Validation of a multimodal set-up for the study of zirconium alloys claddings’ behaviour under simulated LOCA conditions

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Abstract
In a previous paper, Campello et al. presented a combined experimental/numerical approach to identify the creep behaviour of as-fabricated Zircaloy-4 claddings under simulated LOCA conditions. The current paper deals with the uncertainties and errors estimation of the two key methods used to measure the thermal and kinematic full fields during the creep tests: near infrared thermography (NIRT) and two-dimensional digital image correlation (2D-DIC). The NIRT uncertainties are evaluated as 0.7% of the actual temperature. They are mainly due to the thermocouple measurements used to calibrate the radiometric model of the NIRT. A combined 2D-DIC/edge detection approach is proposed to quantify the error related to 2D-DIC when measuring the ballooning of the tubular specimen. The 2D-DIC error is evaluated as 0.1% of the actual equivalent strain even for ballooning inducing a radius increase of 20%.

KEYWORDS
digital image correlation, measurement error, near infra-red thermography, uncertainties

1 INTRODUCTION
During its operating life, the water in the primary loop of a pressurized water reactor (PWR) is pressurized at 155 bar and heated by fuel pellet stacks up to 320 °C. The fuel pellets are inserted in claddings assembled in a 27 × 27 bundle. They are made of zirconium alloys. The claddings are designed to be the first safety barrier in French PWR. In operating life cycle, filling gas and fission gas release also internally pressurizes the fuel claddings. A loss of coolant accident scenario (LOCA) postulates a breach in the primary loop system. The water is depressurized limiting the coolant efficiency. Both the water and the fuel rods are then heated, and the claddings are loaded with internal pressure. It can lead to rod ballooning and, potentially, to rod bursting. Reflooding the nuclear core reactor interrupts this accidental sequence. The fuel rod ballooning can impede the core cooling capacity by flow blockage. The PERFROI project, detailed in Repetto et al.,[1] aims to study this complex scenario.

Campello et al.[2] presented the global picture of the coupled experimental/numerical approach to identify the steady-state creep behaviour of as-fabricated Zircaloy-4 claddings under simulated LOCA conditions. The study targeted thermal–mechanical conditions corresponding to the lower bound of phase transformation from α towards α + β where several creep mechanisms are potentially activated (i.e., temperatures between 750 and 850 °C, stress between 7 and 100 MPa). The approach is validated in a previous paper.[3]
45 MPa). Figure 1 summarizes the methodology. The experimental set-up enabled the internal pressurization of an unirradiated Zircaloy-4 cladding by stage. An induction heating system induced an axisymmetric but axially heterogeneous thermal loading. Thermal and kinematic surface fields were monitored by optical full-field measurement methods during the ballooning. Hence, several thermal–mechanical conditions were studied during each experiment. The parameters of local Norton power laws were identified by finite element model updating by minimizing the difference between experimentally measured and calculated secondary creep strain rates. The approach enables a substantial reduction of the test matrix and associated discrepancies compared with other traditional set-up.3–9

Since the 1990s, non-contact techniques in both kinematic and thermal fields measurements have been improved. Digital image correlation10,11 and edge detection12 are frequently used for strain measurements in experimental mechanics. Recent improvements in algorithms (global approaches with finite element basis,13 multigrid solver,14 integrated-DIC,15 FEMU16) allow for material behaviour identification as proposed by Réthoré et al.17

Infrared (IR) cameras are now commonly used in the field of experimental mechanics for computing thermal fields as demonstrated in Maynadier et al.18 with infrared image correlation or in Chrysochoos et al.19 to explore the energy balance associated with high-cycle fatigue. The IR cameras remain very expensive compared to standard cameras and do not allow for high spatial resolution. In order to avoid these drawbacks, the near infrared (NIR) measurement methods have also been developed.20–22 Their use (for the steel industry,23 for example, or a hot specimen in an aggressive environment24) has been greatly improved in the recent years.

This paper focuses on the validation of the experimental set-up detailed in Campello et al.2 and more specifically on uncertainties and error quantification of the two key optical full-field measurement methods applied in the test configuration: NIR thermography (NIRT) and two-dimensional digital image correlation (2D-DIC).

First, the experimental set-up is recalled. The post-processing of NIRT and 2D-DIC are detailed. The NIRT protocol is then assessed. Finally, error made by the use of 2D-DIC to analyse the ballooning of the tubular specimen is then quantified by the comparison with a more accurate combined edge detection/2D-DIC method.

2 | EXPERIMENTAL SET-UP

The homemade experimental set-up is depicted in Figure 2. The set-up enabled a combined biaxial compression/internal pressurisation loading of the tubular Zircaloy-4 sample. A local thermal loading was applied by induction heating. The specimen was surrounded by an enclosure to maintain an inert environment during the test. Windows were distributed over the circumference in order to enable the thermal and kinematic optical full-field measurements. Details on the set-up are given in the following.

![Figure 1](image-url)  
**FIGURE 1** Summary of the identification process detailed in Campello et al.2
2.1 | Material

The material was stress relieved annealed (SRA) Zr-4 manufactured by CEZUS. The claddings in service have a 9.5-mm outer diameter, a 0.57-mm thickness, and are 4 m long. The claddings were cut by an electro discharge machining into 90 mm long samples.

2.2 | Specimen preparation

High temperature image correlation measurement requires meticulous preparation. A black undercoating (ULFALUX thermo-coating 1,200 °C) was sprayed on the outer specimen surface. A white speckle was then applied using BND painting. The speckle size ranged from 10 to 120 μm (usual pixel size of the optical measurement was 9 μm). A degreaser was used for removing the painting along the z direction at two circumferential positions separated by a 180 °C angle. Three type K thermocouples (in Figure 2) were spot-welded in each of the painting free azimuth. The two wires of each thermocouple were separated using a single hole round ceramic insulator (SH-1-24). The diameter of the wires (CAB KX 04) was 0.078 mm to lower the intrusive effect of the thermocouples.

2.3 | Set-up

The test specimen was connected (in Figure 2) onto a Schenck 10 kN servo-hydraulic tensile machine (1, 2) using custom grips (3) designed by Tardif et al.[25] An enclosure (5) was fitted to the machine for working in an inert environment. Argon flushing (6, 7) was kept during the entire test with a constant flow.

A 6-kW induction generator (CELES) control the tube heating. The regulation was enclosed in a K-type thermocouple (4) measurement loop. The coils (8, 12) let a visual access to the warmest part of the specimen. The height of the region of interest (ROI, 13) is \( z_0 = 20 \text{ mm} \).

A proportional pressure regulator (IMF) linked to an argon cylinder controlled the pressurization (8) of the specimen. Two pressure gages (P8AP from HBM, 9) mounted onto the upper and lower grips measured the internal pressure. The pressure induced bottom–end effect was mechanically compensated by an axial compressive force \( F \) inducing a uniaxial hoop loading.

Five sapphire glasses were distributed over the enclosure to enable optical monitoring of the ROI by four digital cameras (10) equipped with 200 mm macro optics (NIK AF MICRO-NIKKOR 200MM F/4 D IF-ED).

Two 12 MP CMOS cameras (VC-12MC-M65E0-FM) performed the 2D-DIC on the tubular specimen surface at temperatures ranging from 750 to 850 °C. At such temperatures, the cladding surface emits radiation in the near infrared (NIR) spectral range. To get rid of incandescence, blue LED rings (CCS LDR2-70-BL2, 470 nm, 11) were set up above and below
the induction coils. The LED rings were pulsing blue light. Band-pass filters (MIDOPT FIL BP470/62) centred on 470 nm (useful range: 425–495 nm) were fitted to the 12 MP cameras used for DIC as proposed by Pan et al.\textsuperscript{[26,27]}

Additionally, two 16 MP CCD cameras (Prosilica GE4900) shot images without any filtering when the blue lights were put off for NIRT. This way, only the light emitted by the specimen surface radiation was captured.

3 | DEDICATED TEST PROCEDURES FOR ERRORS AND UNCERTAINTIES ASSESSMENT OF THE FULL FIELD MEASUREMENTS

3.1 | Test procedure Test A for NIRT assessment

A thermal cycling test was performed on a cladding at three different temperature levels. The thermal loading history is plotted versus time in Figure 3. The cladding was first heated then three thermal cycles were successively performed and had actual both heating and cooling rates of 2.2°C s\textsuperscript{−1}. Argon flushing was kept during the whole test. The force was also set to zero. Note that the dedicated test conditions were aggravating compared with those in Campello et al.\textsuperscript{[2]} (isothermal creep). Radiometric models were calibrated for each cycle during its own heating part. A Prosilica GE4900 camera shot pictures at a 1 Hz frequency, with a f/11 aperture.

The test procedure will be referred as Test A in the following.

3.2 | Test procedure Test B for 2D-DIC assessment

The same test procedure as in Campello et al.\textsuperscript{[2]} was chosen to assess the 2D-DIC. The test procedure is shown in Figure 4. At the beginning of the test, the enclosure was filled with argon gas and flushing was kept on during the whole test. A controlled axial force of 0 N was set during the 3°C s\textsuperscript{−1} thermal ramp up to a first plateau. The first plateau enabled the evacuation of the smoke induced by the heating of the paint. Then the thermal ramp was started again up to the set point (795 °C). Then, the mechanical loading was applied by the combination of the compressive force and the internal pressure. Three mechanical plateaus were set so that the J2 equivalent strain reaches at least 4% at each plateau.

The cameras configuration is shown in Figure 5a. Images shot by Cam 1 and Cam 2 (see Figure 5b,c) were respectively dedicated to 2D-DIC and edge detection. This additional digital image analysis provided the out-of-plane displacement due to the tube ballooning.

The test procedure will be referred as Test B in the following.

4 | POST-PROCESSING METHODS

4.1 | Near infrared thermography

The design of the set-up was chosen to apply a 20 °C heterogeneous thermal axial distribution in the ROI. This temperature distribution had a strong impact on the creep strain rates as can be seen in Figure 1. Hence, full-field thermal

![Figure 3](https://example.com/figure3.png)

**FIGURE 3** Procedure Test A: Near infrared thermography assessment
measurement must be preferred to local measurements such as type K thermocouples. Near-infrared thermography is well suitable to the thermal measurement of metal at temperature higher than 750 °C as it can be set up with a cheap CCD or CMOS camera. These cameras types have a higher spatial resolution than usual infrared cameras. The calibration of the radiometric model requires a reference temperature measurement provided by type K thermocouples.

4.1.1 Principle of radiometric measurements

Any surface emits radiation (with a wavelength $\lambda$) at a given temperature $T$. The surface is characterized by an emissivity ($0 \leq \varepsilon(\lambda) \leq 1$) depending on the radiation wavelength. The total emittance $\phi_{\lambda,T}$ of this surface is estimated using its emissivity and the Planck law according to Equation (1). The Planck law provides the total emittance of a black-body $\phi_{\lambda,T}^{0}$ in a hemisphere using the Planck constant $h$, the speed of light $c$ and the Boltzman constant $k$. Note that the emissivity of a black-body is equal to 1.

![FIGURE 4](image-url)

**FIGURE 4** Procedure Test B: 2D-DIC assessment. The dashed black lines are the setting point. The plain lines are the measurements.

![FIGURE 5](image-url)

**FIGURE 5** Procedure Test B. (a) Top view of the experimental set-up—position of the cameras, (b) picture of CAM1, 2D-DIC performed inside the white box, data extracted along the yellow line, (c) picture of CAM2, edge detection performed along the white line, edge in the initial configuration.
\[ \phi_{\lambda,T}^r = \varepsilon(\lambda) \phi_e(\lambda, T) = \varepsilon(\lambda) \frac{2hc^2\lambda^{-5}}{\exp\left(\frac{hc}{k\lambda T}\right) - 1} \]  

(1)

Meriaudeau et al.\cite{20} detailed the concept of a radiation thermometer (RT). A radiometer senses the radiant flux of a target. This flux is the sum of the emitted flux \( \phi_{\lambda,T}^e \) and a reflected flux \( \phi_{\lambda,T}^{\text{ref}} \) as detailed in Equation (2).

\[ \phi_{\lambda,T}^{\text{tot}} = \phi_{\lambda,T}^e + \phi_{\lambda,T}^{\text{ref}} = \varepsilon(\lambda) I^0(\lambda, T) + [1 - \varepsilon(\lambda)] \phi_{\text{rec}}. \]  

(2)

\( \phi_{\lambda,T}^{\text{ref}} \) comes from the flux \( \phi_{\lambda,T}^{\text{rec}} \) that the surface receives from the surroundings. A single detector (gain \( K \) and exposure time \( t_i \)) of a digital radiometer is now considered. Its digital level output \( I \) is written in Equation (3) using the spectral response of the optical system \( W(\lambda) \) and the total radiant flux of the target \( \phi_{\lambda,T}^{\text{tot}} \). Finally, the radiometric model gives the relation between the Temperature and the digital level recorded by the camera.

\[ I = t_i \int W(\lambda) \phi_{\lambda,T}^{\text{tot}} d\lambda. \]  

(3)

4.1.2 Calibration of the radiometric model during the heating step

In the proposed set-up, induction heating induces negligible environmental heating (enclosure, argon, ...). There was no other hot object in the surroundings. Moreover, the tubular geometry cannot lead to the reflection of the specimen itself. The calculation of \( \phi_{\lambda,T}^{\text{tot}} \) was simplified to the emitted flux assuming that \( \phi_{\lambda,T}^{\text{rec}} = 0 \).

The spectral response \( W(\lambda) \) of the optical image acquisition chain combined the argon’s, the sapphire’s and the objectives’ transmittances (respectively \( \tau_{\text{ar}}(\lambda), \tau_{\text{sap}}(\lambda), \tau_{\text{obj}}(\lambda) \)), and the detector’s quantum efficiency \( \eta_{\text{det}}(\lambda) \), as written in Equation (4).

\[ W(\lambda) = \tau_{\text{ar}}(\lambda) \tau_{\text{sap}}(\lambda) \tau_{\text{obj}}(\lambda) \eta_{\text{det}}(\lambda). \]  

(4)

A review of several calibration methods can be found in Rotrou et al.\cite{28} The radiometric model was calibrated using the thermocouples local measurements during the heating phase of each test. This method is particularly well adapted since the spectral response \( W(\lambda) \) is not known. Note that the thermocouples and the NIRT acquisition were triggered at exactly the same time.

Figure 6 shows five pictures shot during the end of the heating. The thermocouples are located on the left side of the digital images. Three digital thermocouples were numerically built, close to actual Tc. They are depicted by the blue, red, and green boxes in Figure 6. An averaged grey level intensity \( I_{\text{eq}} \) was calculated into these boxes to be correlated to the associated thermocouple measurements.

Inside the digital thermocouples, the emissivity of the surface is heterogeneous because of the speckle applied onto the specimen. In order to achieve a good sensitivity to the radiation emitted by the surface, only the brightest 30% pixel intensities were averaged for computing \( I_{\text{eq}} \).

![Figure 6](attachment:image.png)
As detailed by Rotrou,[29] the concept of equivalent wavelength \( \lambda_{eq} \) is useful to analytically assess a measured temperature \( T_{mes} \) based on a digital level intensity \( I_{eq} \). The chosen radiometric model is detailed in Equation (5). The parameters \( K_1 \) and \( K_2 \) of Equation (6) were calibrated using the correlation between digital and real thermocouple measurements.

\[
T_{mes} = \frac{K_1}{\ln\left(\frac{K_2}{I_{eq}} + 1\right)}.
\]  

(5)

\[
K_1 = \frac{h.c}{k.\lambda_{eq}} \quad K_2 = 2.\varepsilon(\lambda_{eq}).c.\lambda_{eq}^{-4}.W(\lambda_{eq}).t_1.
\]  

(6)

The calibration was performed using a least squares minimization between temperature \( T_{mes} \) and averaged grey level intensity \( I_{eq} \) data.

### 4.2 Kinematic full-field measurements

In Campello et al.,[2] 2D-DIC measured the creep rate distribution along the yellow line in front of the cameras as depicted in Figure 5b. The ROI (white box in Figure 5b) was discretized by isotropic linear Q4 finite elements. Their size was 30 × 30 px². The ill-defined problem of the optical flow conservation was solved using a non-linear least squares method relying on a finite element basis. Axial and hoop displacements were extracted from 2D-DIC results at the mesh nodes. From the gradient tensors, logarithmic strains were computed. True Von Mises equivalent creep strain was calculated over the sample surface assuming material incompressibility (Equation (7)) during high temperature creep.

\[
\varepsilon_{vp}^{zz} + \varepsilon_{vp}^{rr} + \varepsilon_{vp}^{\theta\theta} = 0
\]

\[
\varepsilon_{eq}^{pp} = \left[\frac{2}{3}(\varepsilon_{vp}^{zz} + \varepsilon_{vp}^{rr} + \varepsilon_{vp}^{\theta\theta})\right]^\frac{1}{2}
\]  

(7)

In Test B, a coupled edge detection/2D-DIC approach was used to quantify the error made by the 2D-DIC during the ballooning of the specimen. The edge detection method is based on the analysis of the grey level gradient of an image. Recent improvements allow for a subpixel definition of a curvilinear shape position and low CPU time calculations.[12] The reference line (i.e., edge before loading) was defined between \(-8\) mm and \(+8\) mm of the eulerian variable \( Z \) (see Figure 5c). It was discretized by 30 elements associated with a B-spline shape functions basis.

The software used to perform 2D-DIC[30] and edge detection[12] is called Ufreckles. It has been developed by Réthoré.

The coupled edge detection/2D-DIC approach needs two steps. The first step allows for calibrating the intrinsic parameters of the optical system used for 2D-DIC. Then the displacements and strain measured by 2D-DIC are corrected by the out-of-plane displacements measured by the edge detection measurement.

#### 4.2.1 Calibration of the optical model

Several authors[31,32] reported the effect of out-of-plane motion on in-plane displacements. These displacements can be corrected as proposed by Felipe-Sesé et al. in[33] using the dedicated experiment detailed in Figure 7. The test aimed to calibrate the initial distance between the object and the optical system \( d_0 \), and the position of the intersection between the optical axis (OA) and the detector plane \( O(-d_i, x_c, y_c) \).

Cam 1 (i.e. Figure 5a) was mounted onto a sliding calliper and was translated in order to induce in-plane displacements \( u_r \). When sliding the calliper, the 2D-DIC measures the virtual displacement of the measured point M in the detector plane \((x_2-x_1) \overrightarrow{x} + (y_2-y_1) \overrightarrow{y})\). This virtual displacement depends on three parameters \( d_0, x_c \) and \( y_c \). Considering a linearized optical system model, the virtual displacement can be deduced from system Equation (8).

\[
d_0.(x_1-x_c) = (d_0-u_r).(x_2-x_c)
\]

\[
d_0.(y_1-y_c) = (d_0-u_r).(y_2-y_c)
\]  

(8)
The optical system was translated up to a maximum amplitude \( u_r = 1 \text{ mm} \) then moved back to the initial position with 0.1 mm displacement steps. Parameters are determined using a least squares minimization between the displacements calculated with the optical model and the 2D-DIC. Resulting parameters \( d_0, x_c \) and \( y_c \) were respectively identified as 613 mm, \(-122\) px, and \(-62\) px.

The virtual strain associated to the virtual displacement is depicted as a function of the normalised in-plane displacement \( u_r \) in Figure 8. The linearization of the optical system model is validated at least for an in-plane displacement \( u_r \) of 1 mm. Note that the optical system used in these experiments is not strongly affected by the out-of-plane displacement.

### 4.2.2 Correction of the cladding ballooning

Figure 9 illustrates the description of the combined edge detection/2D-DIC approach.

2D-DIC was performed on the region of interest (white box in Figure 5b) of the pictures shot during Test B. Displacements and strains in both \( x \) and \( y \) directions of the detector plane were extracted along the yellow line.

The edge detection provided the radial displacement \( u_r \) of every point of the deformed edge (Figure 10) in the eulerian coordinate system (Figure 5c). The resulting point \( Q' \) in the detector plane corresponding to point \( M' \) can be calculated using Equation (9) where \( M = \frac{d_i}{d_0} \) is the magnification of the optical system.

\[
y' - y_c = \frac{M \cdot d_0}{d_0 - u_r} (Z - Z_c).
\] (9)

### FIGURE 7
Procedure Test B. Scheme of the experiment used to calibrate the optical system parameters: \( d_0, x_c, y_c \)

### FIGURE 8
Procedure Test B. Virtual in-plane strain versus the normalized out-of-plane displacement \( u_r / r_0 \)
The initial position \( Q_0 \) of the deformed point \( Q' \) was determined in the detector plane using the 2D-DIC results as follows:

\[
y_0 - y_c = y' - y_c - u_y (Q'),
\]

with \( u_y (Q') \), the displacement of \( Q \) measured by the 2D-DIC in the \( y \) direction of the detector plane.

The initial axial position \( Z_0 - Z_c \) of the deformed point \( M' \) was finally calculated using Equation (11):

\[
Z_0 - Z_c = \frac{y_0 - y_c}{C_0/C_1}.
\]

The axial and radial displacements of each point of the yellow line during the transformation from the initial to the deformed configurations were thus determined. The logarithmic strains were calculated using deformed curvilinear positions and their associated initial positions.

5 | RESULTS AND DISCUSSION

5.1 | NIRT assessment

5.1.1 | Uncertainties related to the thermocouples measurement

Five components were involved in the acquisition chain: a thermocouple wire, a LEMO connector, a compensation wire, a converter TEPI (BEP304 model), and a FlexTest SE controller. Each of the components is a source of error affecting the temperature uncertainties. Table 1 summarizes the manufacturers’ data.
The uncertainties induced by the BEP304 take into account the internal cold junction measurement. It has the highest influence on the temperature measurement uncertainties. This manufacturer data accounts for the heating time of the cold junction. Performing measurement once the converter behaviour is stabilized can reduce the uncertainties. A calibrator (fluke 725 multifunction process calibrator) was placed before the compensation wire for assessing errors due to the compensation wire combined with the converter. It simulated the temperature of a K-type thermocouple. Five tracks of the converter were tested. The measurements were performed after 1.5 operating hour of the converter. Temperature was imposed in a range of 720 to 880 °C temperature steps. The maximal error was 0.4% of the setting temperature, and the averaged error was 0.18%. The calibration of the NIRT relied on the thermocouple measurements. The errors related to the thermocouples acquisition chain were thus passed on the final temperature estimation.

### TABLE 1

| Acquisition chain uncertainties       |
|---------------------------------------|
| TC wire                               |
| Compensation                        |
| BEP304                               |
| MTS FlexTest recorder                |
| 0.004/°T                              |
| ±2.5°C                               |
| ±6°C                                 |
| <3.10⁻⁵/°T                           |

### 5.1.2 Test A NIRT uncertainties

The temperatures calculated using the calibrated radiometric model were compared with the thermocouples measurements during Test A (Figure 3).

The parameters determined using the calibration process and the silicon sensor time exposure $t_i$ are reported in Table 2 for each cycle.

The effective wavelength $\lambda_e$ was calculated using Equation (6). Note that $\lambda_e$ is decreasing with increasing temperature level as expected. The digital thermocouple (DT) and thermocouples (TC) measurements are plotted for the second temperature level cycle in Figure 11a. The comparison between the NIRT and the thermocouple measurements are reported in Table 3 for each cycle.

Temperatures were calculated using the three radiometric models and grey level intensities ranging from 120 to 200. Results are plotted in Figure 11b versus the grey levels normalized by their respective time exposure. The radiometric

### TABLE 2

| Radiometric model parameters calibrated during each heating |
|------------------------------------------------------------|
| Cycle 1 | Cycle 2 | Cycle 3 |
| $t_i$ (ms) | 70 | 30 | 14.2 |
| $K_1$ ($K$) | 1.60 $10^4$ | 1.66 $10^4$ | 1.67 $10^4$ |
| $K_2$ (GL) | 5.96 $10^8$ | 4.34 $10^8$ | 2.4 $10^8$ |
| $\lambda_e$ (nm) | 897 | 869 | 862 |

![FIGURE 11](a) Procedure Test A. (a) Comparison NIRT—Thermocouples measurements for the second cycle of Test A, (b) radiometric model identification—one model per thermal cycle
model continuity from one calibration to another is highlighted. It was expected because of the linearity between the pixel intensity and the time exposure.

The maximal difference on the temperature prediction compared to thermocouples measurements remained lower than 0.7% when considering the entire test data.

Finally, the uncertainties estimation of the NIRT method was inherent to the thermocouples measurements and remains lower than 0.7% of the true temperature and the averaged error was 0.32% of the true temperature.

5.2 | TEST B: 2D-DIC ASSESSMENT

Several aspects of the 2D-DIC measurements will be discussed in the following. First, the influence of the set-up on the 2D-DIC noise will be studied at room temperature and at high temperature (respectively at markers tA and tB in Figure 4). Then, the error induced by the out-of-plane displacement will be regarded at different ballooning levels (markers t1 to t4 in Figure 4) by using the combined 2D-DIC/edge detection approach.

5.2.1 | Analysis of the influence of noise in 2D-DIC measure

At markers tA and tB, (respectively, at room and high temperature), Cam 1 shot 30 pictures, under a constant thermal mechanical loading, for a noise analysis purpose. A stationary spatial thermal distribution was reached at tB.

Figure 12a shows the grey level histogram of the ROI (red box, 1851 × 301 px²). The histogram is plotted considering all the data (i.e., the pixels grey level of all pictures associated to each marker). The first pictures of the sets tA and tB are

| Cycle | $|\Delta T/T|_{\text{mean}}$ (%) | $|\Delta T/T|_{\text{max}}$ (%) |
|-------|-------------------------------|-------------------------------|
| 1     | 0.25                          | 0.7                           |
| 2     | 0.14                          | 0.54                          |
| 3     | 0.12                          | 0.6                           |

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

**FIGURE 12** Procedure Test B. (a) Grey level histograms of the sets of pictures associated to markers tA and tB, respectively, at room and high temperature (see Figure 4), (b) displacement histograms of the sets of pictures associated to markers tA and tB, (c) axial ($\varepsilon_{yy}$) and hoop strains ($\varepsilon_{xx}$) histograms related to marker tA, (d) axial ($\varepsilon_{yy}$) and hoop strains ($\varepsilon_{xx}$) histograms related to marker tB
also shown as an example of the effect of the heating on the speckle pattern. The heating results in a decrease of the contrast between black and white speckles. The white speckles grey levels diminished and were smoothed. It is worth mentioning that the test constraints induce a poor speckle pattern quality either at high or room temperature as the highest quality being a wide and uniform histogram.

2D-DIC was performed with these data sets. Figure 12b shows the displacement histogram over the whole data sets \( t_A \) and \( t_B \) (i.e., the displacement of all the nodes of each pictures). Figure 12c,d depict the histograms of the strains respectively at room temperature and at high temperature. The mean values and the standard deviations of each histogram are summarized in Table 4. Note that the histograms include the DIC noise but also the physical displacements induced by the thermal mechanical loading noise (see Figure 4). The increase of noise between room and high temperature can be explained by several reasons. The dynamic of the pictures are narrower at high temperature. Little residual smoke induced by the heating of the paint could affect the measurement. However, no mirage effect was observed presumably because of the combined effect of the induction volume heating and the argon sweeping.

Hence, the strain uncertainty at high temperature is less than \( 1.0 \times 10^{-4} \). The strain noise is less than \( 1.5 \times 10^{-3} \). The identification process shown in Figure 1 used the stationary strain rates profile along the axial position of the ROI at each mechanical loading plateau. These stationary strain rates are calculated over a Von Mises equivalent strain range that is typically higher than \( 0.01 \) and over more than 20 pictures. The strain range is far higher than the strain uncertainty. The 20 pictures are enough to smooth the noise effect.

### 5.2.2 Correction of the cladding ballooning

The error of the 2D-DIC measurements induced by the out-of-plane displacement is quantified in the following at different ballooning levels (markers \( t_1 \) to \( t_4 \) in Figure 4) by using the combined 2D-DIC/edge detection approach. The marker \( t_4 \) is picked because of its extremely large ballooning state.

The axial strain, calculated by 2D-DIC, and the curvilinear strain, calculated by the combined edge detection/2D-DIC approach, are plotted in Figure 13a.

The correction effect is negligible for times \( t_1 \to t_3 \) but it becomes significant for time \( t_4 \) when the balloon is pronounced. After correction, the axial deformation is lowered in the middle of the specimen because of the out-of-plane displacement combined to a low curvature. The opposite phenomenon is observed at the sample regions that were no longer perpendicular to the optical axis. The in-plane projection induced an artefact contribution to \( \varepsilon_{yy} \).

The hoop strain levels were higher than those of axial strains. The tube curvature was not accounted for considering the low chord error induced by the finite element discretization of the circumference of the tube at the generator location. The hoop strains calculated using 2D-DIC were thus only corrected by subtracting the virtual strain related to the out-of-plane displacement (see Figure 8). The 2D-DIC hoop strain and the corrected one are plotted versus the position \( Z \) in Figure 13b. The correction is not significant in the hoop direction.

In Campello et al.,[2] the equivalent Von Mises plastic strain was used for the FEMU based identification. The equivalent true strains were computed with and without the out-of-plane displacement correction. The error \( er \) defined in Equation (12) is plotted in Figure 13c at the four markers.

\[
er^2 = \left( \frac{2D_{eq} - \varepsilon_{eq}^{pure} + \varepsilon_{eq}^{pure}}{\varepsilon_{eq}^{pure}} \right)^2.
\] (12)

The error associated to the 2D-DIC was lower than 1% of the equivalent strains accounting for the out-of-plane displacement even when the balloon was pronounced.
The combined experimental/numerical approach detailed in Campello et al.[2] for identifying the creep behaviour of Fresh zirconium alloys under simulated LOCA conditions was assessed.

The paper focused on uncertainties and error quantification of the two key optical full field measurement method: NIRT and 2D-DIC. The NIRT uncertainties mainly result from the thermocouples acquisition chain used for the calibration of the radiometric model. The physically based radiometric model tends to lower these uncertainties during the calibration by correcting the discrepancies between thermocouples. An uncertainty of 0.7% of the actual temperature was quantified.

2D-DIC measured the ballooning of the tube. A correction method is proposed to take into account the out-of-plane displacement of the tube during the ballooning. The method relies on a combined 2D-DIC/edge detection approach. Applied to the used optical system, the correction is lower than 1% of the equivalent plastic strain even for a 20% increase of radius during the ballooning, a value far higher than the ones used in Campello et al.[3] for the identification process. However, in the test configuration, axial strains are unaccurately estimated at this strain level and must be corrected from a radius increase of 10%. The proposed approach would have been particularly necessary for anisotropy identification in multiple biaxial stress states as enables the set-up.

The combined 2D-DIC/edge detection approach can be used with a single camera for axisymmetric ballooning as during the above discussed testing conditions. It simplifies the set-up and test procedure compared to 3D DIC.

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