Novel image-based inertial high strain rate tests: an overview

F. Pierron[1a], F.M. Davis[1], L. Fletcher[1], X. Régal[1], R. Seghir[2], J. Van Blitterswyk[1]

[1]Faculty of Engineering and the Environment, University of Southampton, Southampton, UK

[2]Institut de Recherche en Génie Civil et Mécanique - UMR CNRS 6183, Nantes, France

[a]f.pierron@soton.ac.uk

Abstract: the Photodyn project[1] has now been running for nearly four years and has produced some exciting new methods to test materials at high strain rates. This paper provides an overview of the methodologies and details the strengths and limitations of the newly developed methods. The objective of this presentation is to help introduce the contributions from the other members of the group in the dedicated Photodyn session.

Introduction

The recent developments in ultra-high speed (UHS) imaging technology has allowed new ideas to emerge in the area of high strain rate testing of materials. The current gold standard for high strain rate testing is the Kolsky or split Hopkinson bar, which relies on a few strain gauges located away from the specimen. Unlike the Kolsky bar, UHS-based full-field measurements through DIC or the grid method provide data-rich information. This allows some experimental constraints to be relieved, like the need for uniform and uniaxial stresses in a Kolsky bar specimen. More interestingly, the sub-microsecond temporally-resolved displacement fields lead to acceleration fields which can be used to derive equilibrium equations which removes the need to directly measure the impact load.

There are a number of situations where the Kolsky bar methodology fails to deliver appropriate data, like low impedance and brittle materials. The lack of robust data for the high strain rate interlaminar properties of polymer matrix fibre composites above a few 100s of s^{-1} provides a good example [1]. The present effort aims to design new image-based tests to cover the shortcomings of the current high strain rate methods.

Loading configurations

Two main loading configurations were developed as part of the Photodyn project. The first one is direct inertial impact through a projectile launched by a gas gun. This has been named Image-Based Inertial Impact (IBII). Figure 1 shows the main components of the test. A compression wave is imparted into the specimen through the impact between the gas gun launched impactor and the waveguide. The wave enters the test specimen, then reflects off the free surface as tensile. Depending on the impactor length, pulses of different spatial lengths can be introduced into the specimen, with a choice to either perform compressive loading and unloading [2] or tensile spall [3]. Strain rates above 1000 s^{-1} can easily be achieved with impactor speeds of only several tens of $m.s^{-1}$.

The second loading method uses a power ultrasonic device to excite a specimen at one of its longitudinal resonance frequencies (Figure 2). At the first resonance mode, the strain is maximum in the centre and zero at the edges. Each section provides a different thermo-mechanical state, from which a strain rate and temperature dependence map of stiffness can be constructed in a single test [4]. This methodology has been named Image-Based Ultrasonic Test (IBUT). This method can achieve strain rates on the order of 100s^{-1}.

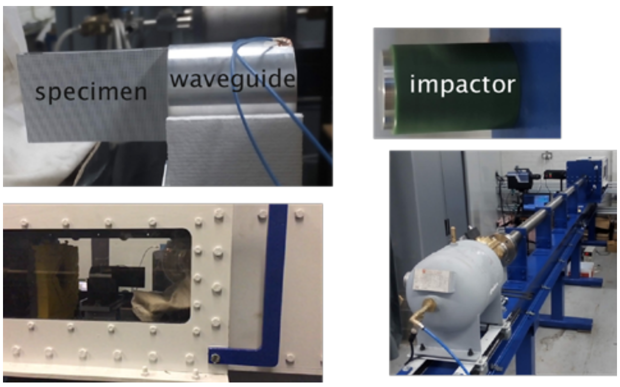

Figure 1: Direct inertial impact - specimen and waveguide, impactor, impact chamber with specimen and gas gun (left to right, top to bottom)

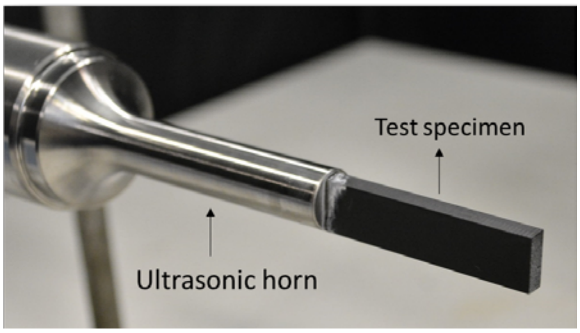

Figure 2: Inertial ultrasonic loading

From acceleration to stress

[1] www.photodyn.org

The principle of virtual work, written below, provides a flexible tool to write equations relating stress to acceleration in transient dynamics. Different approaches have been used so far, from the simple stress-gauge formulae [2, 3] to the full Virtual Fields Method for linear [2, 5] and non-linear [6] models. The underpinning idea is that there is no need to measure the impact load independently as the information is contained directly in the images.

$$-\int_V \sigma : \varepsilon^* dV + \int_{\partial V} T.u^* dS = \int_V \rho a.u^* dV \qquad (1)$$

Key features

The IBII and IBUT methods rely on a number of key features driving the quality of the derived data.

- Because only surface deformation is measured, stress and strain have to be 2D for the volume integrals in Eq. 1 to be evaluated. This generally requires thin plate-like specimens and care must be given to the loading introduction.
- Spatial and temporal resolutions need to be high enough to capture the strain gradients and the acceleration peaks. Synthetic image deformation is now systematically used to verify this [4]. It can also be used to determine optimal smoothing parameters and for test design [7].
- Because UHS camera sensors generally have low spatial resolution, the grid method [8] is preferred to Digital Image Correlation. It provides a better compromise between spatial resolution and displacement resolution at the cost of having to bond/print/transfer a grid onto the specimen surface. Currently, our favoured method is to print the grid directly onto the specimens using a flatbed printer[2]. The iterative grid method [8] is systematically used to mitigate the effect of small grid defects.
- It is essential to have data right up to the specimen edge, particularly for the free edge when the stress wave reaches there in the IBII test. With the grid method, one grid pitch is lost and then, spatial smoothing may compromise edge data further. Different strategies have been studied and some robust reconstruction methods are now implemented.
- The quality of the UHS camera images is paramount. Currently, the Specialized Imaging Kirana and Shimadzu HPV-X have been used for IBII tests. The former did not lead to satisfactory acceleration fields, while the HPV-X proved to provide exceptional image quality. It is worth noting that the new model, HPV-X2, has a noisier sensor. Data are currently being acquired with the HPV-X2 for comparison purposes. A Cordin 580 will also be used in the near future to provide comparative data.
- Pulse shaping is key to design a pulse that is optimized for the properties to be identified. Systematic explicit finite element computations are used to design the test configuration for each new problem.

Conclusion

The Photodyn project has only barely scratched the surface of the potential of UHS imaging and inverse identification of high strain rate properties of materials. There are many years of research ahead of us to design novel test procedures optimized for particular situations. It is an exciting area of research but quite dependent on the technology of ultra-high speed cameras. Until a few years back, this was a tiny niche market but the emergence of in-situ image storage cameras has made this technology more accessible. However, the 'ideal camera' for this kind of work is still missing. An effort is needed to design and build such a camera for the Photodyn methodologies to become the next generation of high strain rate tests.

References

1. Van Blitterswyk, J., L. Fletcher, and F. Pierron, *Characterisation of the interlaminar properties of composites at high strain rate: a review.* Advanced Experimental Mechanics (JSEM), 2017. **2**: p. In press.
2. Pierron, F., H. Zhu, and C. Siviour, *Beyond Hopkinson's bar.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2014. **372**(2023): p. 20130195.
3. Fletcher, L., J. Van Blitterswyk, and F. Pierron, *Novel image-based spalling test for the transverse properties of unidirectional composites at high strain rates.* Composites Part A: Applied Science and Manufacturing, 2017. **Submitted.**
4. Seghir, R. and F. Pierron, *A novel image-based ultrasonic test to map material mechanical properties at high strain-rates.* Experimental Mechanics, 2018. **58**(2): p. 183-206.
5. Moulart, R., et al., *Full-field strain measurement and identification of composites moduli at high strain rate with the virtual fields method.* Experimental Mechanics, 2011. **51**(4): p. 509-536.
6. Dreuilhe, S., *Development of novel inertial tests for the identification of elasto-plastic material model parameters at high strain rates* in *Engineering and the Environment*. 2017, University of Southampton.
7. Rossi, M., et al., *Effect of DIC spatial resolution, noise and interpolation error on identification results with the VFM.* Strain, 2015. **51**(3): p. 206-222.
8. Grédiac, M., F. Sur, and B. Blaysat, *The Grid Method for in-plane displacement and strain measurement: a review and analysis.* Strain, 2016. **52**(3): p. 205-243.

---

[2] http://photodyn.org/wp-content/uploads/2016/03/Report_UniversityPrintCentre.pdf