Plane Deviation (CPD)
  - other...

Integral methods



Compute X_i on all planes

$$X = aver\ (X_i)$$

$$D = f(X,...)$$

Papadopoulos, Kenmeugne et al.

- Averaging ~ Integration
- Integrate:
  - Complete damage parameter
  - Individual variables

Solutions for fatigue limit estimation today

- In fatigue solvers:

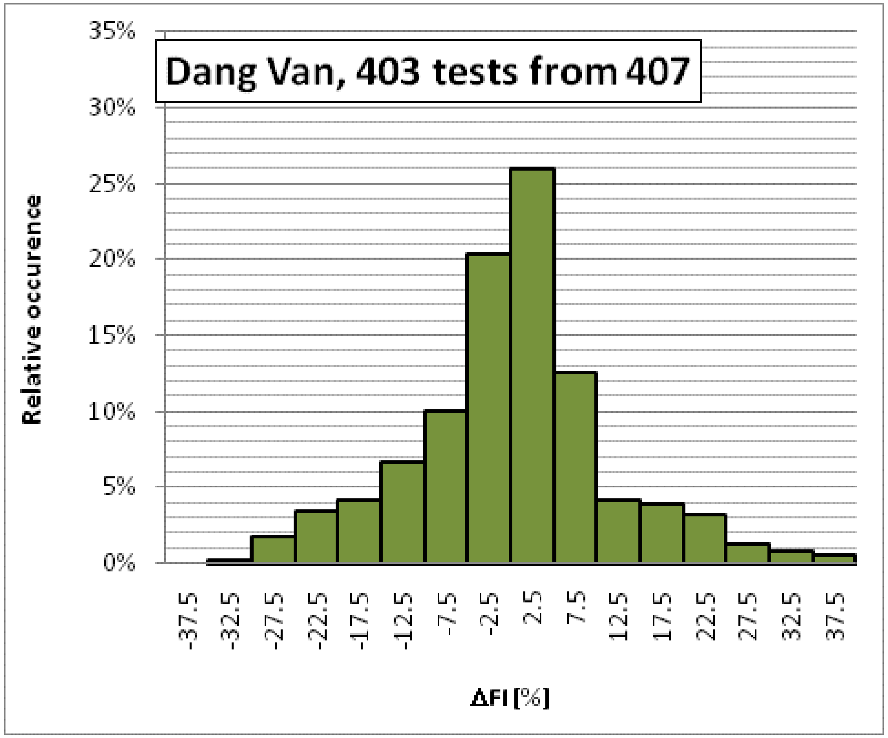
	Commercial							Non-commercial				Test set 407 exps.	
Methods	Fe-Safe	MSC.Fatigue	Femfat	FEARCE	nCode DesignLife	LMS Virtual. Lab Durability	WinLife	eFatigue	Code Aster	PragTic	FatLab	Mean relative error [%]	St. deviation of relative error [%]
Dang Van (1973)	X	X		X	X	X	X	X	X	X		-0.1	12.2
Findley (1957)							X	X		X	X	8.7	15.2
McDiarmid (1991)		X		X	X					X		-6.2	12.0
Sines (1959)								X		X		-4.3	17.9
Matake (1977)									X	X		6.4	15.8
Other solution			X						X	X	X		

- ΔFI – relative error between predicted and experimental fatigue limit
  - ΔFI =0 ideal
  - ΔFI >0 conservative
  - ΔFI <0 non-conservative

Dang Van criterion

$$a_{DV} \cdot C_a + b_{DV} \cdot \sigma_{H,\max} \leq f_{-1}$$

- Critical plane criterion
- The most often used representative of multiaxial criteria
- Use of maximum hydrostatic stress does not seem to give acceptable results
- C: MS, Ax+Ax
- N-C:
  - nMS, OP
  - MS,To



average: -0.1%

range: 92.9%

standard deviation: 12.2%

Weakness of Dang Van method

- Hard to believe: multiaxial fatigue

Mean values of ΔFI in individual groups (tests)	CRO	DV
All (407)	−8.0	−0.1
nMS (171)	−3.1	−0.6
nMS,OP (40)	−11.5	−7.9
nMS,IP (131)	−0.5	1.7

relative difference between predicted and experimental fatigue limit

no mean stress, out-of-phase loading

no mean stress, in-phase loading

- There is a significant difference in mean prediction values depending on the phase shift of individual load channels

Fatigue limit solution today

- In research papers:

Well, the software developers could try also Liu & Mahadevan and maybe should dare to implement Crossland in order to keep the prediction as bad as now

Method:				C&S	Crossland	Dang Van	Findley	Fogue	Goncalves	L&M	L&Z	Matake	McDiarmid	Papadopoulos	Papuga PCr	Robert	Sines	Susmel
Year of publication:				2001	1956	1973	1957	1987	2005	2005	1989	1977	1991	1994	2008	1988	1959	2001
Ref..	Year	Sets	Items															
	1997	4	43		X							X	X	X			X	
	1999	1	2		X	X												
	2000	?	179								A			X				
	2001	3	30	A			X					X	X					
	2002	52	447											X				A
	2003	3	38		X	X								X				
	2005	4	41		X				A					X				
	2006	1	8			X	X				X			X				
	2007	16	125	X									X					
	2008	4	43		X							X		X				
	2009	40	320		X							X		X				X
	2010	13	131		X	X								X	X			
	2010	6	66		X								X				X	
	2011	49	407	X*	X*	X*	X*	X*	X*	X*	X*	X*	X*	X*	A*	X*	X*	X*
	2011	8	52	A	X*	X*	X*	X*	X*		X*	X*	X*	X*		X*	X*	
	2013	8	62		X												X	
	2014	2	4		X		X										X	
	2014	18	58	A	X				X					X				
	2014	3	?			X	X						X	X				
	2015	25	269				X										X	
	2015	7	26									X		X				
Number of occurrences				2	13	7	7	2	3	1	3	7	7	14	1	2	7	2
Mean relative error [%]				-4.8	-8.0	-0.1	8.7	2.4	0.7	-1.2	0.0	6.4	-6.2	-4.6	-0.5	4.7	-4.3	1.7
St. dev. of rel. error [%]				8.7	11.3	12.2	15.2	10.8	10.9	12.1	8.8	15.8	12.0	10.3	6.1	9.9	17.9	8.4

Manson-McKnight

- So simple, that it can be computed in MS Excel
  - !The cycle has to be detected a priori!
- Amplitude and mean value of each stress component is evaluated:

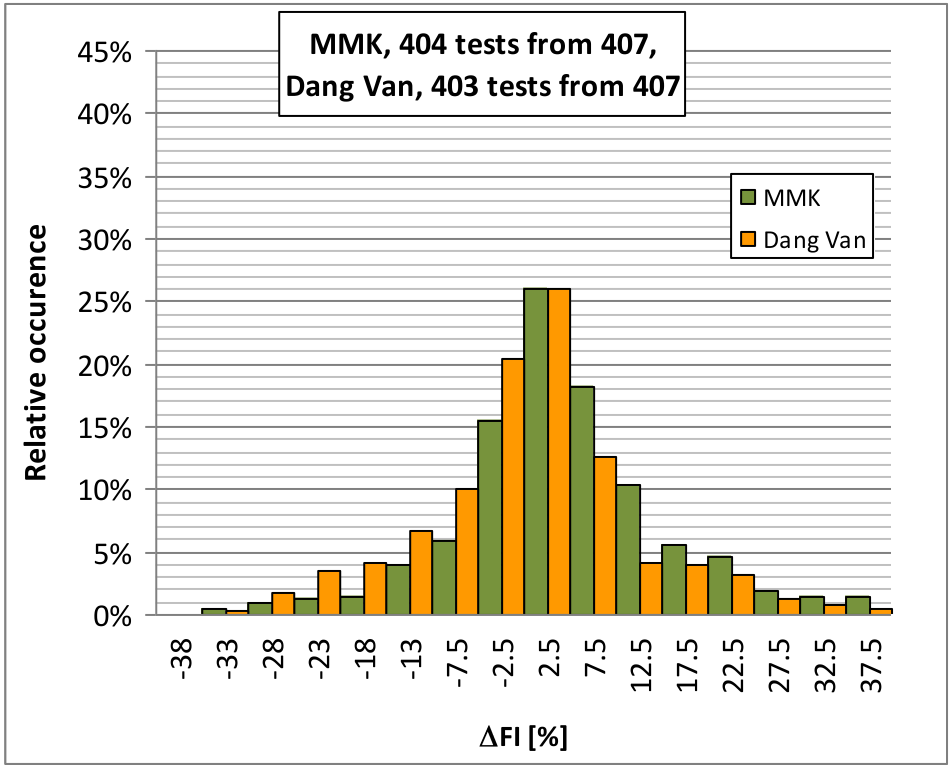
$$\sigma_a = \sqrt{\frac{1}{2}\left[\left(\sigma_{x,a} - \sigma_{y,a}\right)^2 + \left(\sigma_{y,a} - \sigma_{z,a}\right)^2 + \left(\sigma_{z,a} - \sigma_{x,a}\right)^2 + 6\left(\tau_{xy,a}^2 + \tau_{yz,a}^2 + \tau_{zx,a}^2\right)\right]}$$

$$\sigma_m^* = sign\left[I_{1,d}\right] \cdot \sqrt{\frac{1}{2}\left[\left(\sigma_{x,m} - \sigma_{y,m}\right)^2 + \left(\sigma_{y,m} - \sigma_{z,m}\right)^2 + \left(\sigma_{z,m} - \sigma_{x,m}\right)^2 + 6\left(\tau_{xy,m}^2 + \tau_{yz,m}^2 + \tau_{zx,m}^2\right)\right]}$$

- The mean equivalent value is signed according to the stress tensor invariant with biggest magnitude

Manson-McKnight - Results

- Not that bad
- Shift to conservative prediction results in many cases (To; nMS-OP; Ax+To; brittle materials)
- Ax+Ax with a phase shift – unsafely non-conservative (mean value ΔFI=-17.2%)
- In many other groups Dang Van better, but fails in MS cases



MMK versus Dang Van

DV – Dang Van critical plane method (1974)

MMKF –Manson-McKnight according to Filippini (2010)

- MMK not to be used for
  - brittle materials
  - MS,Ax+Ax, PS<>0
  - out-of-phase loading
- MMK useful for pressure vessels
  - MS,Ax+Ax,noPS
- The difference is not big overall!

ΔFI in individual groups (tests)	Mean values			Range			Standard deviation		
	DV	MMKF	Diff	DV	MMKF	Diff	DV	MMKF	Diff
All (407)	0	1	1	93	106	13	12	12	-1
nMS (171)	-1	5	5	53	71	18	8	9	1
nMS,OP (40)	-8	8	16	53	70	18	12	14	2
nMS,IP (131)	2	4	2	22	45	22	4	7	3
MS (236)	0	-1	-2	93	82	-11	15	12	-2
MS,Ax (41)	-1	0	1	64	62	-2	13	11	-2
MS,To (18)	-16	-5	11	46	65	19	12	16	4
MS,Ax+Ax (36)	12	-11	-23	57	43	-14	13	12	-1
MS,Ax+Ax,noPS (18)	15	-3	-18	43	22	-20	12	8	-4
MS,Ax+Ax, PS<>0 (18)	9	-19	-28	57	40	-18	14	10	-4
Ax+To (285)	-2	3	5	63	96	33	10	10	0
MS,Ax+To (114)	-3	0	3	61	66	5	12	10	-1
MS-Ax, Ax+To (52)	-1	6	7	61	43	-18	12	9	-4
MS-To, Ax+To (31)	-10	-6	3	41	41	1	9	8	-1
ductile (352)	0	0	0	93	82	-11	13	11	-2
ductile,nMS (118)	-1	4	4	43	30	-12	8	5	-3
ductile,nMS,IP (86)	3	3	1	18	18	1	4	5	1
brittle (37)	-1	11	12	42	75	33	7	16	9
brittle, nMS(35)	-1	12	13	42	70	27	7	16	9
brittle,nMS,IP (29)	-2	8	10	16	44	28	3	11	8
extra-ductile (18)	2	0	-2	19	18	-1	5	4	-1
extra-ductile,nMS,IP (16)	3	-1	-4	12	11	-2	3	3	0

Versions of Papuga PCr solution

PCr – original solution (2008) presented in IJF

PCrN – new version (2019) including mean shear stress effect

- New special formula includes both N_m and C_m mean stress parameters – a part of the N_m effect moved to C_m effect
- It improves mean value of MS,To group
- Substantially improves scatter by MS,Ax and MS,Ax+Ax experiments!
- Minor worsening in MS-Ax,Ax+To group – a further study will be done before a final publishing

ΔFI in individual groups (tests)	Mean values			Range			Standard deviation		
	DV	MMKF	Diff	DV	MMKF	Diff	DV	MMKF	Diff
All (407)	0	1	1	93	106	13	12	12	-1

ΔFI in individual groups (tests)	Mean values			Range			Standard		
	PCr	PCrN	Diff	PCr	PCrN	Diff	PCr	PCrN	Diff
All (407)	-1	1	2	37	31	-6	6	5	-1
nMS (171)	1	1	0	23	23	0	4	4	0
nMS,OP (40)	0	0	0	23	23	0	6	6	0
nMS,IP (131)	1	1	0	17	16	0	3	3	0
MS (236)	-1	2	3	37	31	-6	7	6	-2
MS,Ax (41)	-2	2	4	33	24	-9	7	5	-2
MS,To (18)	-8	-2	7	17	16	0	5	4	-1
MS,Ax+Ax (36)	-4	4	8	32	20	-12	7	5	-2
MS,Ax+Ax,noPS (18)	-4	4	8	25	19	-5	8	6	-2
MS,Ax+Ax, PS<>0 (18)	-4	4	8	27	15	-11	7	4	-3
Ax+To (285)	1	1	1	36	31	-4	5	5	0
MS,Ax+To (114)	1	2	1	36	31	-4	6	6	0
MS-Ax, Ax+To (52)	0	3	3	28	31	3	6	6	0
MS-To, Ax+To (31)	3	3	0	24	19	-5	5	5	0
ductile (352)	-1	2	2	37	31	-6	6	5	-1
ductile,nMS (118)	1	1	0	22	22	0	4	4	0
ductile,nMS,IP (86)	2	2	0	14	14	0	3	3	0
brittle (37)	0	-1	0	17	17	0	4	4	0
brittle, nMS(35)	-1	-1	0	17	17	0	4	4	0
brittle,nMS,IP (29)	-2	-2	0	9	9	0	2	2	0
extra-ductile (18)	2	2	0	12	12	0	3	3	0
extra-ductile,nMS,IP (16)	3	3	0	12	12	0	3	3	0

The divergence: Engineering vs Research

Real applications:

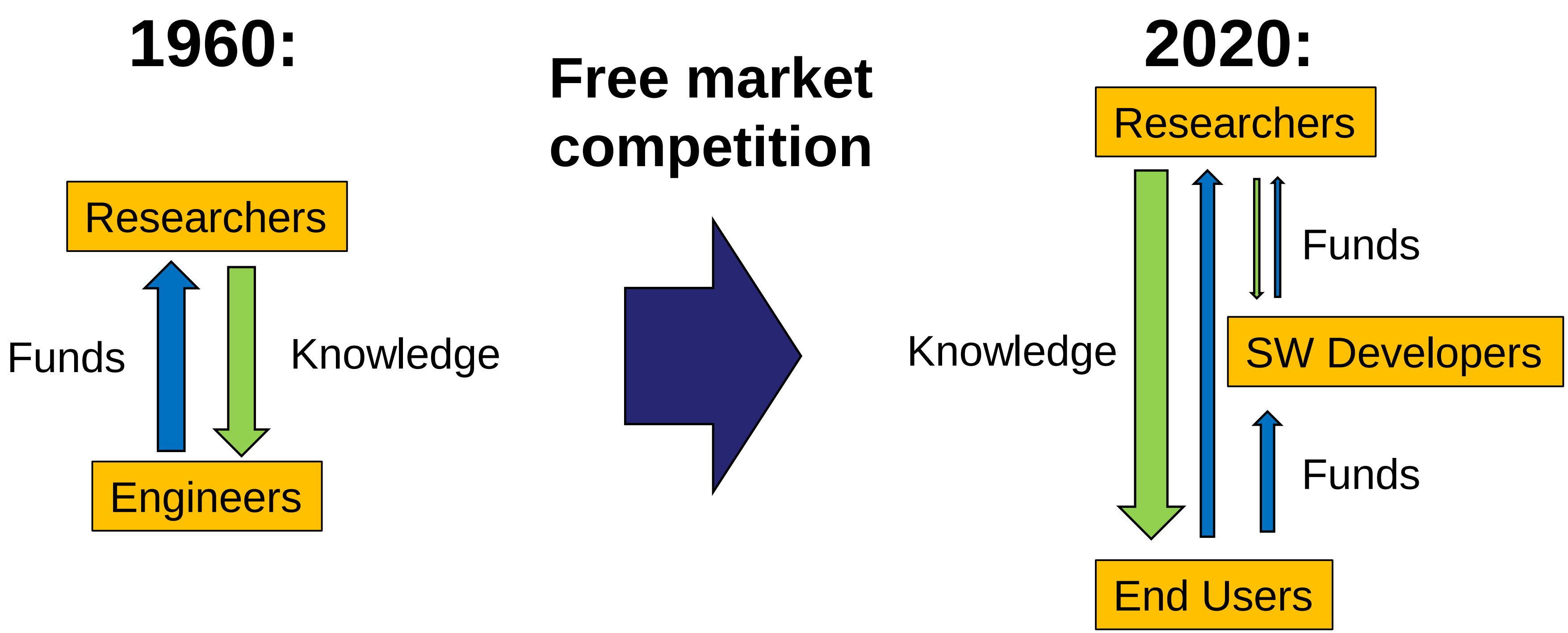
How they can live together?

Research:

Methods	Commercial: Fe-Safe	Commercial: MSC.Fatigue	Commercial: Femfat	Commercial: FEARCE	Commercial: nCode DesignLife	Commercial: LMS Virtual. Lab Durability	Commercial: WinLife	Non-commercial: eFatigue	Non-commercial: Code Aster	Non-commercial: PragTic	Non-commercial: FatLab	Test set 407 exps.: Mean relative error [%]	Test set 407 exps.: St. deviation of relative error [%]
Dang Van (1973)	X	X		X	X	X	X	X	X	X		-0.1	12.2
Findley (1957)							X	X		X	X	8.7	15.2
McDiarmid (1991)		X		X	X					X		-6.2	12.0
Sines (1959)								X		X		-4.3	17.9
Matake (1977)									X	X		6.4	15.8
Other solution			X						X	X	X		

Method:				C&S	Crossland	Dang Van	Findley	Fogue	Goncalves	L&M	L&Z	Matake	McDiarmid	Papadopoulos	Papuga PCr	Robert	Sines	Susmel
Year of publication:				2001	1956	1973	1957	1987	2005	2005	1989	1977	1991	1994	2008	1988	1959	2001
Ref..	Year	Sets	Items															
[8]	1997	4	43		X							X	X	X			X	
[9]	1999	1	2		X	X												
[10]	2000	?	179								A			X				
[11]	2001	3	30	A			X					X	X					
[12]	2002	52	447											X				A
[13]	2003	3	38		X	X								X				
[14]	2005	4	41		X				A					X				
[15]	2006	1	8			X	X				X			X				
[16]	2007	16	125	X									X					
[17]	2008	4	43		X							X		X				
[18]	2009	40	320		X							X		X				X
[19]	2010	13	131		X	X								X	X			
[20]	2010	6	66		X								X				X	
[4]	2011	49	407	X*	X*	X*	X*	X*	X*	X*	X*	X*	X*	X*	A*	X*	X*	X*
[21]	2011	8	52	A	X*	X*	X*	X*	X*		X*	X*	X*	X*		X*	X*	
[22]	2013	8	62		X												X	
[23]	2014	2	4		X		X										X	
[24]	2014	18	58	A	X				X					X				
[25]	2014	3	?			X	X						X	X				
[26]	2015	25	269				X										X	
[27]	2015	7	26									X		X				
Number of occurrences				2	13	7	7	2	3	1	3	7	7	14	1	2	7	2
Mean relative error [%]				-4.8	-8.0	-0.1	8.7	2.4	0.7	-1.2	0.0	6.4	-6.2	-4.6	-0.5	4.7	-4.3	1.7
St. dev. of rel. error [%]				8.7	11.3	12.2	15.2	10.8	10.9	12.1	8.8	15.8	12.0	10.3	6.1	9.9	17.9	8.4

Interaction of groups on market



***"… The users don't really want to do their own research anymore. They expect nCode etc to "build-in" any new concept. Unfortunately this has stifled research by others. The major fatigue research labs in N.America are dying off*. …"

From personal e-mail communication with Al Conle (retired from Ford), 2009

Fatigue solvers – Pros and Cons

+

- Computational power
- Ability to quickly iterate various design versions
- A „standardized“ solution
- Stabilized quality of the output
- Cheaper than personnel costs
- No fear from leaves of crucial employees

-

- Dependence on knowledge generated and maintained out of house
- No idea how the solver really works
- Very limited possibility to improve solution, when it is obviously weak
- Warranty denial

	EUR	CZK	Reason
Year 1	30000	780000	Purchase
Year 2	7500	195000	Maintenance
Year 3	7500	195000	Maintenance
Year 4	7500	195000	Maintenance
Year 5	7500	195000	Maintenance
Average/Year	12000	312000	
Average/Month	1000	26000	

	EUR	CZK	Reason
Year 6	7500	195000	Maintenance
Year 7	7500	195000	Maintenance
Year 8	7500	195000	Maintenance
Year 9	7500	195000	Maintenance
Year 10	7500	195000	Maintenance
Average/Year	9750	253500	
Average/Month	812.5	21125	

Warranty disclaimer issue

- **Researcher:**
  - Proposes a new criterion
  - Proves its validity on limited data he has in hands
  - His **only (vague) responsibility** is for these research results
- **Solver developer:**
  - Selects and implements the method
  - I do not know about any case, where further testing was sponsored by such a company with publicly available results
  - Decides to what extent to release publicly details of the implementation (so that the competitors would not steal his ideas)
  - **Disclaims any responsibility** for the results of the software
- **End user - engineer:**
  - Gets a very expensive tool in his hands
  - Due to high price is forced to use it to maximum
  - Does not have time enough to get through all the theoretical basis or validation studies (if there are any available)
  - **Would like to believe** that the previous two persons were responsible

Warranty denial vs Advertisement

- *„MSC Fatigue enables durability engineers to quickly and accurately predict how long products will last under any combination of time-dependent or frequency-dependent loading conditions.“*
  MSCsoftware.com (2018). MSC Fatigue: FE Based Durability Solution. [online] Available at: http://www.mscsoftware.com/product/msc-fatigue [Accessed August 30, 2018]

- *"Do I need to be a fatigue expert?*
  No, you can leave that to us. There are factors which cannot be ignored if results are to be trusted. However, because fe-safe is technically advanced, it is configured to take into account many variables which will affect the accuracy of your results automatically."
  3ds.com. (2018). FE-SAFE - SIMULIATM 3D Software - Dassault Systèmes®. [online] Available at: https://www.3ds.com/products-services/simulia/products/fe-safe/ [Accessed August 30, 2018].

Why it went this way?

- Computerized society
- Cost cuts: Own research is too expensive and unpredictable
- Increased complexity of computational models
- Humans from the perspective of managers:
  - Unreliable
  - Expensive
  - Hard to raise
  - Unstable: Prone to leave if not well kept

The goal today - Search for an intelligent system: The same (wo)man builds the virtual CAD model, meshes it, adds boundary conditions and runs the FE-analysis, which (s)he then uses for the subsequent fatigue analysis. The computer (program) assists to these actions and prevents any potential errors.

Reminder: Engineering vs Research

Real applications:

How they can live together?

Research:

Is the free market self-correcting?

Yes, it would be, if there had been somebody responsible

Methods	Commercial							Non-commercial				Test set 407 exps.	
	Fe-Safe	MSC.Fatigue	Femfat	FEARCE	nCode DesignLife	LMS Virtual. Lab Durability	WinLife	eFatigue	Code Aster	PragTic	FatLab	Mean relative error [%]	St. deviation of relative error [%]
Dang Van (1973)	X	X		X	X	X	X	X	X	X		-0.1	12.2
Findley (1957)							X	X		X	X	8.7	15.2
McDiarmid (1991)		X		X	X					X		-6.2	12.0
Sines (1959)								X		X		-4.3	17.9
Matake (1977)									X	X		6.4	15.8
Other solution			X						X	X	X		

Method:				C&S	Crossland	Dang Van	Findley	Fogue	Goncalves	L&M	L&Z	Matake	McDiarmid	Papadopoulos	Papuga PCr	Robert	Sines	Susmel
Year of publication:				2001	1956	1973	1957	1987	2005	2005	1989	1977	1991	1994	2008	1988	1959	2001
Ref..	Year	Sets	Items															
[8]	1997	4	43		X							X	X	X			X	
[9]	1999	1	2		X	X												
[10]	2000	?	179								A			X				
[11]	2001	3	30	A			X					X	X					
[12]	2002	52	447											X				A
[13]	2003	3	38		X	X								X				
[14]	2005	4	41		X				A					X				
[15]	2006	1	8			X	X				X			X				
[16]	2007	16	125	X									X					
[17]	2008	4	43		X							X		X				
[18]	2009	40	320		X							X		X				X
[19]	2010	13	131		X	X								X	X			
[20]	2010	6	66		X								X				X	
[4]	2011	49	407	X*	X*	X*	X*	X*	X*	X*	X*	X*	X*	X*	A*	X*	X*	X*
[21]	2011	8	52	A	X*	X*	X*	X*	X*		X*	X*	X*	X*		X*	X*	
[22]	2013	8	62		X												X	
[23]	2014	2	4		X		X										X	
[24]	2014	18	58	A	X				X					X				
[25]	2014	3	?			X	X						X	X				
[26]	2015	25	269				X										X	
[27]	2015	7	26									X		X				
Number of occurrences				2	13	7	7	2	3	1	3	7	7	14	1	2	7	2
Mean relative error [%]				-4.8	-8.0	-0.1	8.7	2.4	0.7	-1.2	0.0	6.4	-6.2	-4.6	-0.5	4.7	-4.3	1.7
St. dev. of rel. error [%]				8.7	11.3	12.2	15.2	10.8	10.9	12.1	8.8	15.8	12.0	10.3	6.1	9.9	17.9	8.4

Market doesn't favor the best but the cheapest

1. Engineering companies wanted to cut their costs for fatigue analyses.
2. They started to buy fatigue solvers, which can be developed cheaply, without the need to support own research.
3. The money paid for fatigue solvers enabled developers to develop solvers, but there was little real research underlying them.
4. Solver developers became aware that they cannot substitute research, so they avoided providing a warranty.
5. Academia lost interest in what was implemented in fatigue solvers (no more money, no research).
6. Nobody has been taking care of the core methods in fatigue solvers. They are generally considered or assumed to be good enough (whatever this means).

The outcome?

- **1. Researchers**
  - The big losers - no gain anywhere
  - They have lost the funding for research to confirm or reject the implemented methods, to publish results, and to create and publish benchmarks.
- **2. End users**
  - Win on the level of their company (savings on investment)
  - They have lost control over potential prediction quality.
- **3. Solver developers**
  - The only current winners (money from their customers).
  - In the long-term, however, they are doomed to lose their credibility, unless they start to re-invest into research.
  - The only relevant customers for them are the bigger customers, who are able to do their own benchmarking.

Room for Verification Authority

- To bridge the gap between research and commercial application
- Need for verification of
  - methods implemented in SW
  - the implementation ways themselves
  - new calculation methods where a great potential of commercial implementation exists

NAFEMS case

„By the late 1970's and early 1980's, as computing power became more widely available, increasingly industry was starting to solve practical engineering problems using finite element analysis techniques.

There was however considerable concern that the accuracy of the methods, and software implementations, required to be verified in order to allow the results to be effectively used.“

from: http://www.nafems.org/about/about_nafems/history/

- NAFEMS (*National Agency for Finite Element Methods and Standards*) established in 1983 ***„To promote the safe and reliable use of finite element and related technology“***
- Funded for 7 years by UK government
- Then switched to a non-profit organization funded by its activities and members
- Shift in the focus
  - Originally – Benchmarks to test the FE-solvers
  - Now – Continuous education of FE-analysts

NAFEMS outcome?

- *"Except as specifically permitted in this Agreement, Customer agrees not to: (a) … (e) provide, disclose or transmit any results of tests or benchmarks related to any DS Offering to any third party,…"*
  DASSAULT SYSTEMES. (2018). Customer License and online service agreement. [v. 11.2], DASSAULT SYSTEMES.

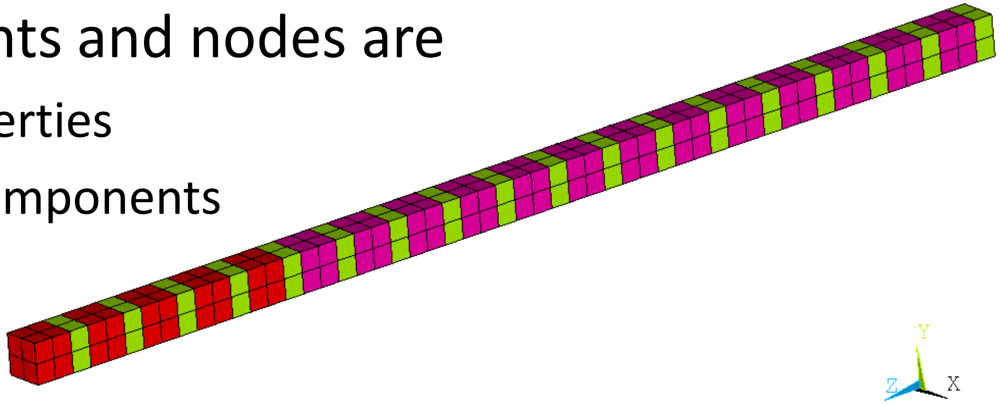
- This means, that every customer is left alone, without any legal chance to understand better the offer on the market

Why this could happen?

- Engineers
  - Love complex technical systems
  - They are happy somebody / something pretends to remove their responsibility
  - …
  - …
  - …
  - **They are not demanding the responsibility of others**

FADOFF –> Fatigue Limit (Dummy Model)

- New solution prepared within FADOFF
- APDL script in ANSYS to prepare a single fictitious (dummy) model, where on elements and nodes are
  - predefined material properties
  - history of stress tensor components



- 325 experimental items now
- **Effect:**
  - Any user of a commercial fatigue solver can
    - use it as an input for preparing fatigue prediction
    - solve it by the methods implemented in his fatigue solver
    - **check the prediction capability of his fatigue solver**

Some output…

- Two commercial fatigue solvers (CFS) available for testing
- Two more could be checked this year

Group	N of items	average ΔFI				standard deviation of ΔFI			
		CFS#1 Dang Van	CFS#2 Optimum	PragTic PCR	PragTic Dang Van	CFS#1 Dang Van	CFS#2 Optimum	PragTic PCR	PragTic Dang Van
All	325	-13.2%	-0.5%	1.6%	-2.9%	30.6%	15.3%	7.6%	17.1%
MS	190	-17.4%	-0.6%	1.4%	-5.5%	32.9%	17.4%	7.9%	19.9%
nMS	133	-7.6%	-0.6%	1.9%	0.8%	26.1%	11.9%	7.2%	11.1%
Sync	72	-18.0%	-1.9%	2.9%	-3.6%	34.2%	13.9%	8.9%	17.6%
brittle	38	-0.7%	2.5%	3.7%	2.5%	26.6%	16.3%	8.2%	21.6%
brit,nMS	23	-0.7%	-1.0%	1.4%	0.9%	14.5%	14.4%	6.5%	13.1%
ex-duct	45	-28.7%	3.4%	-3.7%	-16.5%	31.9%	22.9%	9.1%	15.8%
AT	219	-14.2%	-2.6%	2.1%	-3.1%	30.1%	13.0%	8.0%	14.5%
2-3A	39	6.9%	-7.0%	2.3%	11.2%	15.2%	15.3%	7.4%	16.4%
IP	112	-5.4%	2.6%	1.6%	1.2%	25.3%	8.9%	6.5%	12.3%
IP,nMS	100	-2.0%	3.4%	2.6%	3.7%	22.1%	8.2%	5.7%	8.2%
IP,nMS,s	57	-2.2%	3.0%	2.5%	3.4%	23.2%	9.5%	6.1%	9.4%
IP,nMS,t	43	0.3%	3.5%	2.5%	3.7%	15.5%	6.2%	5.3%	6.2%
MS,Ax	43	-21.0%	8.6%	1.0%	-6.3%	38.8%	16.9%	4.8%	21.6%
MS,To	23	-25.4%	12.6%	-2.4%	-19.1%	21.1%	17.6%	7.3%	13.0%
OP	82	-14.1%	-13.0%	0.7%	-4.5%	27.8%	12.6%	9.1%	19.2%
OP,nMS	31	-21.5%	-14.4%	-0.3%	-9.8%	24.7%	11.5%	10.7%	12.9%
OP90,nMS	23	-23.8%	-18.0%	-1.1%	-12.6%	22.3%	10.3%	11.8%	13.0%
OP,MS	52	-9.9%	-12.0%	1.6%	-1.5%	28.5%	13.1%	8.2%	21.3%
OP,MS,AT	27	-27.3%	-10.3%	2.8%	-15.6%	27.9%	14.6%	9.9%	16.2%

- CFS#1 (Dang Van)
  - ¾ of results agree very well with PragTic (Dang Van), the rest does not
  - no similar markers for failure, results tend to be too unsafe
  - Was communicated to the developer – No interest!

The financial support of the **Technology Agency of the Czech Republic** (TA01011274 project) and of the the **Grant Agency of the Czech Technical University in Prague** (SGS17/175/OHK2/3T/12 project) during the works output of which is presented here is gratefully acknowledged.