Identification of elastic properties of a Si-based joint using deformation fields determined by using Digital Image Correlation -Application to the mechanical behaviour of CMC brazed composites-

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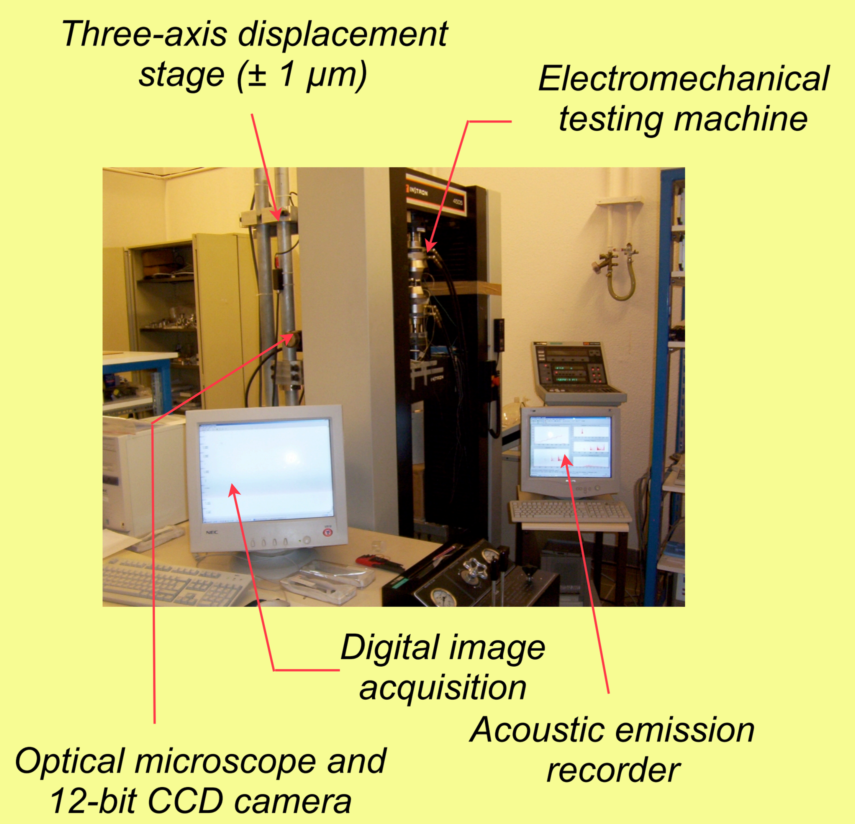
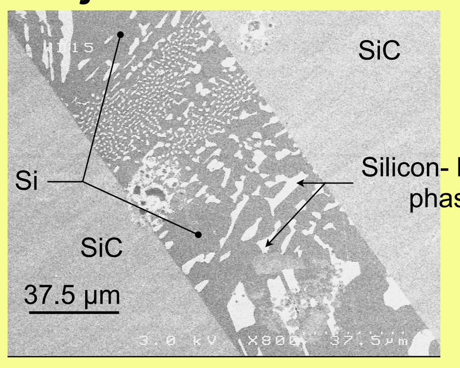
1. Scope

- Specific adhesives are required for ceramics and CMCs: BraSiC [1] (Si-based braze) for SiC-based materials, e.g., monolithic SiC and 2D SiC_f/SiC composites.
- Data on joint materials are required for design purposes and failure predictions [2].
- Determination of joint properties is generally difficult because of the size and volume of available samples (less than 100 µm thick).
- This study aims at extracting elastic properties (E_{joint} and ν_{joint}) from strain fields determined using Digital Image Correlation [3] with a view to analyzing brazed composites structures.

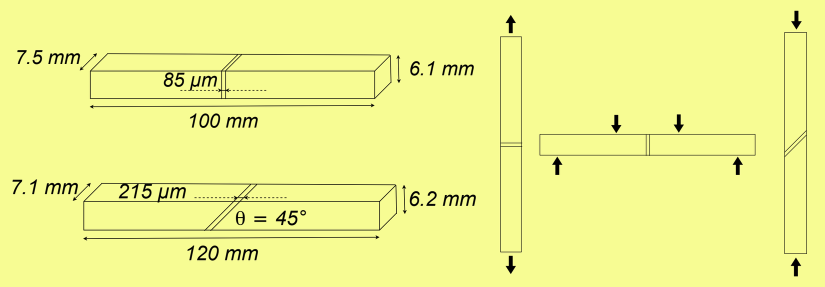
2. Experimental procedure & materials



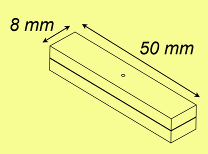
- BraSiC joint microstructure



- SiC brazed specimens & tests

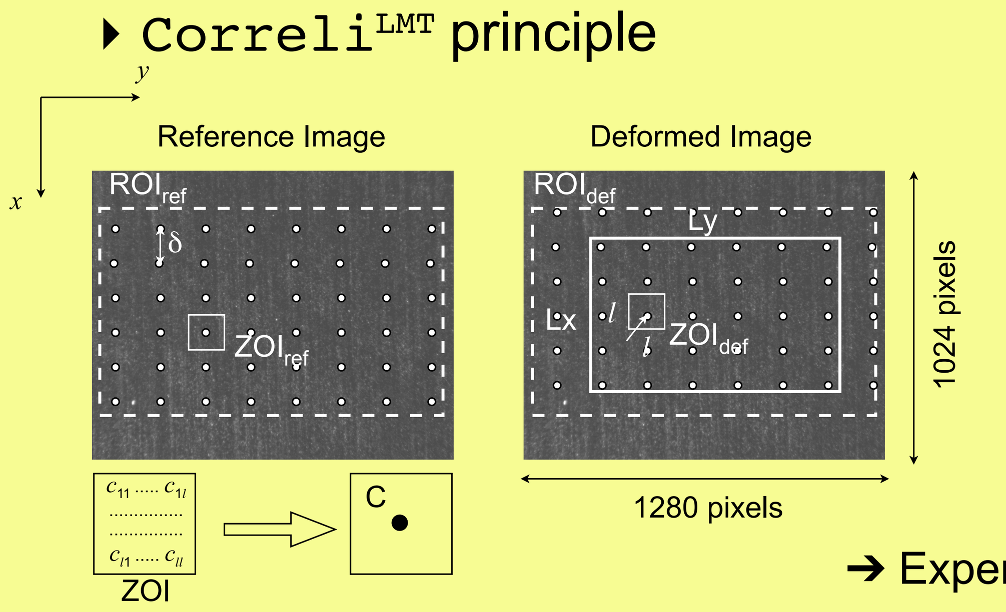


- 2D SiC_f/SiC: 4-point bending



3. Strain measurements: Digital Image Correlation technique

- `Correli^LMT` principle



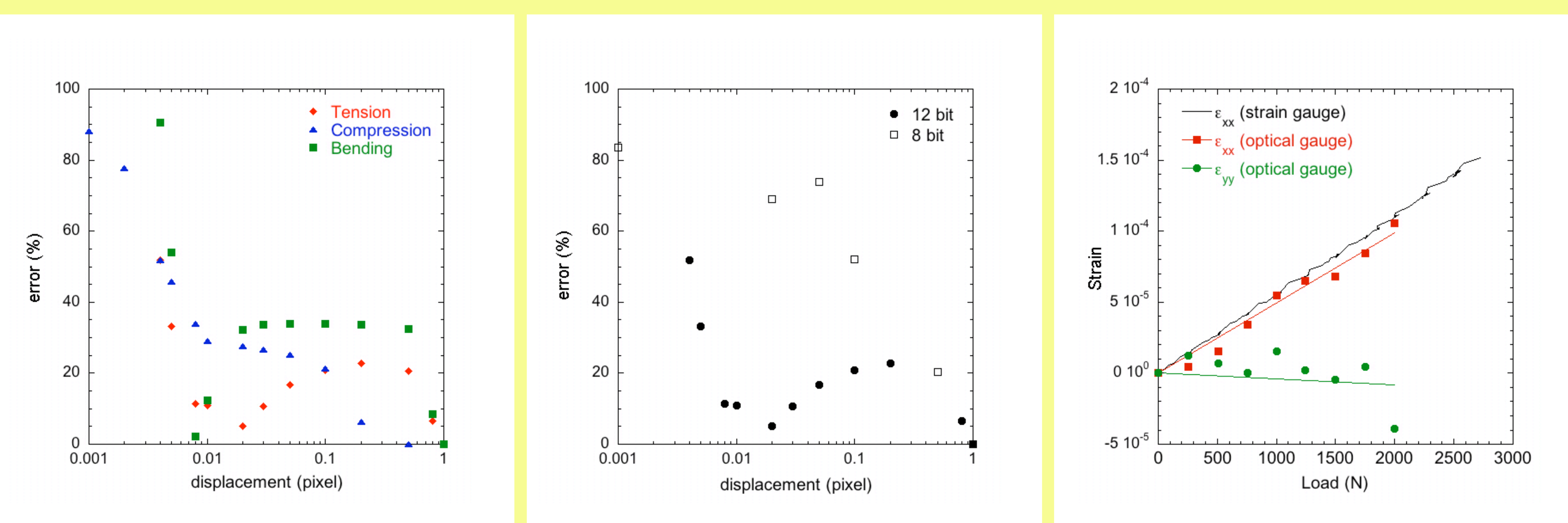
ROI: region of interest
ZOI: zone of interest
c_{ij}: gray level
C: center of ZOI

Lx, Ly: optical gauge size

➔ Experimental strain tensor $\underline{\underline{\epsilon}}_{exp.}$

- Measurements at high magnification

➔ An error is calculated by comparing DIC displacement results of an image numerically shifted by a constant vector and the prescribed displacement.



(a) Average error for different images (magnification: 1 pixel = 0.33 µm)

(b) Average error *vs.* image coding (magnification: 1 pixel = 0.33 µm)

(c) Comparison of optical and strain gauge measurements: *rms* error = 9×10^{-6} (SiC beam tested in uniaxial tension)

References

[1] F. Moret *et al.*, *Brazing of SiC based materials using the BraSiC process chemical and thermal application,* Int. Conf. on joining of advanced materials, 1998.
[2] M. Singh *et al.*, *Design, fabrication, and testing of ceramic joints for high temperature SiC/SiC composites*, J. of Eng. for Gas Turbines and Power, **123**, pp. 288–292, 2001.
[3] F. Hild *et al.*, *Multiscale displacement field measurements of compressed mineral-wool samples by digital image correlation*, Appl. Optics, **41**(2), pp. 6815–6827, 2002.
[4] S. Pompidou *et al.* , *Model of deviation of cracks at interfaces/interphases based on the Cook and Gordon's mechanism*, HTCMC-5, In press, 2004.

4. Extraction of elastic properties

- Equations of strains

➔ Transverse displacements in the BraSiC joint are dictated by Poisson effect in the SiC substrate

- *Tension (T):*

$$\begin{cases} U_{y,\mathrm{joint}} = U_{y,\mathrm{SiC}} \\ U_{z,\mathrm{joint}} = U_{z,\mathrm{SiC}} \end{cases} \Rightarrow \epsilon^{(T)}_{xx,\mathrm{joint}} = \frac{F}{S}\left[\frac{1}{E_{\mathrm{joint}}} - \frac{2\nu_{\mathrm{joint}}}{1-\nu_{\mathrm{joint}}}\left(\frac{\nu_{\mathrm{joint}}}{E_{\mathrm{joint}}} - \frac{\nu_{\mathrm{SiC}}}{E_{\mathrm{SiC}}}\right)\right]$$

- *Off-axis compression (C45):*

$$U_{z,\mathrm{joint}} = U_{z,\mathrm{SiC}} \Rightarrow \begin{cases} \epsilon^{(C45)}_{x'x',\mathrm{joint}} + \frac{\nu_{\mathrm{joint}}}{1-\nu_{\mathrm{joint}}}\epsilon^{(C45)}_{y'y',\mathrm{joint}} = \frac{F}{2S}\left[\frac{1}{E_{\mathrm{joint}}} - \frac{2\nu_{\mathrm{joint}}}{1-\nu_{\mathrm{joint}}}\left(\frac{\nu_{\mathrm{joint}}}{E_{\mathrm{joint}}} - \frac{\nu_{\mathrm{SiC}}}{E_{\mathrm{SiC}}}\right)\right] \\ \epsilon^{(C45)}_{x'y',\mathrm{joint}} = \frac{1+\nu_{\mathrm{joint}}}{E_{\mathrm{joint}}}\frac{F}{2S} \end{cases}$$

- *Cost function (J_{3D}):*

$$\mathcal{J}_{3D}(E_{\mathrm{joint}},\nu_{\mathrm{joint}}) = \sum_F\left[\epsilon^{(T)}_{xx,\mathrm{exp.}}(F) - \epsilon^{(T)}_{xx}(F)\right]^2 + \sum_F\left[\left(\epsilon^{(C45)}_{x'x',\mathrm{exp.}}(F) + \frac{\nu_{\mathrm{joint}}}{1-\nu_{\mathrm{joint}}}\epsilon^{(C45)}_{y'y',\mathrm{exp.}}(F)\right) - \left(\epsilon^{(C45)}_{x'x'}(F) + \frac{\nu_{\mathrm{joint}}}{1-\nu_{\mathrm{joint}}}\epsilon^{(C45)}_{y'y'}(F)\right)\right]^2 + \sum_F\left[\epsilon^{(C45)}_{x'y',\mathrm{exp.}}(F) - \epsilon^{(C45)}_{x'y'}(F)\right]^2$$

- FEM computations of strains

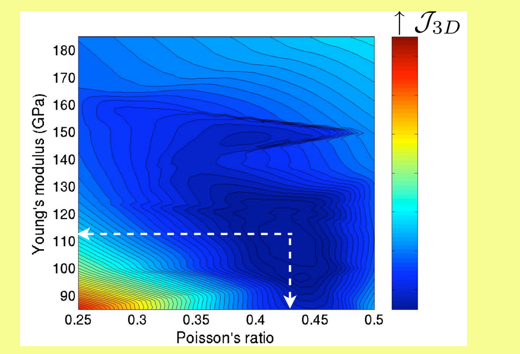
➔ 4-point bending finite element mesh (`MSC.Marc`) is identical to correlation grid (`Correli^LMT`)

- *Cost function (J_{4By}):*

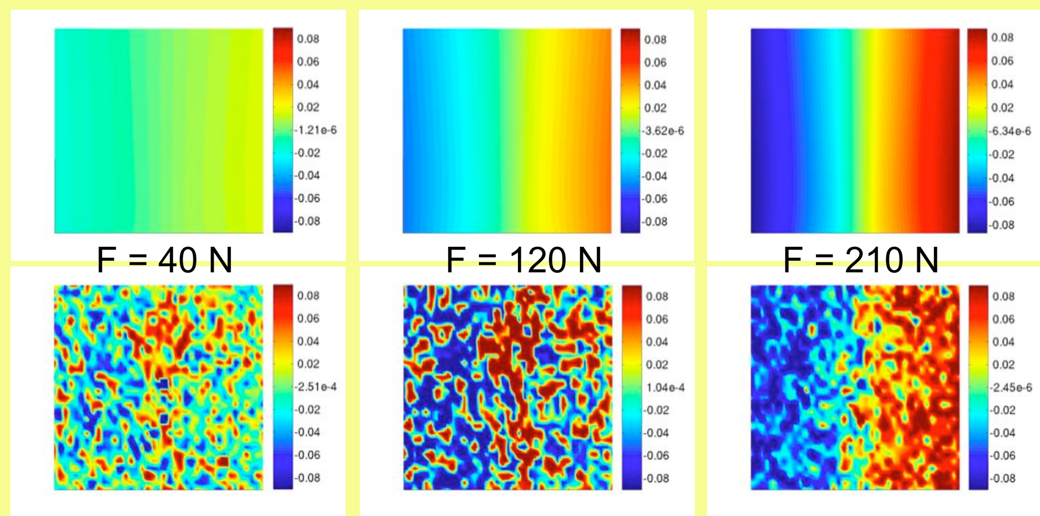
$$\mathcal{J}_{4By}(E_{\mathrm{joint}},\nu_{\mathrm{joint}}) = \sum_F\sum_{\{x,y\}}\left[\mathbf{U}_{y,\mathrm{exp.}}(x,y,F) - \mathbf{U}_{y,\mathrm{FEM}}\left(x,y,F,\frac{E_{\mathrm{joint}}}{E_{\mathrm{SiC}}},\nu_{\mathrm{joint}},\nu_{\mathrm{SiC}}\right)\right]^2$$

5. Identification results

Test	Ref.	E_{joint} (GPa)	ν_{joint}
Tension and compression	J_{3D}	113 ± 18	0.42 ± 0.05
Bending	J_{4By}	166 ± 35	0.43 ± 0.05



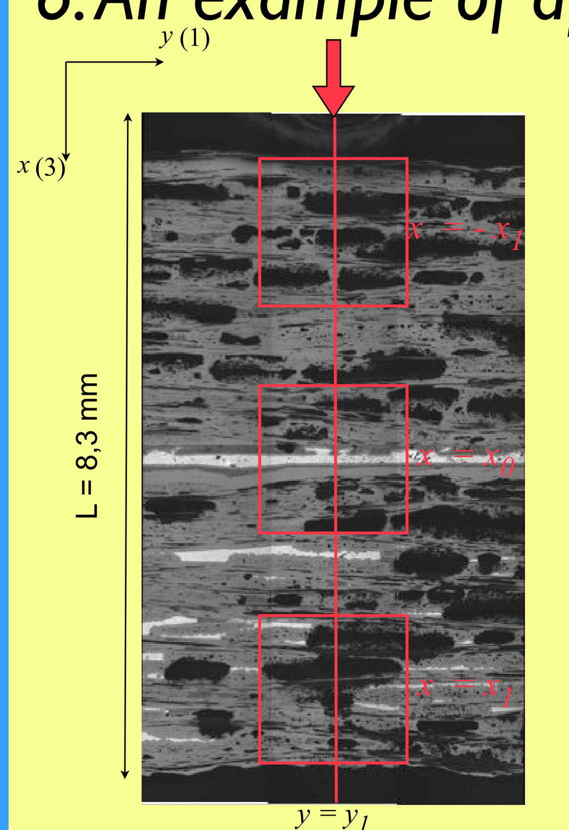
Change of J_{3D} with E_{joint} and ν_{joint}



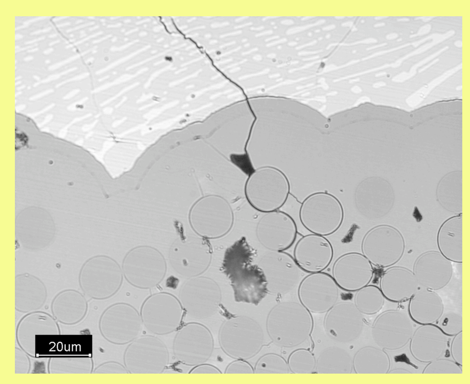
Computed U_y displacement field (pixels)
E_{joint} = 150 GPa and ν_{joint} = 0.4

Experimental U_y displacement field (pixels)

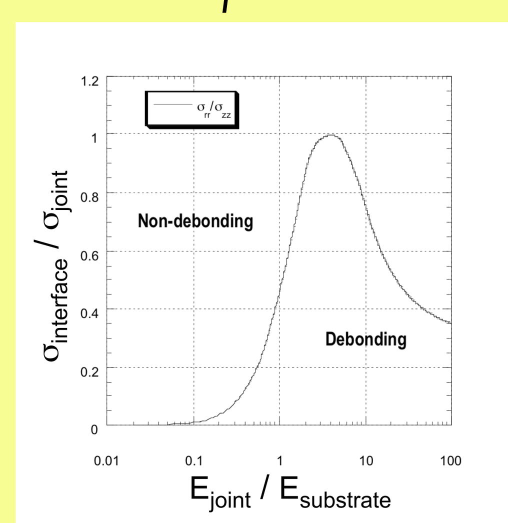
6. An example of application to a brazed 2D SiC_f/SiC



(a) in situ brazed 2D SiC/SiC visualization



(b) SEM micrograph of BraSiC joint / CMC substrate interface ($x = x_0$)



(c) crack arrest capability condition for debonding [4]

Elastic properties

	Young's modulus, E (GPa)	Failure stress, σ^R (MPa)
SiC	420	-
BraSiC	153	80*

$$\frac{E_{\mathrm{BraSiC}}}{E_{\mathrm{SiC}}} = 0.36 \Rightarrow \frac{\sigma^R_{\mathrm{BraSiC/SiC}}}{\sigma^R_{\mathrm{BraSiC}}} = 0.15$$

current situation: $\sigma^R_{\mathrm{BraSiC/SiC}} > 12$ MPa

debonding: $\sigma^R_{\mathrm{BraSiC/SiC}} < 12$ MPa

* determined in a companion study

7. Summary

- Potential of the DIC technique for strain analysis has been demonstrated in extreme conditions: high magnification (1 pixel = 0.33 µm), low strain level ($<10^{-4}$), small amount of material.
- Comparison of strain fields determined using DIC method and theory or finite element computations allow for *in situ* identification of elastic properties of the BraSiC material.
- Joint properties can be used to analyze and understand the mechanical behaviour and failure of CMC composite brazed structures.