ICAF

International Committee
on Aeronautical Fatigue
and Structural Integrity

Topical Review
Fatigue Crack Growth and Life Prediction Methods

Carlos E. Chaves – Embraer S.A.| 26/06/2023

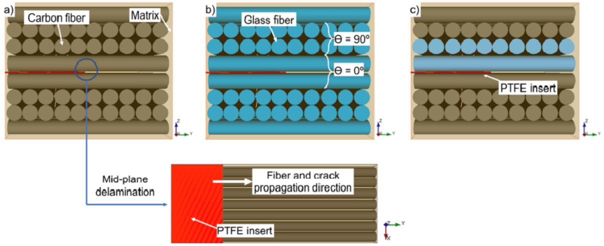
Fatigue in carbon-glass fiber/epoxy hybrid composite - the influence of hybrid interface in individual Mode I and II

Author: Francisco Maciel Monticeli (State University of São Paulo - Unesp)

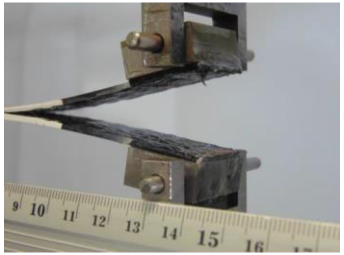
Objectives:

- To characterize the interlaminar damage progression in hybrid composites (continuous carbon/ glass fiber)

COMPOSITE SPECIMENS:
(a) CFC, (b) GFC (c) HC.



DCB SETUP & SPECIMEN

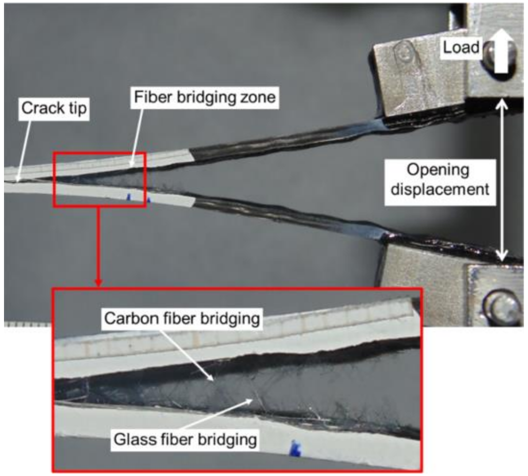


- To develop an analytical crack propagation model, considering the physical fracture mechanisms characterized through the hybrid interface

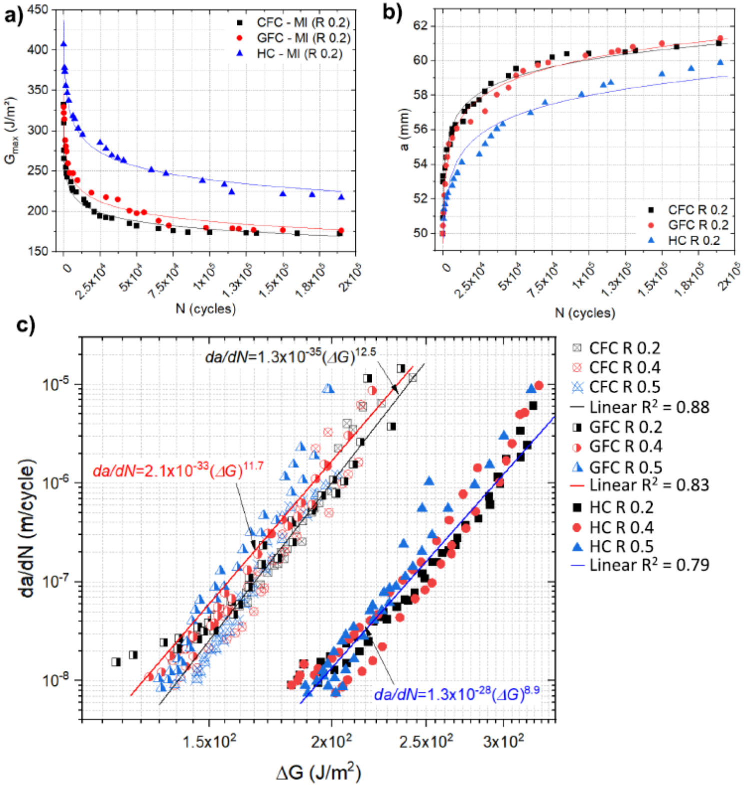
- To describe a model capable to predict the behavior of hybrid and non-hybrid laminates with two or more types of reinforcement

Fatigue in carbon-glass fiber/epoxy hybrid composite - the influence of hybrid interface in individual Mode I and II

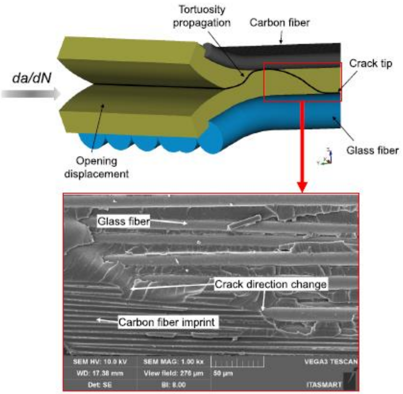
- Highlights



Hybrid fiber bridging in Mode I fatigue delamination.



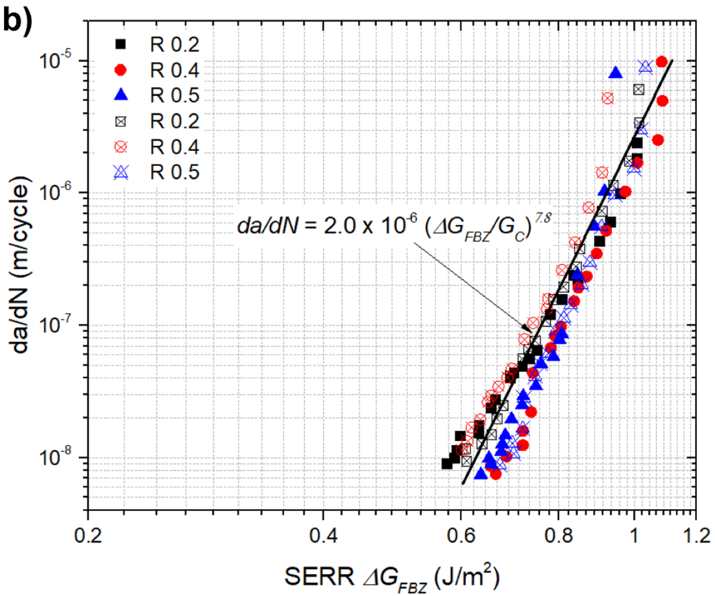
Fatigue delamination test results – Mode I: (a) crack length vs. cycles, (b) SERR vs. cycles, and (c) Paris law.

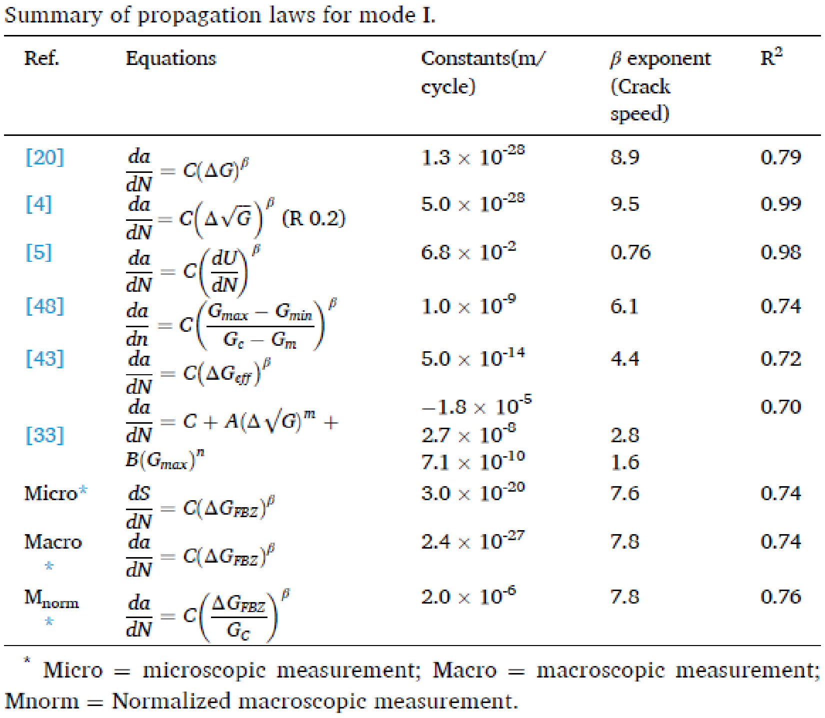


Fracture mechanism at the hybrid composite interface.

Fatigue in carbon-glass fiber/epoxy hybrid composite - the influence of hybrid interface in individual Mode I and II

- Highlights
  - Cyclic loading prediction model development and implementation





Summary of propagation laws for mode I.

Ref.	Equations	Constants(m/ cycle)	β exponent (Crack speed)	R^2
[20]	$\frac{da}{dN} = C(\Delta G)^{\beta}$	1.3×10^{-28}	8.9	0.79
[4]	$\frac{da}{dN} = C\left(\Delta\sqrt{G}\right)^{\beta}$ (R 0.2)	5.0×10^{-28}	9.5	0.99
[5]	$\frac{da}{dN} = C\left(\frac{dU}{dN}\right)^{\beta}$	6.8×10^{-2}	0.76	0.98
[48]	$\frac{da}{dn} = C\left(\frac{G_{max} - G_{min}}{G_c - G_m}\right)^{\beta}$	1.0×10^{-9}	6.1	0.74
[43]	$\frac{da}{dN} = C(\Delta G_{eff})^{\beta}$	5.0×10^{-14}	4.4	0.72
[33]	$\frac{da}{dN} = C + A(\Delta\sqrt{G})^{m} + B(G_{max})^{n}$	-1.8×10^{-5} 2.7×10^{-8} 7.1×10^{-10}	 2.8 1.6	0.70
Micro*	$\frac{dS}{dN} = C(\Delta G_{FBZ})^{\beta}$	3.0×10^{-20}	7.6	0.74
Macro*	$\frac{da}{dN} = C(\Delta G_{FBZ})^{\beta}$	2.4×10^{-27}	7.8	0.74
M$_{norm}$*	$\frac{da}{dN} = C\left(\frac{\Delta G_{FBZ}}{G_C}\right)^{\beta}$	2.0×10^{-6}	7.8	0.76

* Micro = microscopic measurement; Macro = macroscopic measurement; Mnorm = Normalized macroscopic measurement.

Fatigue in carbon-glass fiber/epoxy hybrid composite - the influence of hybrid interface in individual Mode I and II

- Publications
  - Monticeli, F.M., Fatigue in carbon-glass fiber/epoxy hybrid composite: the influence of hybrid interface in individual mode I and II – **Ph.D. Thesis**, Unesp, 2021 (in Portuguese)
  - Monticeli, F.M.; Cioffi, M.O.H.; Voorwald, H.J.C. Mode II delamination of carbon-glass fiber/epoxy hybrid composite under fatigue loading. **International Journal of Fatigue 2022**, 154: 106574. https://doi.org/10.1016/j.ijfatigue.2021.106574.
  - Monticeli, F.M.; Voorwald, H.J.C.; Cioffi, M.O.H. The influence of carbon-glass/epoxy hybrid composite under mode I fatigue loading: Physical-based characterization. **Composite Structures 2022**, 286(5):115291. https://doi.org/10.1016/j.compstruct.2022.115291.
  - Monticeli, F.M.; Voorwald, H.J.C; Cioffi, M.O.H. The influence of carbon-glass/epoxy hybrid composite under mode I fatigue loading: Hybrid fiber bridging zone model. **Composite Structures 2022**, 286(1): 115274. https://doi.org/10.1016/j.compstruct.2022.115274.
  - Monticeli, F.M.; Pitanga, M.Y.; Cioffi, M.O.H.; Voorwald, H.J.C. Mode I and mode II delamination of carbon/glass/epoxy hybrid composite: A statistics-based analysis. **Polymer Composites 2021**, 42(8): 3857-3869. https://doi.org/10.1002/pc.26098.

Post-buckling fatigue crack propagation on curved stiffened panels

Author: Felipe Rezende Belem (Aeronautics Institute of Technology)

Structure under evaluation: leading edge, basic Al construction, subjected to buckling

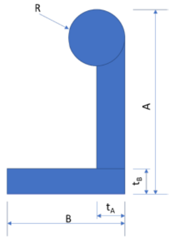
Objectives:

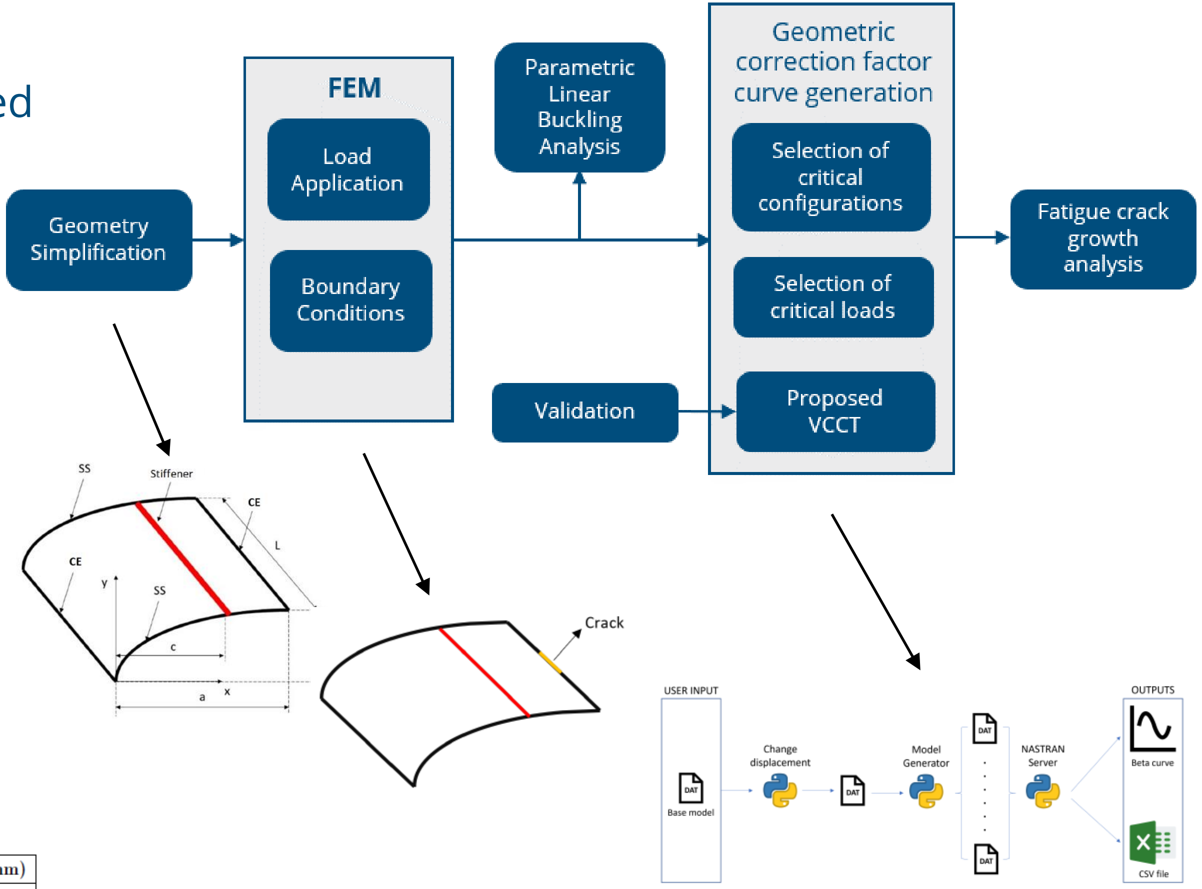
- To evaluate the influence of post-buckling behavior for a possible crack nucleation and propagation
- To develop a methodology accounting for the stress redistribution influence in crack growth, assuming an existing crack
- To provide future design guidelines

Post-buckling fatigue crack propagation on curved stiffened panels

- Highlights
  - 16 configurations analyzed
    - c/a = 0.6, 0.7, 0.8, 0.9
    - 4 stiffener types

Stiffener Number	Model	A (mm)	B (mm)	t_A (mm)	t_B (mm)	R (mm)	I (mm^4)
1	AND10135-0401	12.70	12.70	1.02	1.02	1.52	1274.38
2	AND10135-1001	25.40	17.53	1.27	1.27	1.91	10996.74
3	AND10135-1004	25.40	22.35	2.03	2.03	2.97	19878.64
4	TMS60-19794	28.58	20.65	2.39	2.39	2.97	28661.37




Geometry Simplification

FEM

Load Application

Boundary Conditions

Parametric Linear Buckling Analysis

Validation

Geometric correction factor curve generation

Selection of critical configurations

Selection of critical loads

Proposed VCCT

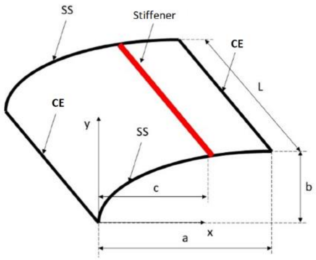
Fatigue crack growth analysis

- 7000 Al alloy
- General dimensions:

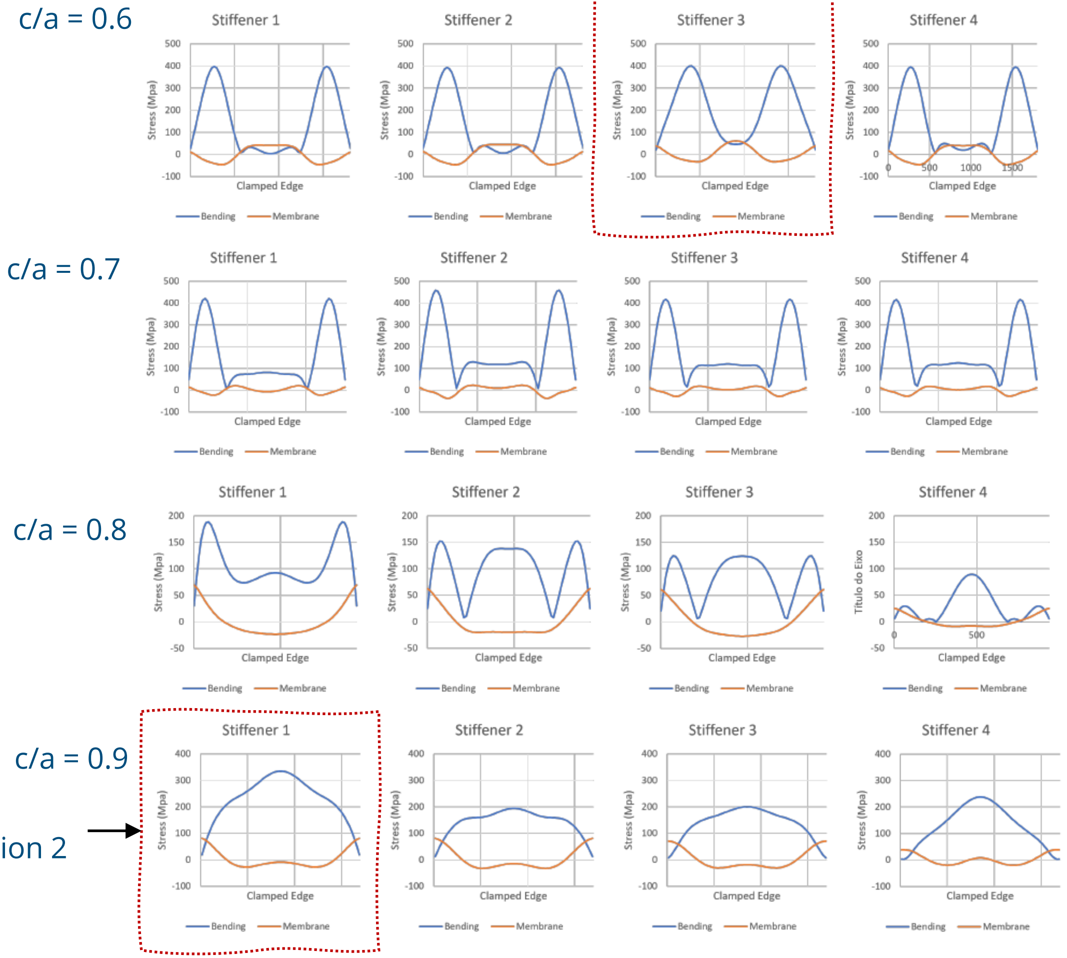
a (mm)	b (mm)	c/a	L (mm)	Plate thickness (mm)
340	160	0.6-0.9	340	1.5

Post-buckling fatigue crack propagation on curved stiffened panels

- Highlights
  - Selection of 2 critical configurations



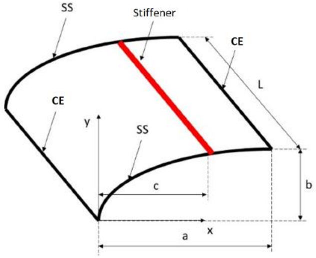
Critical Configuration 1

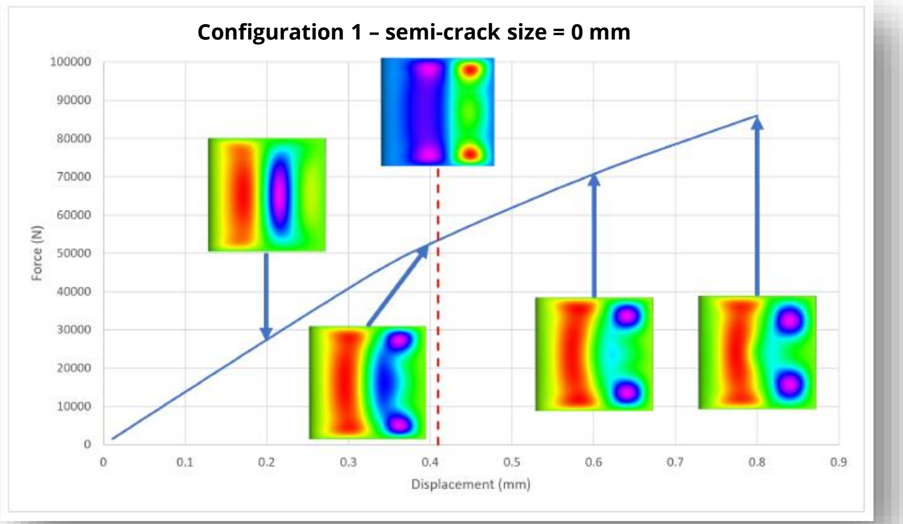


Critical Configuration 2

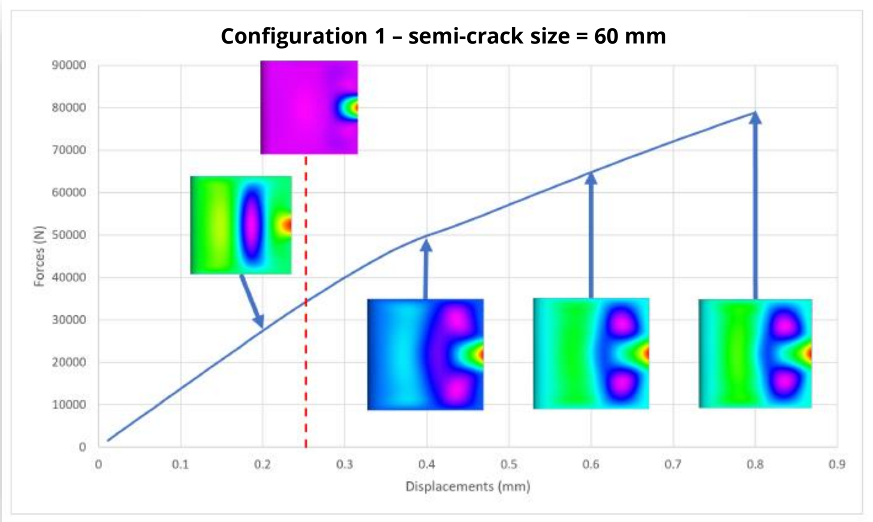
Post-buckling fatigue crack propagation on curved stiffened panels

- Highlights
  - Selection of load (prescribed displacement) cases, considering pre-buckling and post-buckling conditions
  - Example: Critical configuration 1 (stiffener type 3, c/a = 0.6)





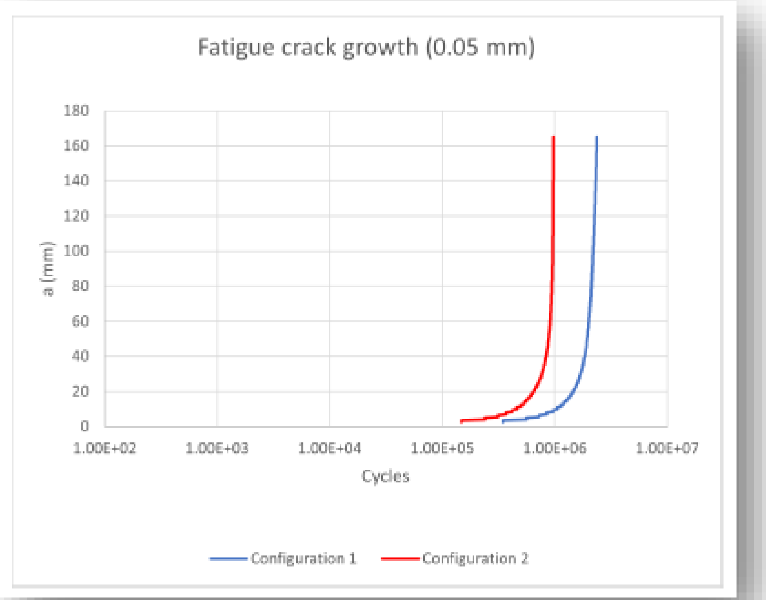
Configuration 1 – semi-crack size = 0 mm



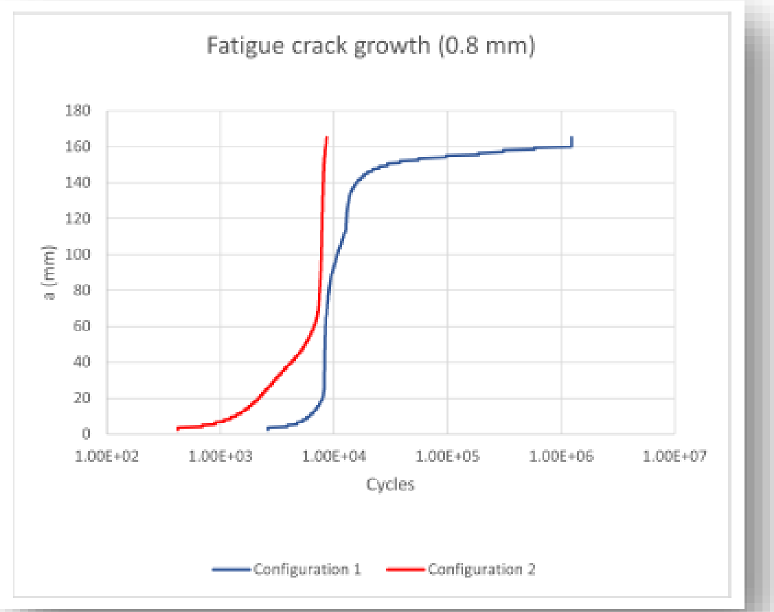
Configuration 1 – semi-crack size = 60 mm

Post-buckling fatigue crack propagation on curved stiffened panels

- Highlights
  - Crack growth analysis for pre-buckling and post-buckling conditions



– Comparisons for the pre-buckling geometric correction factors – Crack growth cycles



– Comparisons for the post-buckling geometric correction factors – Crack growth cycles

Post-buckling fatigue crack propagation on curved stiffened panels

- Publications
  - Belem, F.R., *Post-buckling fatigue crack propagation on curved stiffened panels*, **M.Sc. Dissertation**, Aeronautics Institute of Technology, 2022.

Experiments, modelling and analysis of fretting fatigue for Inconel 718 and Ti-6Al-4V under time-varying contact normal load at room and high temperature

Author: Gabriel M. J. Almeida (University of Brasília – UnB*)

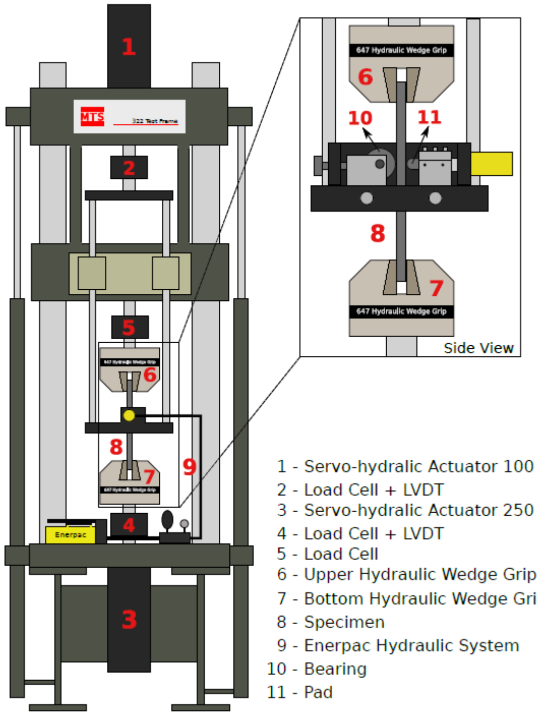
Objectives:

- To design and construct a new four actuators fretting fatigue apparatus
- To evaluate the effect of cyclic contact normal load in fretting fatigue strength for the titanium alloy Ti-6Al-4V at room temperature and for the Inconel 718 alloy at room and elevated temperature
- To apply FEM including wear effects and a multiaxial fatigue parameter to estimate fretting life

* Dual Ph.D. degree with Université Paris-Saclay, France, with support from Safran Engines

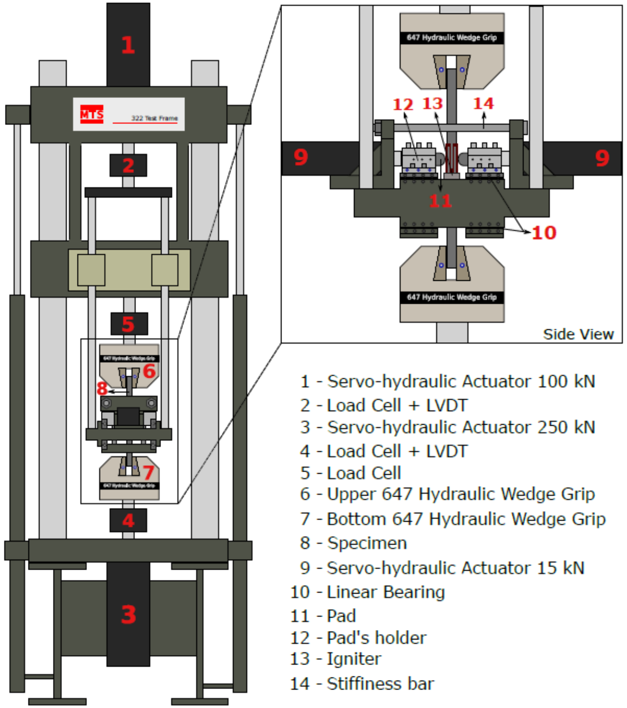
Experiments, modelling and analysis of fretting fatigue for Inconel 718 and Ti-6Al-4V under time-varying contact normal load at room and high temperature

Previous Fretting Fatigue Machine



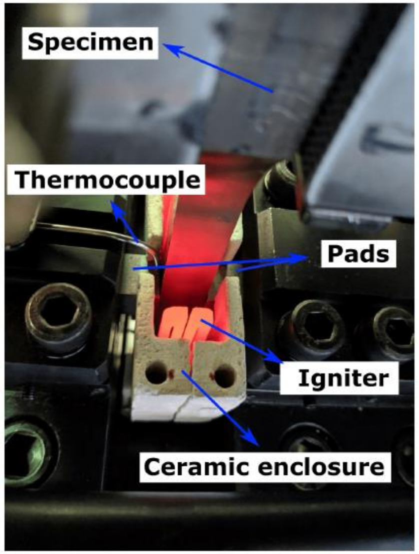
1 - Servo-hydralic Actuator 100 kN
2 - Load Cell + LVDT
3 - Servo-hydralic Actuator 250 KN
4 - Load Cell + LVDT
5 - Load Cell
6 - Upper Hydraulic Wedge Grip
7 - Bottom Hydraulic Wedge Grip
8 - Specimen
9 - Enerpac Hydraulic System
10 - Bearing
11 - Pad

New Fretting Fatigue Machine



1 - Servo-hydraulic Actuator 100 kN
2 - Load Cell + LVDT
3 - Servo-hydraulic Actuator 250 kN
4 - Load Cell + LVDT
5 - Load Cell
6 - Upper 647 Hydraulic Wedge Grip
7 - Bottom 647 Hydraulic Wedge Grip
8 - Specimen
9 - Servo-hydraulic Actuator 15 kN
10 - Linear Bearing
11 - Pad
12 - Pad's holder
13 - Igniter
14 - Stiffiness bar

Heating system tested in a real fretting testing conditions



Experiments, modelling and analysis of fretting fatigue for Inconel 718 and Ti-6Al-4V under time-varying contact normal load at room and high temperature

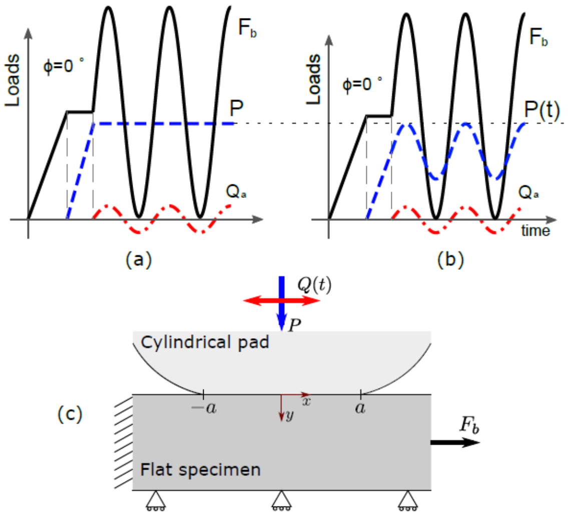
- Highlights

Schematic of loading history for:

(a) Testing Set 1 (constant contact normal load - 4 tests/material)

(b) Testing Set 2 (cyclic contact normal load – 4 tests/material)

(c) Experimental fretting fatigue configuration



Fatigue life estimation

SWT fatigue damage parameter
Theory of critical distances
Wear effect in simulation
Numerical modelling

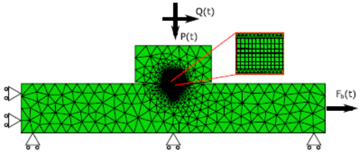
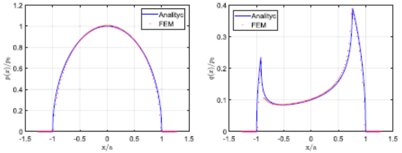


Fig. 9. Finite element model used to simulate fretting fatigue.



Normal and shear tractions

Results

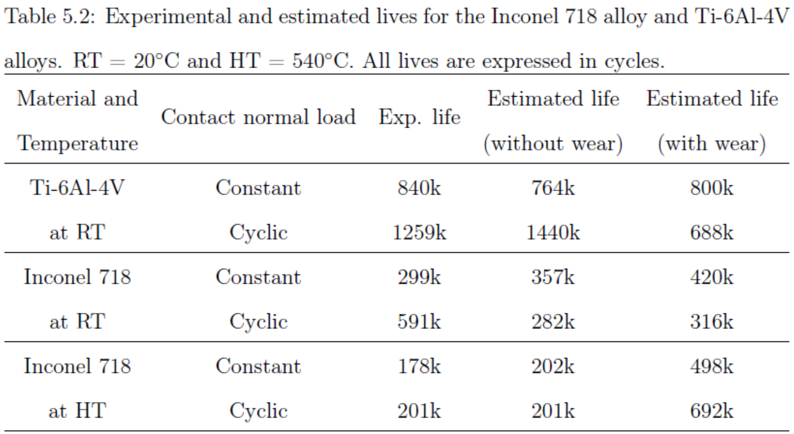


Table 5.2: Experimental and estimated lives for the Inconel 718 alloy and Ti-6Al-4V alloys. RT = 20°C and HT = 540°C. All lives are expressed in cycles.

Material and Temperature	Contact normal load	Exp. life	Estimated life (without wear)	Estimated life (with wear)
Ti-6Al-4V	Constant	840k	764k	800k
at RT	Cyclic	1259k	1440k	688k
Inconel 718	Constant	299k	357k	420k
at RT	Cyclic	591k	282k	316k
Inconel 718	Constant	178k	202k	498k
at HT	Cyclic	201k	201k	692k

Experiments, modelling and analysis of fretting fatigue for Inconel 718 and Ti-6Al-4V under time-varying contact normal load at room and high temperature

- Publications

Almeida, G. M. J., Experiments, modelling and analysis of fretting fatigue for Inconel 718 and Ti-6Al-4V under time-varying contact normal load at room and high temperature, **Ph.D. Thesis**, University of Brasília and Université Paris-Saclay, 2022.

Almeida, G. M. J., Cardoso, R. A., Garcia, M. A., Chassaing, G., Pommier, S., & Araújo, J. A. (2022). Four actuators fretting fatigue rig and tests with cyclic normal load for Ti-6Al-4V. **Theoretical and Applied Fracture Mechanics**, 119, 103292.

Almeida, G. M. J., Cardoso, Chassaing, G., Pommier, S., & Araújo, J. A. (2023). Fretting fatigue of Inconel 718 at room and elevated temperatures considering both constant and cyclic normal contact loads, **Tribology International** 183 (2023) 108382.

Fretting fatigue under variable amplitude loading

Author: André Luiz Pinto (University of Brasília – UnB*)

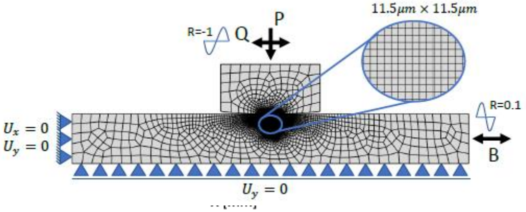
Objectives:

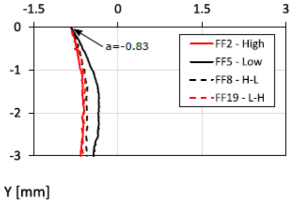
- To develop a FE model to estimate crack initiation (life and orientation) which considers the update of the worn surface profile
- To develop a numerical model to compute crack propagation path and life under mixed cyclic loading mode
- To perform a set of new fretting fatigue tests under variable amplitude shear loading blocks to investigate the effects of the loading sequence in the life assessment of cylinder on plane contact configurations, where both specimens and pads were made of the aeronautical Al 7075-T651 alloy

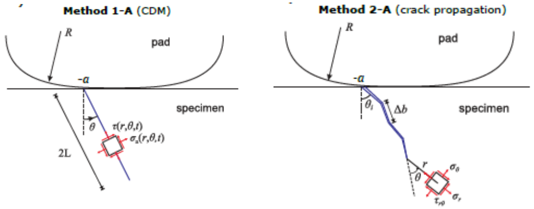
* Dual Ph.D. degree with KU Leuven, Belgium

Fretting fatigue under variable amplitude loading

- Highlights
  - Background of the fatigue problem, fretting fatigue, multiaxial fatigue theories, fracture mechanics, contact mechanics, wear modelling and damage accumulation
  - Experimental work (material characterization, fretting fatigue tests under variable amplitude loading) with AA 7075-T761
  - Numerical analysis: crack simulation with XFEM, new method developed for crack propagation path estimation with non-proportional loading, surface wear effects
  - Development of two methods for crack initiation direction prediction in fretting problems with partial slip conditions
  - Development of robust numerical model encompassing wear in nucleation, initiation angle estimation , and crack propagation until failure. Validation with experimental fatigue data under variable amplitude loading





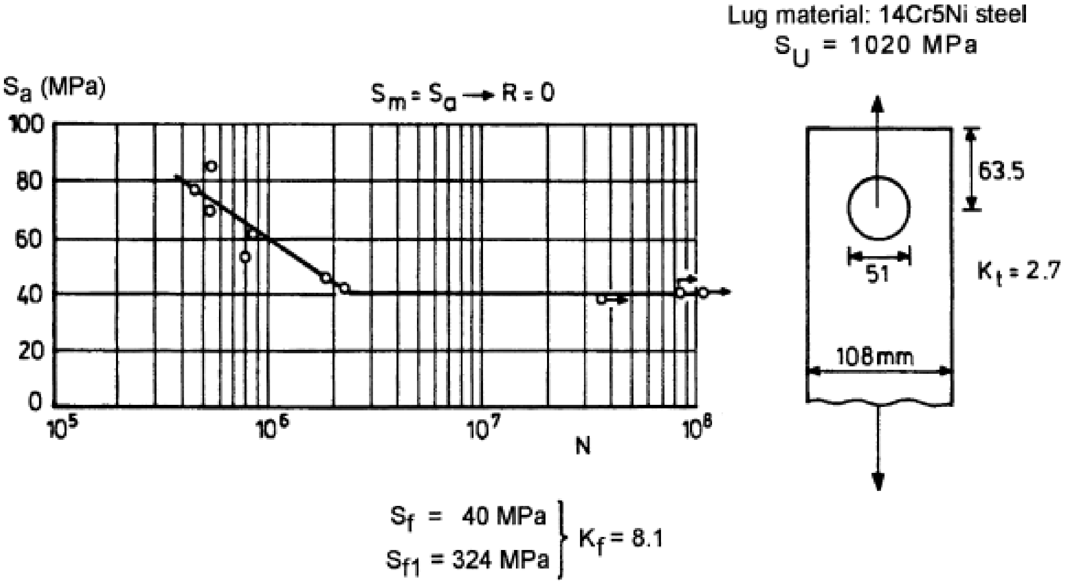


Fretting fatigue under variable amplitude loading

- Publications
  - Pinto, A.L., *Fretting fatigue under variable amplitude loading,* **Ph.D. Thesis**, University of Brasília and KU Leuven, September 2022.
  - Pinto, A. L., Cardoso, R. A., Talemi, R., & Araújo, J. A. (2020). Fretting fatigue under variable amplitude loading considering partial and gross slip regimes: Numerical analysis. **Tribology International**, 146, 106199.
  - Pinto, A. L., Araújo, J. A., Talemi, R. (2021). *Effects of fretting wear process on fatigue crack propagation and life assessment.* **Tribology International**, 156, 106787.
  - Pinto, A. L., Talemi, R., Araújo, J. A. (2022). *Fretting fatigue total life assessment including wear and a varying critical distance.* **International Journal of Fatigue**, 156, 106589.
  - Pinto, A. L., Cardoso, R. A., Talemi, R., Araújo, J. A. (2022). *Early crack orientation prediction methods under fretting fatigue loading including wear effects.* **International Journal of Fatigue**, 161, 106893.
  - Pinto, A. L., Talemi, R., Araújo, J. A. (2023). *Fretting fatigue under variable amplitude shear loading blocks considering partial slip regime: Experimental/numerical analysis.* **Tribology International**, 108367.

Considerations – Fretting Fatigue

- How much do we explore fretting fatigue?
  - Engine manufacturer
  - OEM / Design Office
- Multi-scale approaches



Ref. Schijve, J. Fatigue of Structures and Materials, Second Edition, Springer, 2008

Thank You!

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