Ramakrishnan, R., Quino Quispe, G., & Barton , J. M. (2022). COMBINED DIC-INFRARED THERMOGRAPHY FOR HIGH STRAIN RATE TESTING OF COMPOSITES. In *Composites meet Sustainability : Proceedings of the 20th European Conference on Composite Materials* (Materials). MDPI AG. https://eccm20.org/program/

Composites Meet Sustainability – Proceedings of the 20th European Conference on Composite Materials,
ECCM20. 26-30 June, 2022, Lausanne, Switzerland

COMBINED DIC-INFRARED THERMOGRAPHY FOR HIGH STRAIN RATE TESTING OF COMPOSITES

Karthik Ram, Ramakrishnan[a], Gustavo, Quino[a], Janice, Dulieu-Barton[a]

a: Bristol Composites Institute, University of Bristol, Bristol, United Kingdom
* Corresponding author email: Karthik.ramakrishnan@bristol.ac.uk

Abstract: *Infrared Thermography (IRT) is a full-field measurement technique for evaluating defects or damage in a material by localized variation in the surface temperature observed using a thermal camera. The occurrence of damage in composite structure is accompanied by heat dissipation and a subsequent temperature evolution on the specimen surface. The thermal images provide quantitative information about location and magnitude of hot spots and, in turn, of the damage mechanisms. Therefore, surface temperature analysis using an infrared camera can be applied to better understand the damage mechanisms and energy absorption in composites. In this paper, simultaneous high-speed white-light and infrared imaging were conducted to obtain quantitative description of thermomechanical response of the material and to study the formation and propagation of shear localizations from the temperature history.*

Keywords: full-field imaging; high strain-rate; composites; in-plane shear; thermography

1. Introduction

Composites materials are widely used in a diverse range of applications due to the several benefits they provide (lightweight, multifunctionality, corrosion-resistance, etc.). However, composites may encounter dynamic loads during service. For instance, during an impact event such as bird strike, the local strain rates near the impact location are very high and it is known that mechanical properties such as the in-plane shear strength or the fracture toughness are sensitive to the strain rate. Therefore, reliable characterisation of mechanical properties over a wide range of strain rates and temperatures is required to safely design components with these materials. The Split Hopkinson Pressure Bar (SHPB) is an experimental technique used to measure mechanical properties at strain rates in the order of 100 to 1000 s^{-1}[1]. Though there are several works studying the use of SHPB for rate-dependent compressive properties of composite materials, there is limited work investigating tensile or shear properties of composite materials under high rates of loading [2,3]. One of the main failure mechanisms of unidirectional fibre composites is inter-fibre failure under in-plane shear. It is mainly driven by the properties of the polymeric matrix which due to its viscoelastic nature, is highly strain-rate dependent. Some experimental works have investigated the effects of strain rate on the in-plane shear behaviour of composites [4–6]. Cui et al. [4] reported that the shear stiffness and yielding strength increased with strain rate, while the failure strain decreased. The initiation and growth of micro cracks was not only responsible for the shear driven failure, but this failure mechanism also changed considerably with strain rate.

There is also literature on the application of temperature measurement for the characterisation of the mechanical behaviour of composites. Various authors have used infrared thermography (IRT) to identify damage in FRP materials [7–9]. IRT is a full-field measurement technique based on the principle that electromagnetic radiation in the infrared spectrum (wavelength in the range of 0.75–1000 um) is emitted by all objects above absolute zero temperature. IRT can be used to monitor the surface temperature during loading. In addition to the change in material temperature due to a change in applied stress (thermoelastic effect), heat generation in composites can be due to various mechanisms such as fracture, damping caused by viscoelastic behaviour of the matrix or the frictional sliding between fibre-fibre and fibre-matrix interfaces. Libonati and Vergani [7] studied the damage evolution in GFRP under static loading conditions and showed that IR thermography is a powerful tool for damage analysis and the thermal maps and thermal profiles allowed the detection of defects, damage formation, and evolution. For instance, small amount of energy is dissipated during the formation of microcracks, which can be observed as small temperature increase in the thermal images, while fibre breakage causes large dissipation of energy and a corresponding local increase of temperature. Jiménez-Fortunato et al. [8] explored the possibility of combining Digital Image Correlation (DIC) with thermal imaging conducted using low-cost bolometer IR cameras for assessing defects in composite materials. However, the use of thermography for high strain rate applications is limited by the capabilities of the currently available IR detectors [10]. The temperature variation occurs during a short duration of the order of milliseconds and their visualization is only possible with high-speed imaging. The high acquisition rates (>10kHz) required to capture the phenomena in dynamic tests means reduced integration times which adversely affects the signal to noise ratio. Pan et al. [11] used high-speed thermal imaging to identify localization of temperature rise, adiabatic shear band, resin matrix softening, damages and failures during the dynamic failure of 3-D braided composite material. Johnston et al. [9] used a Telops FAST-IR 2K camera capable of frame rates up to 90,000 frames per second in sub-window mode to capture the temperature fields of a composite panel impacted using a gas gun and found that the generated temperatures in the local region near the point of impact was over 252 °C. This large temperature rise surpassing the glass transition temperature of the matrix causes thermal softening and subsequent deformation localization. Similar localized temperature rise exceeding the Tg of the resin matrix was reported to cause stress concentration and subsequent failure in warp/weft fibre tows in localized positions in non-crimp fabric reinforced polymer composites [12]. Johnsen et al. [13] reported an increase in temperature of almost 50 °C during high strain rate testing of rubber-modified polypropylene, when adiabatic heating conditions are met. It was also noted that the self-heating introduces a softening in the material and increases the locking stretch for higher strain rates. Tarfaoui et al. [3] developed an experimental setup for Hopkinson bar compression tests in which simultaneous full-field deformation and temperature measurements were obtained. It was reported that the observed V-shaped hot zones, localized at the centre of the specimen coincided with the damage area observed from the white light imaging. Similar tests conducted on pultruded glass fibre composites also observed maximum temperatures in the fracture zones exceeding 80 °C and it can be concluded that simultaneous optical and IR imaging can be used to obtain quantitative description of thermo-mechanical response of the material and to study the formation and propagation of shear localizations from the temperature history [14].

In this paper, we characterise the in-plane shear response of carbon fibre composite laminates at high strain rates using combined white light imaging and infrared thermography. The results will serve as a basis for the development of improved strain rate sensitive, physically-based constitutive models for composites.

2. Experimental setup

2.1 Material

Tensile dogbone specimens were cut by water jet cutting from a 300x300 mm plate made of IM7/8552 prepreg, [+45, -45]8s, with an approximate thickness of 2mm. Specimen geometry is displayed in Fig. 1. 3M DP460 epoxy-based adhesive was employed to glue metallic endcaps to the specimens. The M12 threaded endcaps were impedance matched and used for gripping into the Hopkinson bars. A specially designed rig was used to ensure the alignment and co-axiality of these endcaps during curing of the epoxy. The subset matching based DIC requires surfaces containing a random pattern. Prior to testing, coupons were prepared with a black speckle on white background to obtain full-field measurement of the strains by DIC. The speckle patterns were applied on the samples using the temporary tattoo or water slide paper method developed by Quino et al [15]. In this method, a random speckle pattern created by Speckle Generator software from Correlated Solutions was printed on commercially available special paper for temporary tattoo and wet-transferred to the surface of the specimen.

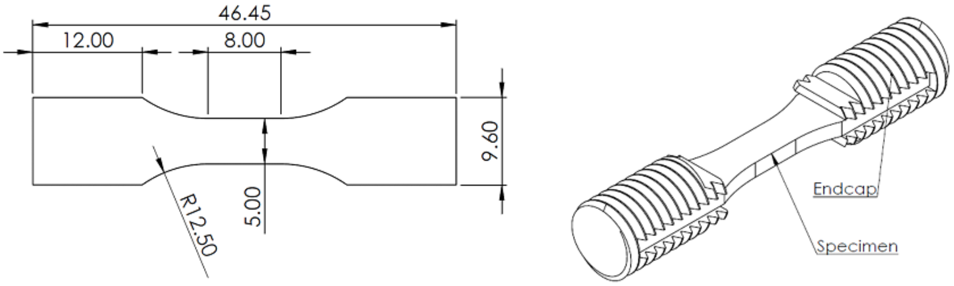

Figure 1 Specimen geometry to characterise the in-plane shear behaviour.

2.2 High rate characterisation

Dynamic characterisation was performed in a Split Hopkinson bar system (see Fig. 2) to achieve strain rates up to 900s^{-1}. The bars were instrumented with three sets of strain gages (see Fig. 2) from which the history of loads across the specimen was calculated following 1D wave propagation theory as described in reference [16]. The calculated axial stress σ_{xx} was then converted into shear stress τ_{12} with $\tau_{12} = -\sigma_{xx}/2$. The history of strains was obtained from DIC analysis of high-speed images taken with a Kirana camera (Specialised Imaging Ltd, UK) at a rate of 250000 fps. The image acquisition of the camera was triggered by the stress pulse arriving at the first strain gage. A delay of 380 μs was set as the Kirana camera can only capture 180 frames. Digital image correlation (DIC) analysis of the high-speed camera images were conducted using Davis software to obtain the displacement across the speckled gage section of the composite specimens and the corresponding strain were evaluated. It was found that the strain distribution within gage area was reasonably uniform and an average strain from the centre of the sample was used to plot the stress vs. strain curves.

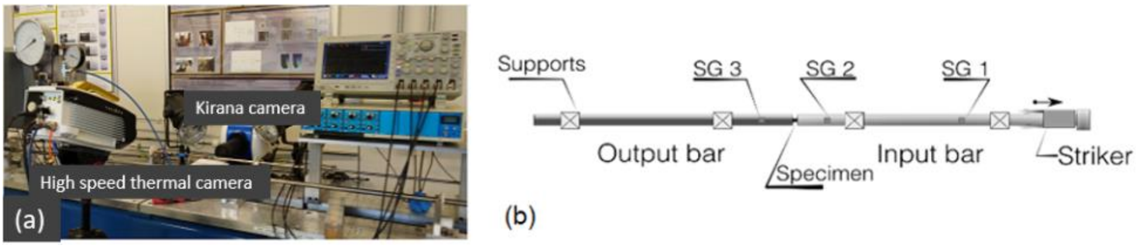

Figure 2 (a) Experimental setup with combined high-speed imaging, (b) Schematic diagram of a Split Hopkinson Tension bar

A Telops FAST M3K photon detector camera was used to capture IR images at a resolution of 64 x 8 pixels and a frame rate of 93000 fps. It was necessary to use a subwindow mode to obtain the high frame rate required for the dynamic test. The sample was heated with a heat-gun to get a clear difference in temperature to the surroundings. The window size was progressively reduced to ensure that the 8 pixels of the width coincided with the width of the composite sample. A typical image of the radiometric temperature plot obtained from the Telops camera is shown in Figure 3. An integration time of 5 µs and calibration range from 0 to 176 °C were used in the experiment. The same trigger signal used for the Kirana was used to trigger image acquisition of the Telops camera.

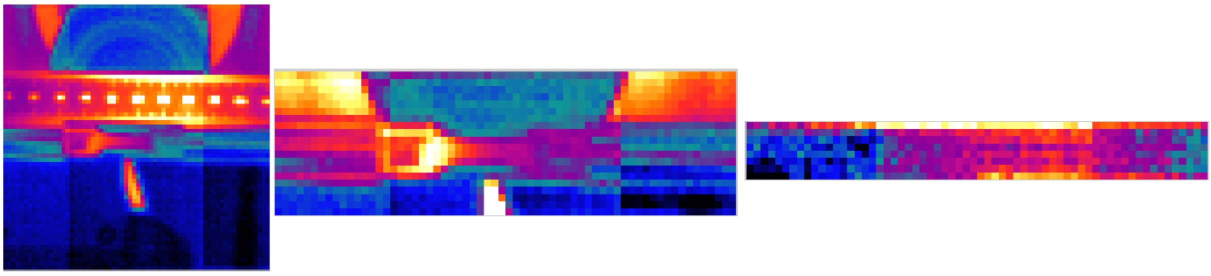

Figure 3 Typical images of surface temperature from IR camera

3. Results and Discussion

The raw signals obtained from the strain gages in the input bar (SG1 and SG2) as well as the output bar (SG3) are shown in Figure 4. The shape of the input pulse obtained from using the rubber pulse shaper is evident. The raw signals from the oscilloscope are post-processed using 1D wave theory equations to obtain the force and stress signals in the composite. The force validity showing equilibrium between the end of input and beginning of output bars is also shown.

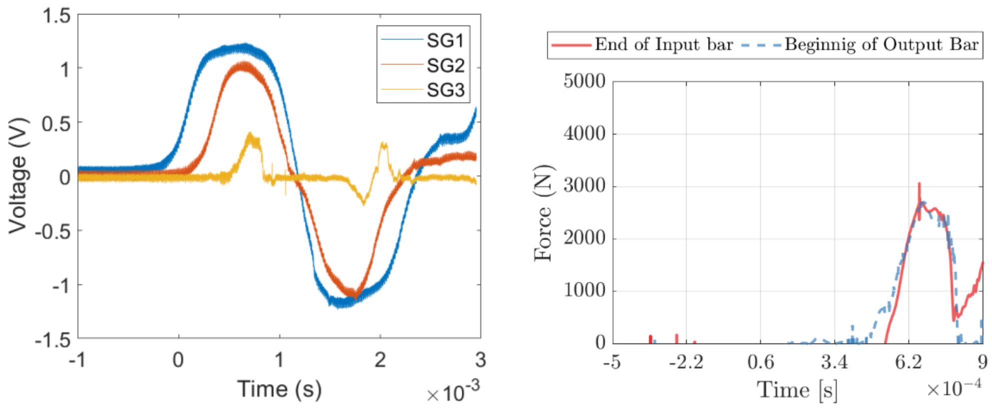

Figure 4 (a) Typical strain gage signals from the SHPB test and (b) Force validity

A time lapse of the images taken with Kirana high speed camera is shown in Figure 5. The threaded endcaps and the speckled pattern in the gage area of the composite are clear. The images are from 80 µs apart and show the shear deformation and failure of the composite.

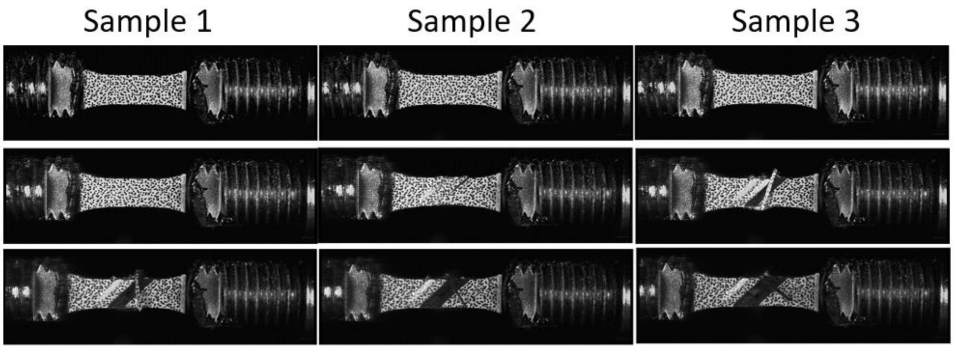

Figure 5 Typical high speed camera images of in-plane shear test of CFRP composite

The displacement measurements in the x-direction (loading direction) obtained from the DIC analysis is shown in Figure 6. A region of interest is chosen in the gage area and a subset size of 17 pixels x 17 pixels was chosen with a step size of 8 pixels. The images correspond to the first image acquired after the trigger (before any stress pulse), (ii) displacement in the composite when the stress wave arrives in the specimen, (iii) localization and beginning of fibre failure and (iv) finally fracture and complete failure of the specimen. It can be noted that the fibre fracture occurs at an angle corresponding to the 45°surface ply.

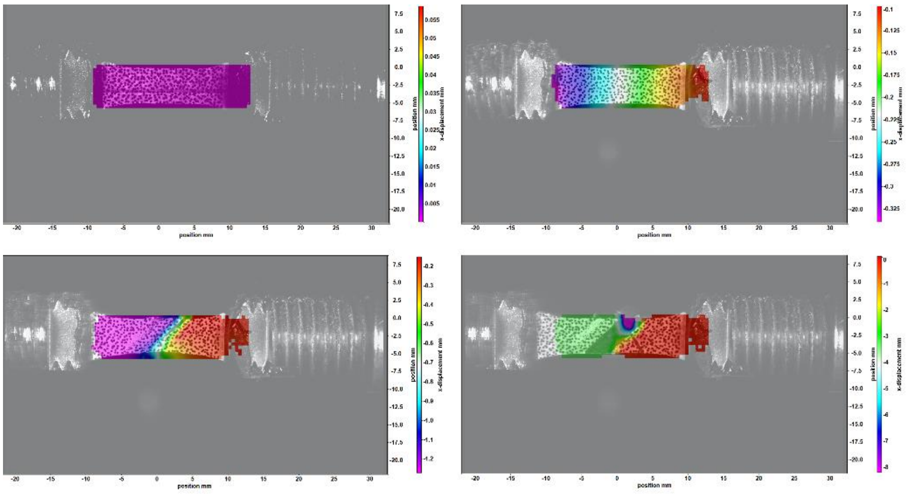

Figure 6 Displacement contours obtained from DIC analysis

The stress obtained from the postprocessing of the strain gage signals and the strain obtained from the DIC analysis were combined to obtain the shear stress vs. strain plot shown in Figure 7. It can be seen that the tests consistently show a nonlinear shear response, and a post-peak strain softening region. The average shear strength measured from the peak stress was 123 MPa, slightly below to the 130MPa reported by Cui et. al for a similar material system [4], possibly because of the higher strain rate in their experiments.

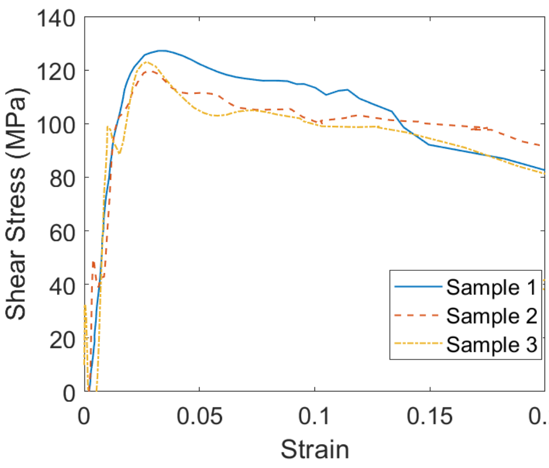

Figure 7 Shear stress vs strain curve at high strain rate for IM7/8552 composite

The radiometric temperature measured from the Telops camera was used to plot the change in temperature (ΔT) in the composite. Figure 8 shows that there is a diffused increase in temperature in the composite during the deformation followed by localized hotspot during fibre fracture. The increase in temperature is almost 100 °C which is consistent with the reported literature. The thermal images clearly show the effect of matrix damage and fibre failure, which will provide additional information about the damage mechanisms in the composite and the effect of the temperature increase on the material performance.

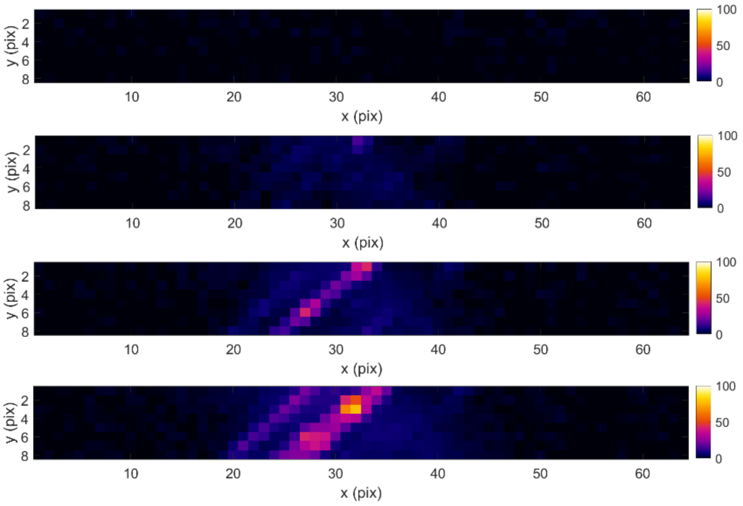

Figure 8 Change in temperature measured from high speed thermal camera

4. Conclusion

A combined high-speed white-light and infrared imaging method was used to study the in-plane shear response of carbon fibre composite at high strain rate. A Split Hopkinson Pressure Bar setup was used to conduct the test on ±45° sample of the composite. DIC analysis of the high speed images were used to obtain the strain history and 1D wave analysis was used to measure the stress history. The thermal images provide quantitative information about location and strength of hot spots and, in turn, of the damage mechanisms. Therefore, surface temperature analysis using an infrared camera can be applied to provide quantitative description of thermo-mechanical response of the material and to study the formation and propagation of shear localizations from the temperature history.

Acknowledgements

The authors acknowledge the Marie Curie Individual Fellowship funded by the European Union's H2020-MSCA-IF-2018 Programme (FIDELITY project, grant agreement n◦ 846458).

5. References

[1] Gerlach R, Kettenbeil C, Petrinic N. A new split Hopkinson tensile bar design. Int J Impact Eng 2012;50:63–7. https://doi.org/10.1016/j.ijimpeng.2012.08.004.

[2] Koerber H, Xavier J, Camanho PP. High strain rate characterisation of unidirectional carbon-epoxy IM7-8552 in transverse compression and in-plane shear using digital image correlation. Mech Mater 2010;42:1004–19. https://doi.org/10.1016/j.mechmat.2010.09.003.

[3] Tarfaoui M, El Moumen A, Ben Yahia H. Damage detection versus heat dissipation in E-glass/Epoxy laminated composites under dynamic compression at high strain rate. Compos Struct 2018;186:50–61. https://doi.org/10.1016/j.compstruct.2017.11.083.

[4] Cui H, Thomson D, Pellegrino A, Wiegand J, Petrinic N. Effect of strain rate and fibre rotation on the in-plane shear response of ±45° laminates in tension and compression tests. Compos Sci Technol 2016;135:106–15.

https://doi.org/10.1016/j.compscitech.2016.09.016.

[5] Taniguchi N, Nishiwaki T, Kawada H. Tensile strength of unidirectional CFRP laminate under high strain rate. Adv Compos Mater Off J Japan Soc Compos Mater 2007;16:167–80. https://doi.org/10.1163/156855107780918937.

[6] Ledford N, Imbert M, May M. High-rate in-plane shear testing of cfrp using the split hopkinson tension bar. AIAA Scitech 2021 Forum 2021;59:1–8. https://doi.org/10.2514/1.j060269.

[7] Libonati F, Vergani L. Damage assessment of composite materials by means of thermographic analyses. Compos Part B Eng 2013;50:82–90. https://doi.org/10.1016/j.compositesb.2013.01.012.

[8] Jiménez-Fortunato I, Bull DJ, Thomsen OT, Dulieu- JM. On the source of the thermoelastic response from orthotropic fibre reinforced composite laminates. Compos Part A 2021:106515. https://doi.org/10.1016/j.compositesa.2021.106515.

[9] Johnston JP, Pereira JM, Ruggeri CR, Roberts GD. High-speed infrared thermal imaging during ballistic impact of triaxially braided composites. J Compos Mater 2018;52:3549–62. https://doi.org/10.1177/0021998318765290.

[10] Fruehmann RK, Dulieu-Barton JM, Quinn S. Thermoelastic Stress and Damage Analysis Using Transient Loading. Exp Mech 2010;50:1075–86. https://doi.org/10.1007/s11340-009-9295-9.

[11] Pan Z, Wu Z, Xiong J. High-speed infrared imaging and mesostructural analysis of localized temperature rise in damage and failure behavior of 3-D braided carbon/epoxy composite subjected to high strain-rate compression. Polym Test 2019;80:106151. https://doi.org/10.1016/j.polymertesting.2019.106151.

[12] Pan Z, Wu Z, Xiong J. Localized temperature rise as a novel indication in damage and failure behavior of biaxial non-crimp fabric reinforced polymer composite subjected to impulsive compression. Aerosp Sci Technol 2020;103:105885. https://doi.org/10.1016/j.ast.2020.105885.

[13] Johnsen J, Grytten F, Hopperstad OS, Clausen AH. Influence of strain rate and temperature on the mechanical behaviour of rubber-modified polypropylene and cross-linked polyethylene. Mech Mater 2017;114:40–56. https://doi.org/10.1016/j.mechmat.2017.07.003.

[14] Pournoori N, Corrêa Soares G, Orell O, Palola S, Hokka M, Kanerva M. Adiabatic heating and damage onset in a pultruded glass fiber reinforced composite under compressive loading at different strain rates. Int J Impact Eng 2021;147:103728. https://doi.org/10.1016/j.ijimpeng.2020.103728.

[15] Quino G, Chen Y, Ramakrishnan KR, Martínez-Hergueta F, Zumpano G, Pellegrino A, et al. Speckle patterns for DIC in challenging scenarios: Rapid application and impact endurance. Meas Sci Technol 2021;32. https://doi.org/10.1088/1361-6501/abaae8.

[16] Quino G, Tagarielli VL, Petrinic N. Effects of water absorption on the mechanical properties of GFRPs. Compos Sci Technol 2020;199:108316. https://doi.org/10.1016/j.compscitech.2020.108316.