Measuring Dynamic Tensile Properties of Saturated Concrete in Spalling Tests using DIC-VFM Approach

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Abstract. This extended abstract presents a novel DIC-VFM approach to measure the dynamic tensile properties of saturated concrete, overcoming the physical limitations of the Grid Method and exploring the influence of the hydrodynamic Stefan effect on the post-peak fracture energy.

Introduction and Experimental Challenge

Accurately characterizing the dynamic tensile properties of water-saturated concrete at high strain rates (> $30\,\mathrm{s}^{-1}$) is essential for predicting the impact resilience of real-world infrastructure. Classical spalling analyses typically rely on the Novikov acoustic approximation, which systematically overestimates dynamic tensile strength by assuming linear-elastic wave propagation until peak tensile stress and ignoring the stiffness dissymmetry caused by pre-peak microcracking [1].

While the Image-Based Inertial Impact (IBII) test, utilizing the Virtual Fields Method (VFM), successfully bypasses these analytical flaws by reconstructing stress fields from full-field kinematics, previous implementations relied on the Grid Method [2]. The Grid Method presents a fundamental limitation: the oven-curing process required for the epoxy grid transfer inherently dries out the concrete, making it impossible to preserve the material's initial moisture content. Consequently, previous full-field dynamic characterizations were strictly limited to oven-dried specimens.

The DIC-VFM Photomechanical Methodology

To overcome this barrier, this work pioneers the coupling of Digital Image Correlation (DIC) with the VFM for dynamic concrete spalling tests. By replacing the physical grid with a high-contrast random speckle pattern (Fig. 1), reliable surface tracking is achieved regardless of the concrete's internal moisture state.

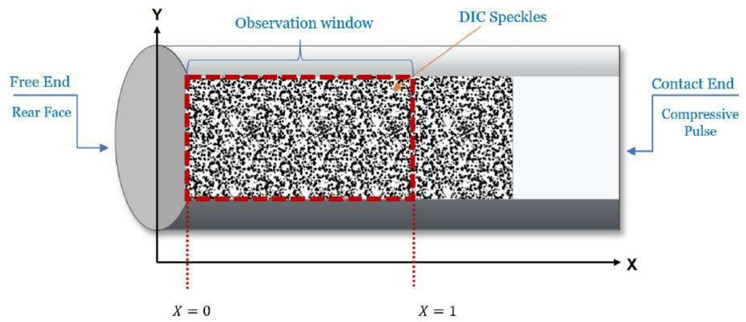


Figure 1: Schematic illustration of the concrete specimen with the applied random speckle pattern for Digital Image Correlation (DIC) tracking.

During the experimental campaign, a modified Hopkinson bar setup is used to impact the sample. A projectile strikes the incident bar, transmitting a dynamic compressive stress wave into the unconfined concrete specimen. Upon reaching the free end of the specimen, this wave reflects as a tensile wave, inducing a spalling fracture.

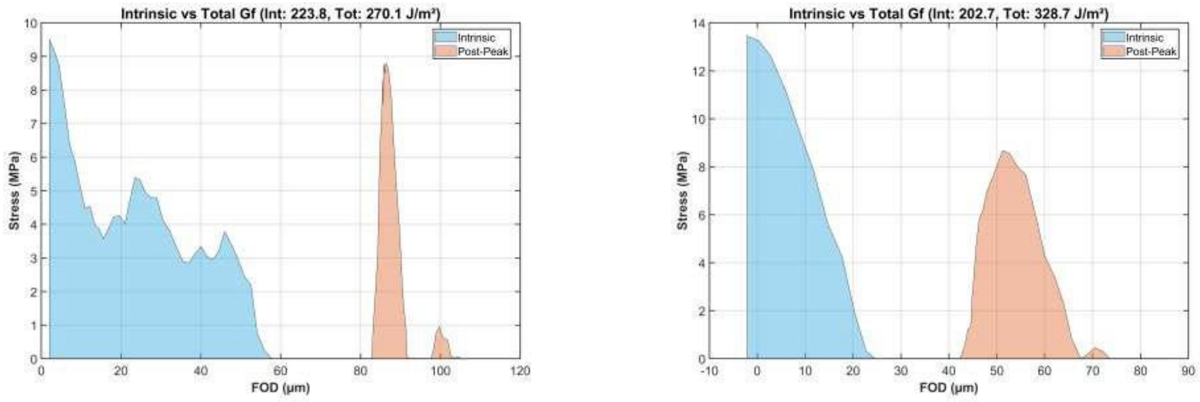
To capture this transient event, a Shimadzu HPV-X2 Ultra-High-Speed (UHS) camera records the deformation at up to 2 million frames per second. The DIC-extracted displacement fields (using a commercial software "MatchID") are numerically differentiated to yield highly resolved full-field acceleration and strain maps. These kinematic fields are then processed via the inertial VFM, where the specimen's own acceleration field acts as a highly resolved internal load cell. This permits the extraction of local stress-strain histories directly at the fracture plane, bypassing the strict requirement of 1D dynamic stress equilibrium and the inherent limitations of 1D acoustic wave approximations.

Dynamic Tensile Strength and Moisture Effects

The experimental campaign investigated the dynamic behavior of concrete across a range of high strain rates (30 to $\sim 200\ \mathrm{s}^{-1}$). The full-field dynamic spalling measurements demonstrated a clear strengthening effect induced by the presence of free water. Specifically, saturated specimens consistently exhibited dynamic tensile strengths 10–20% higher than their oven-dried counterparts across the tested high strain-rate regime. This dynamic enhancement is fundamentally driven by the viscous resistance of free water within the capillary network during rapid loading, a phenomenon directly related to the so called "Stefan effect".

Kinematic Signatures and Fracture Energy

By isolating the true Fracture Opening Displacement (FOD) via DIC and integrating it with the VFM-derived local stress, Stress-FOD curves were constructed.



(a) Dry specimen

(b) Saturated specimen

Figure 2: Comparison of local Stress vs. FOD curves. The saturated specimen (b) exhibits a significantly extended post-peak tail compared to the dry specimen (a).

As shown in Fig. 2, the local Stress-FOD curves reveal a distinct "double stress bump" phenomenon, with kinematic signatures varying significantly depending on the internal moisture state. Dry specimens exhibit a relatively wide initial opening. Conversely, saturated specimens show a constrained opening during this first stress bump but exhibit a significantly broadened and larger FOD during the second bump. This kinematic pattern maps directly onto the energy dissipation: the intrinsic fracture energy (G_f^{int}), associated with the first bump, remains comparable between wet and dry conditions. However, the total energy (G_f^{tot}), associated with the sum of the areas of both curves, diverges sharply, with G_f^{tot}/G_f^{int} ratios of 1.5 for dry specimens increasing to 2 for saturated ones. Free water within the capillary pores provides viscous resistance to the rapid separation of crack faces, a phenomenon governed by the so called Stefan effect, thus extending the fracturing process and increasing the total fracture energy through post-peak viscous dissipation.

Conclusion

The DIC-VFM methodology successfully measures the dynamic tensile properties of saturated concrete, overcoming the physical limitations of the Grid Method and the analytical flaws of classical acoustic equations.

References

[1] Pascal Forquin and Bratislav Lukic´. On the processing of spalling experiments. part i: identification of the dynamic tensile strength of concrete. *Journal of Dynamic Behavior of Materials*, 4(1):34–55, 2018.

[2] Fabrice Pierron and Pascal Forquin. Ultra-high-speed full-field deformation measurements on concrete spalling specimens and stiffness identification with the virtual fields method. *Strain*, 48(5):388–405, 2012.