Design of Cruciform Test Specimens with different Biaxiality ratios for VHCF Fatigue

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Outline

1. Introduction to VHCF
2. Introduction to In-Plane Biaxial Fatigue
3. Biaxial VHCF
4. Design Principles of Cruciform Specimens for VHCF
5. Preliminary Experimental Results
6. Conclusions

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VHCF – Very High Cycle Fatigue

- New equipment with expected life time increased;
- Proper knowledge of the damage and fracture mechanisms is of prime importance;
- Material fatigue must be studied at the very high cycle fatigue (VHCF) domain, to reach 1E9 cycles;
- SN diagrams must be improved.

1850 - Max speed < 100 km/h

2018 - Max speed > 300 km/h

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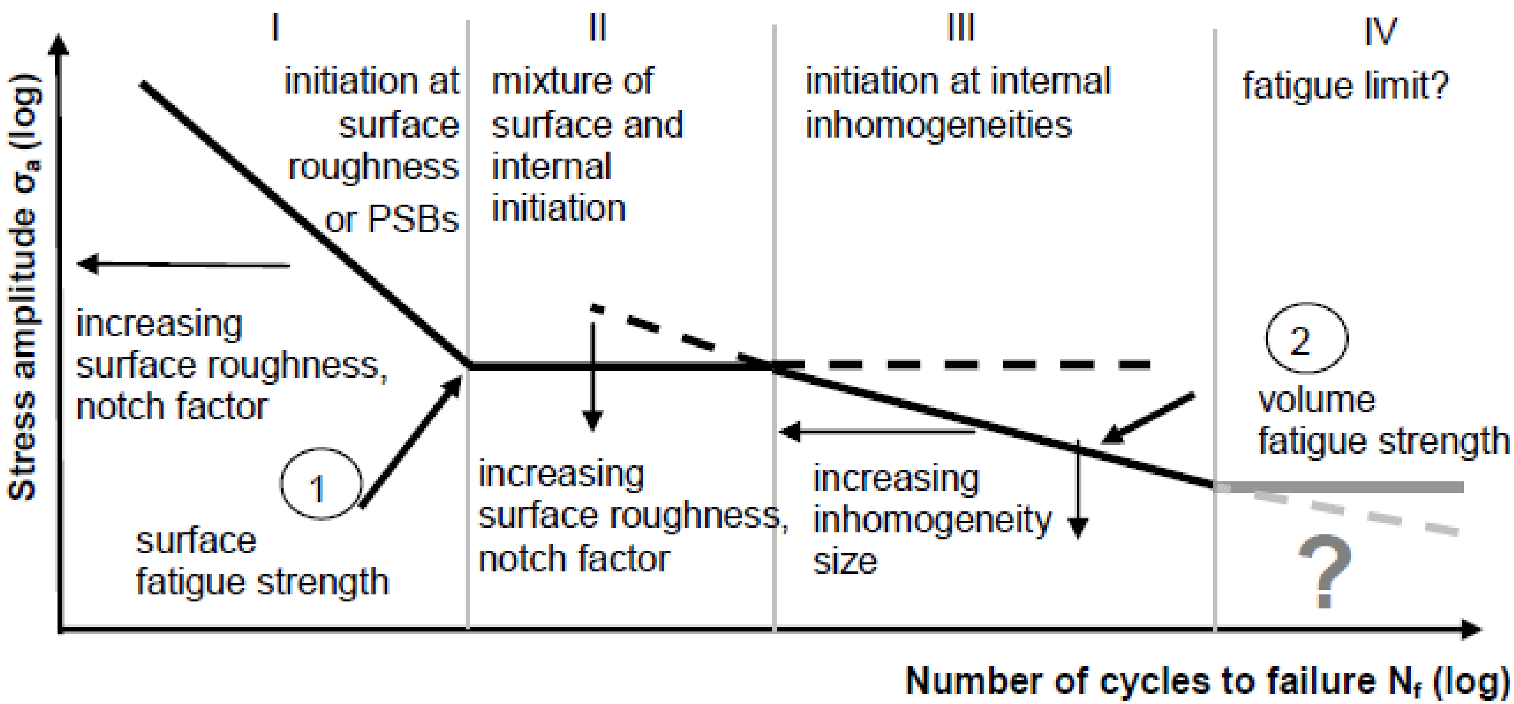
Fatigue Limit

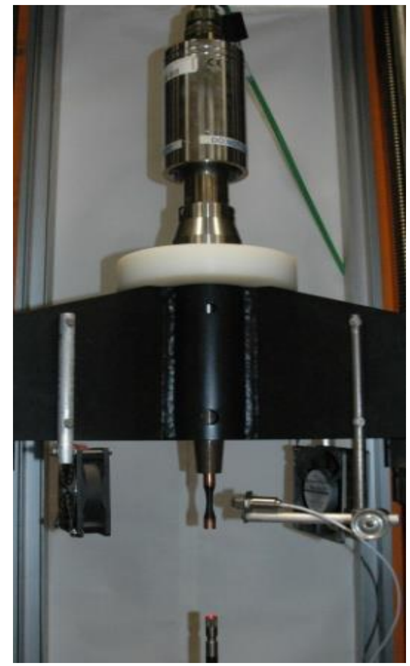


Superimposed *S-N* curves, influencing factors and crack initiation sites [1].

B. Pyttel, D. Schwerdt, C. Berger, Very high cycle fatigue – Is there a fatigue limit?, International Journal of Fatigue, 33, 49-58, 2011.

Ultrasonic Fatigue Machine

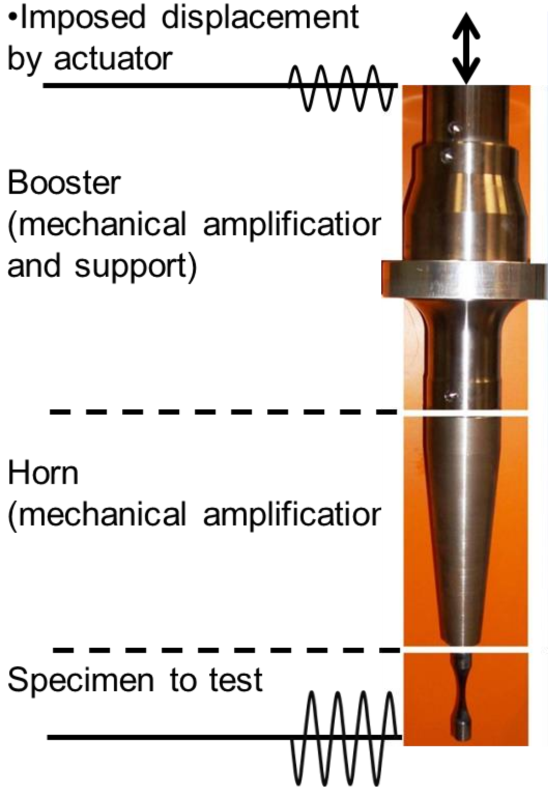
Work Frequency [10 – 50 Hz]	Work Frequency [20 kHz]

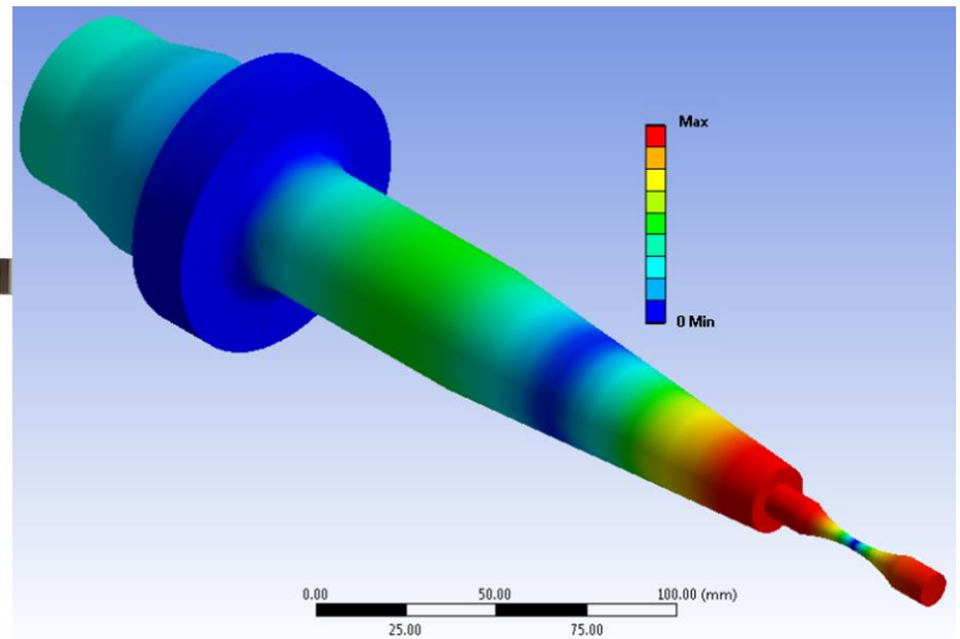


1E9 cycles: Months, Years *vs* Hours, Days

Ultrasonic Fatigue Machine

- Ultrasonic test seek to reproduce free vibration working in axial natural frequency of the specimen.





Modal analysis simulation (Displacement)

Lage, Y., Ribeiro, A., Montalvão, D., Reis, L. & Freitas, M. 2014. Automation in strain and temperature control on VHCF with an ultrasonic testing facility. Journal of ASTM International: Selected Technical Papers in Application of Automation Technology in Fatigue and Fracture Testing and Analysis, ASTM STP 1571 80-100

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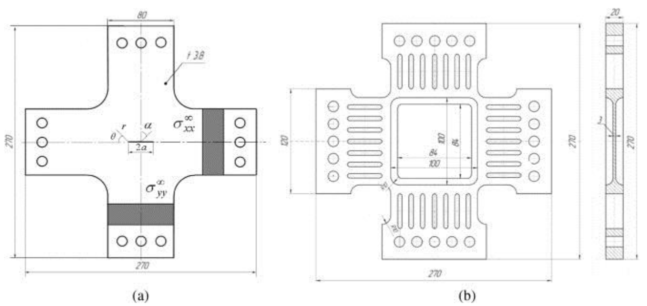
Introduction to In-Plane Biaxial Fatigue

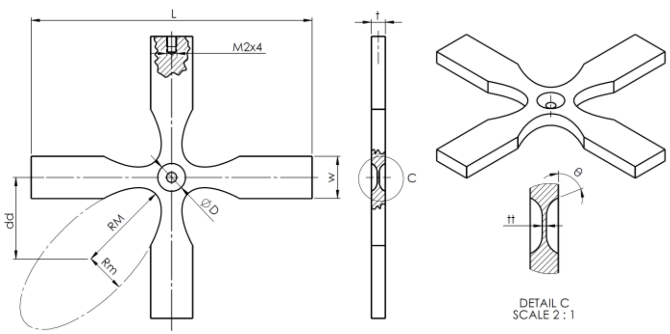
Cruciform Specimens

- Cruciform specimens have been the preferred method for in-plane axial-axial (biaxial) fatigue



Shlyannikov, V., Tumanov, A. & Zakharov, A. 2014. *Theoretical and Applied Fracture Mechanics*, 73, 68-81

Smits, A., Van Hemelrijck, D., Philippidis, T. & Cardon, A. 2006. Composites science and technology, 66, 964-975



Montalvão, D. & Wren, A. 2017. *Heliyon,* 3(11).

Cláudio, R., Reis, L. & Freitas, M. 2014. *Theoretical and Applied Fracture Mechanics,* 73, 82-90

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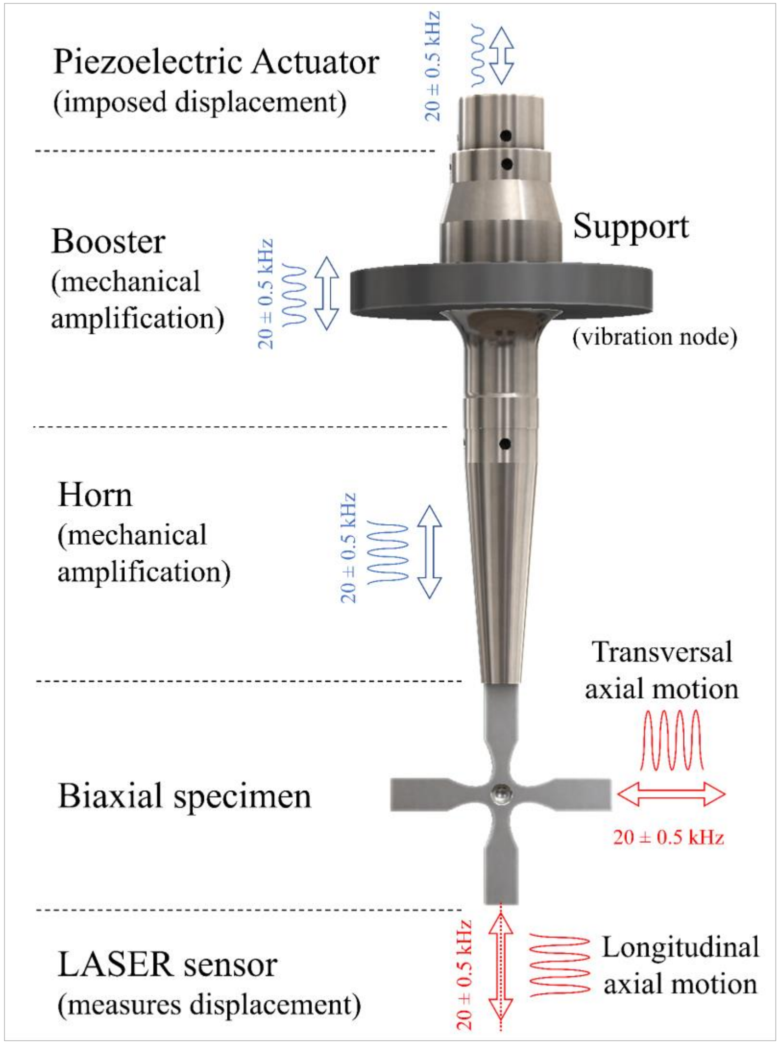
Cruciform Specimens

- Cruciform specimens have two axial mode shapes (in-phase and out-of-phase);
- Different arm lengths can produce different biaxiality ratios:

$$B = \frac{\sigma_x}{\sigma_y}$$

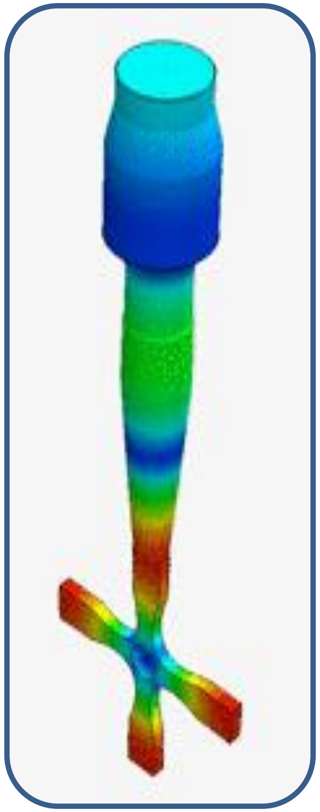
- Only one actuator is needed, as long as the load is applied at any one anti-nodal coordinate, resulting in the stress ratio:

$$R = \frac{\sigma_{x,min}}{\sigma_{x,max}} = \frac{\sigma_{y,min}}{\sigma_{y,max}} = -1$$

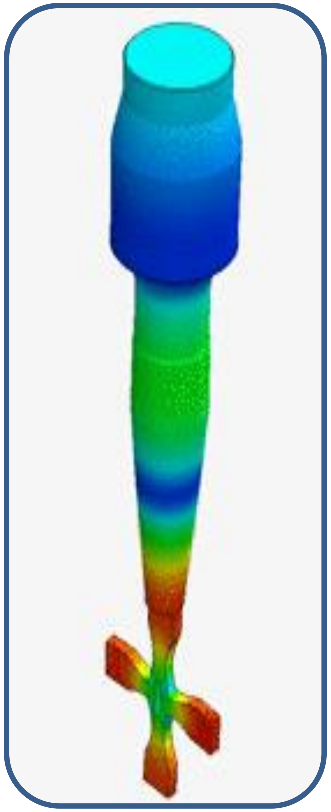


Biaxiality Ratio

Mode TT(in-phase)
$B = 1$

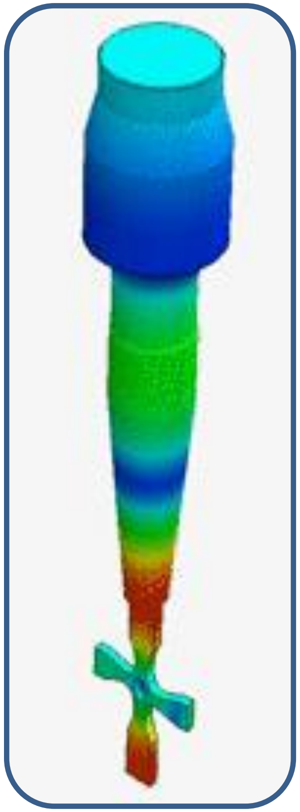


Mode CT (out-of-phase)
$B = -1$



Mode TT (in-phase)
$B > 0 \land B \neq 1$

Mode CT (out-of-phase)
$B < 0 \land B \neq -1$



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Scale Factor

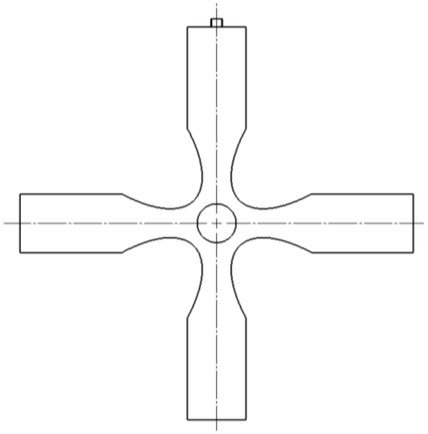
- An existing cruciform specimen like the one from Baptista et al. (2014, 2015) can be enlarged or reduced in size based on (Montalvão and Wren, 2017):

$$s = \frac{f_{UD}}{f_{CD}}$$

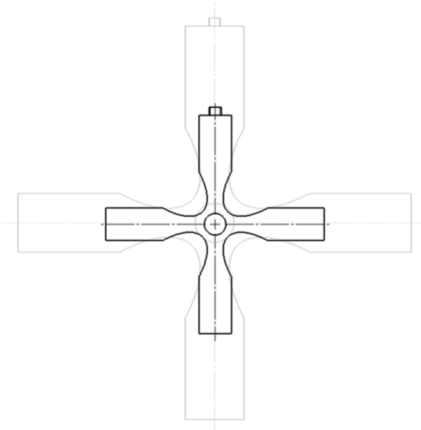
- Where:
  - s is the dimensional scale factor to apply;
  - f_{UD} is the natural frequency of the targeted mode shape (in-phase or out-of-phase) on the uncalibrated design;
  - f_{CD} is the intended new natural frequency of the mode shape on the calibrated design, in this case $f_{CD} = 20kHz$.

Scale Factor

- The scaling principles from Montalvão and Wren (2017) were applied to one specimen from Baptista et al. (2014) to have a TT (in-phase) mode shape at 20 kHz.
- The resulting test specimen is roughly half the size of the original one (*s*=0.5533), but has exactly the same shape.



Original Baptista et al. (2014) model with M6 thread (10 mm thickness)

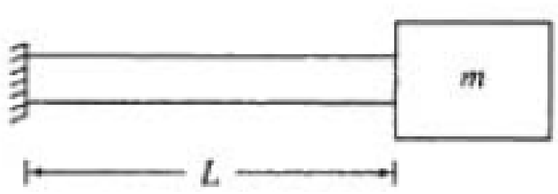


Montalvão and Wren (2017) TT model with M6 thread (5.53 mm thickness)

Change in Arms' lengths/widths

- Another way to change the natural frequency consists in changing the arms lengths/widths, namely at the rectangular tips.

- If one thinks of one arm from the cruciform specimen as a rod under free longitudinal vibration, then the increase in mass at the tip will lead to a reduction in the natural frequency, and vice versa.

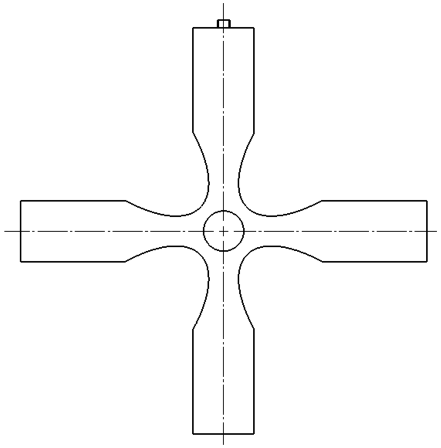


$$f_n = \frac{1}{2\pi}\sqrt{\frac{AE}{mL}}$$

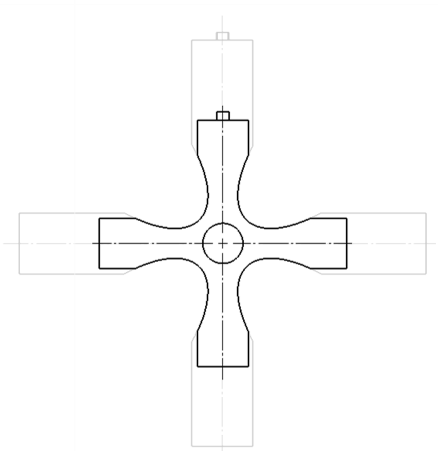
Change in Arms' lengths/width

- One specimen from Baptista et al. (2014) (10 mm thickness) was redesigned to have a TT (in-phase) mode shape at 20 kHz by changing the arms' lengths.

- The resulting test specimen is exactly the same size at the centre, but the arms are shorter and narrower (the thickness is the same).



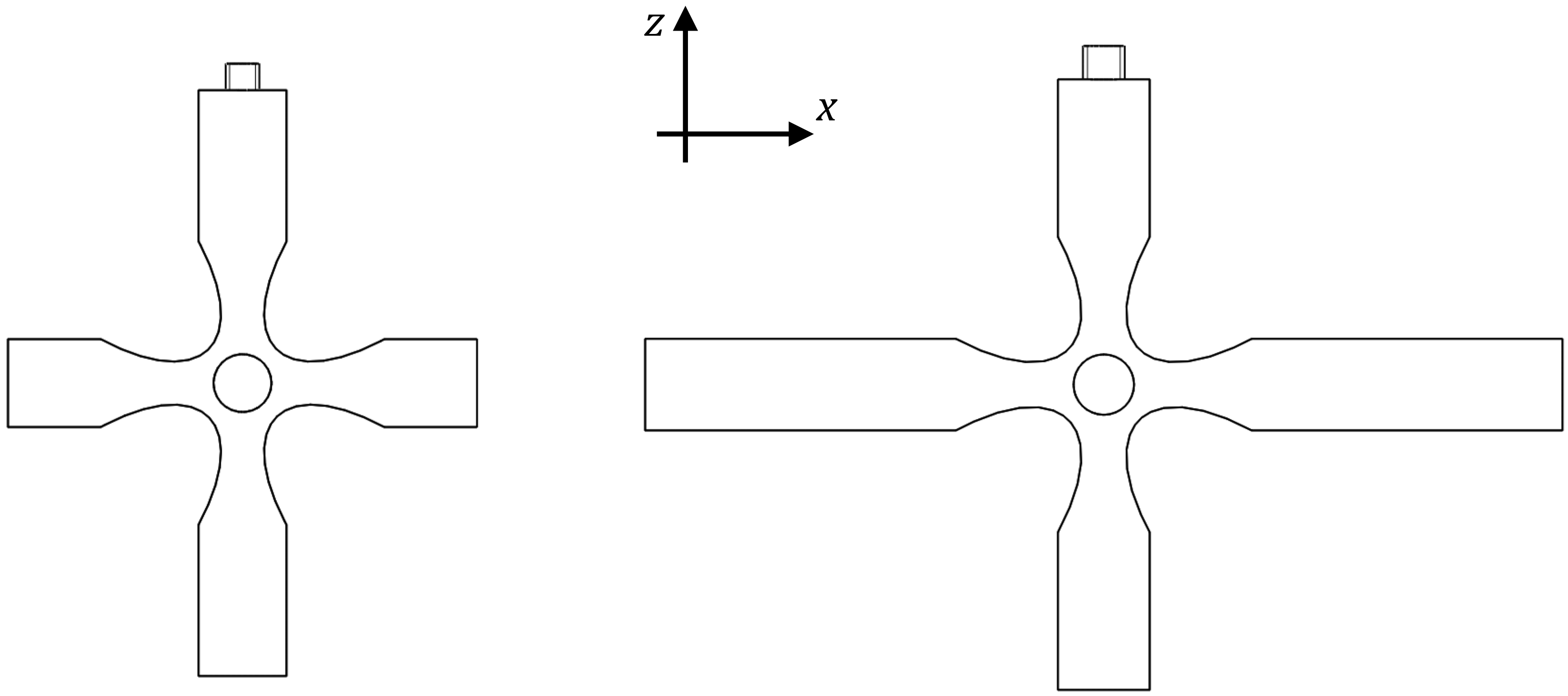
Original Baptista et al. (2014) model with M6 thread (10 mm thickness)



New TT model with M6 thread (10 mm thickness)

Specimens with Non-Unitary Biaxility Ratios

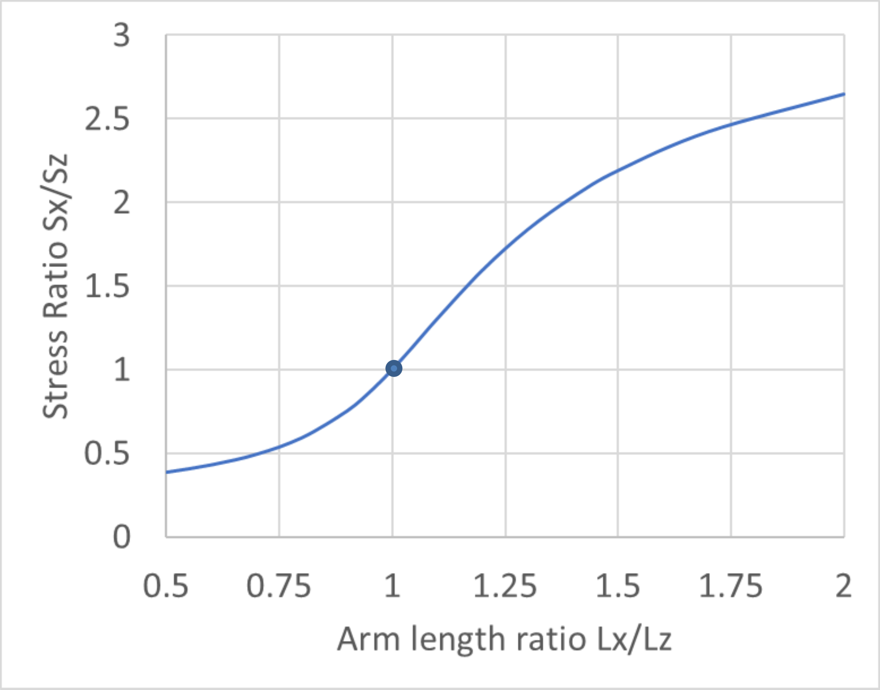
- Specimens with different arm length ratios were designed applying both design principles.

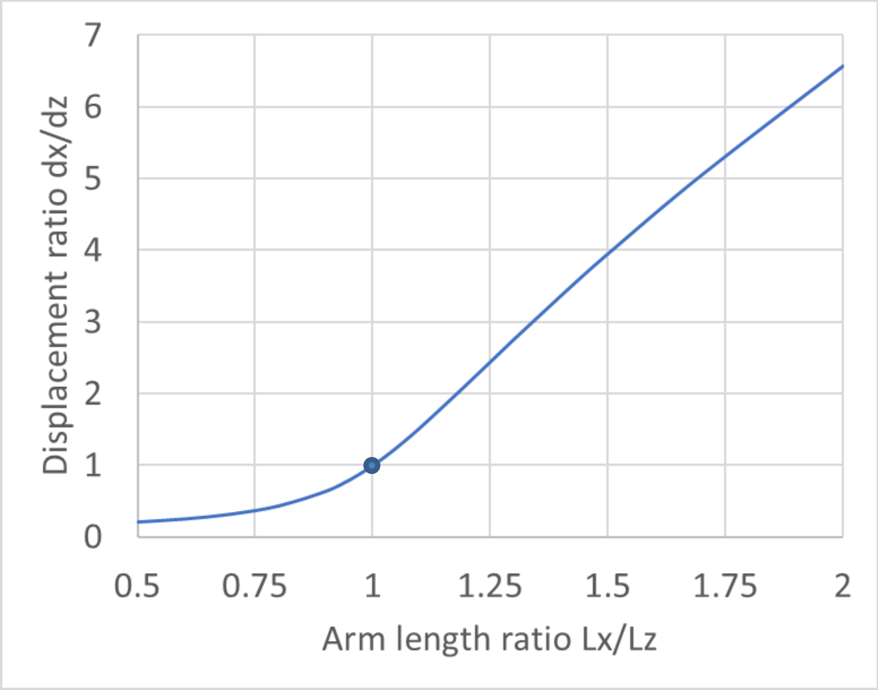


Specimens with Non-Unitary Biaxility Ratios

- Preliminary simulated results (example with CT specimen, absolute values) show that it is possible to achieve different biaxiality ratios.

$$B = \frac{\sigma_x}{\sigma_z}$$





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Preliminary Experimental Results

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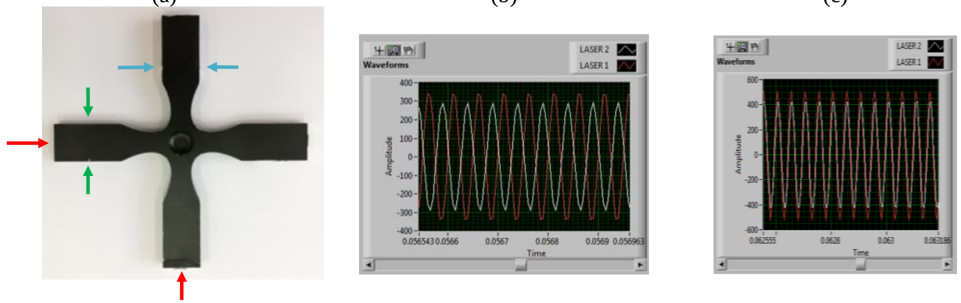
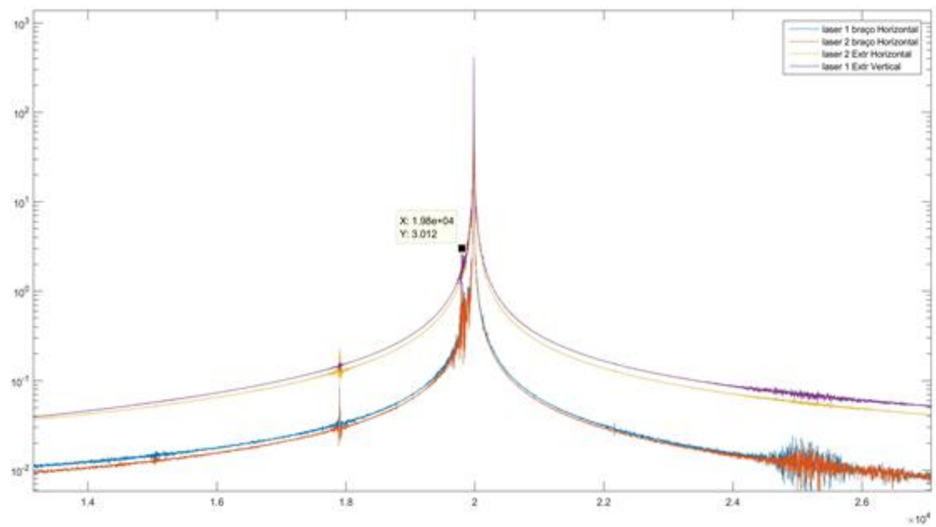
(a) (b) (c)



(a) Photo of one manufactured specimen; (b) deformation waveform at the end of CT in the axial direction (out-of-phase); (c) deformation waveform at the end of TT in the axial direction (in-phase).



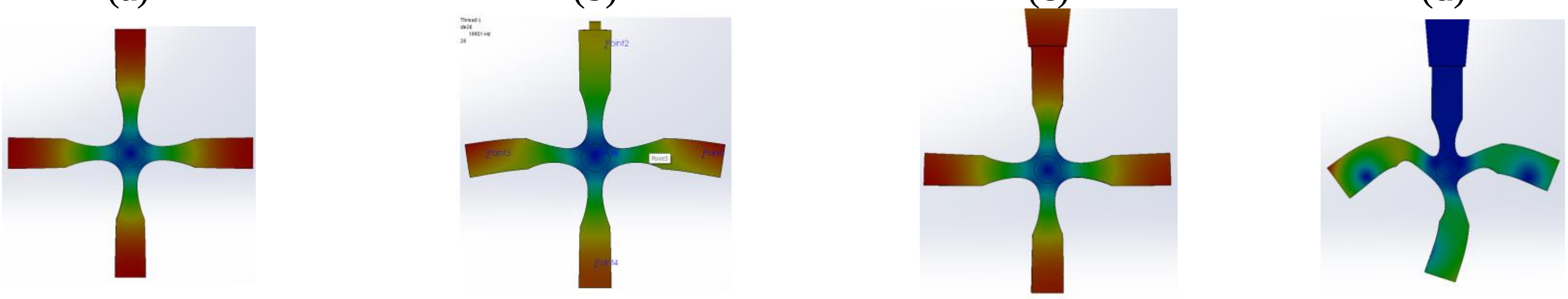
FRFs at: axial direction on the vertical arm's end (purple); axial direction on the horizontal arm's end (yellow); transverse direction at the horizontal arm's sides (blue and orange).

Preliminary Experimental Results

- Experimental results from specimen TT were less predictable than with specimen CT;

- Reasons found include:
  - Manufacturing quality and tolerances;
  - Asymmetry created by the M6 mounting thread – figure (b);
  - Effects from BC's – figure (c);
  - The existence of a mode shape at 19.8 kHz, within the 19.5-20.5 kHz range. This mode shape is not in the range for the CT specimen, but it is for the TT – figure (d)

(a) (b) (c) (d)



(a) ideal (perfectly symmetrical) specimen in free-free vibration at 20 kHz;
(b) specimen with asymmetrical stud on top in free-free vibration at 20 kHz;
(c) assembly of specimen and horn in free-free vibration at 20 kHz;
(d) assembly of specimen and horn in free-free vibration at 19.6 kHz.

Outline

Conclusions

Highlights

- It is possible to 'tune' existing designs of in-plane cruciform specimens to be used in 'conventional' ultrasonic VHCF test machines by following simple principles;

- Only one actuator is needed, as long as connected to an anti-nodal coordinate of the intended mode shape;

- There is a correlation between the biaxiality ratio and the arm length ratios for cruciform specimens used in VHCF.

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Future Work

- Optimise the specimens' design so that there are no 'spurious' mode shapes in the range 19.5-20.5 kHz influencing the results;
- Improve the manufacturing process so that both stresses and biaxiality ratios are as predictable as possible;
- Calibrate the system by running batch experimental tests to validate FEA with stress/strain measurements.

Thank you

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