TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Oldenburger 3D-Tage

Potential of ultra-high speed cameras for quantitative analysis of the material properties in high dynamic concrete impact tests

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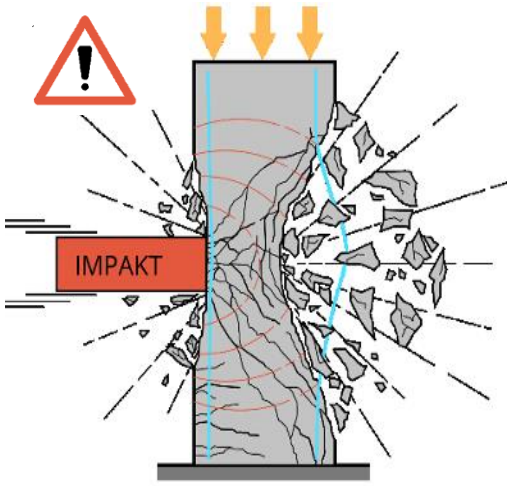
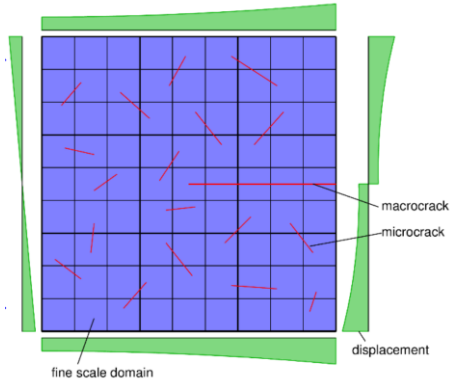
Institute of Photogrammetry and Remote Sensing

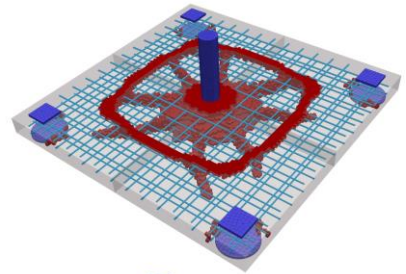
Mineral-bonded composites for enhanced structural impact safety

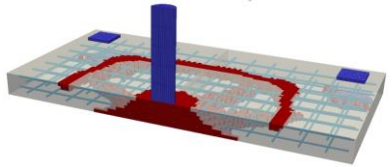
grk2250.de/projects/

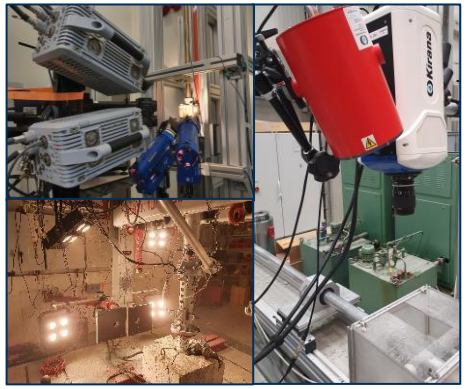
High impact load accelerations

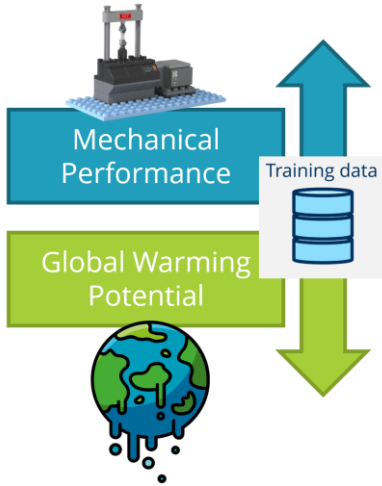






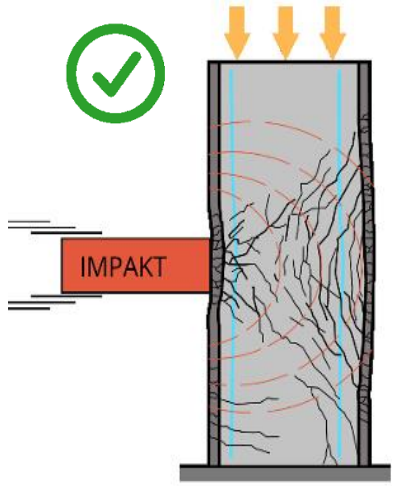






Experimental | Numerical | Interdisciplinary

Impact-resistance performance

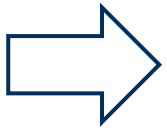


Signorini & Mechtcherine, 2023

Content

1. Evaluation of different ultra-high speed cameras

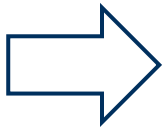
- Setup facility
- Sensor operation
- Measurement potential
- Image acquisition challenges



Acquistion of a new camera with high spatio-temporal resolution

2. Research application case

- Image filtering
- Estimation of the mechanical properties



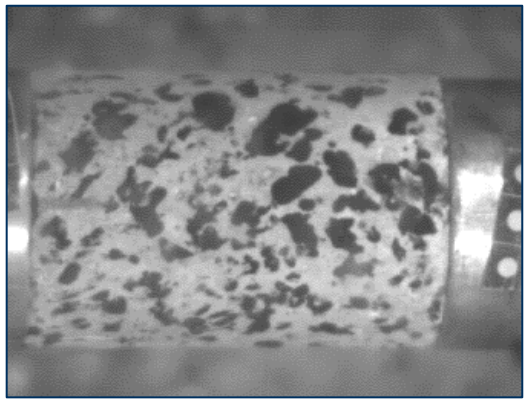
Impact wave propagation velocity

Motivation

Optimization of the material analysis in highly dynamic processes

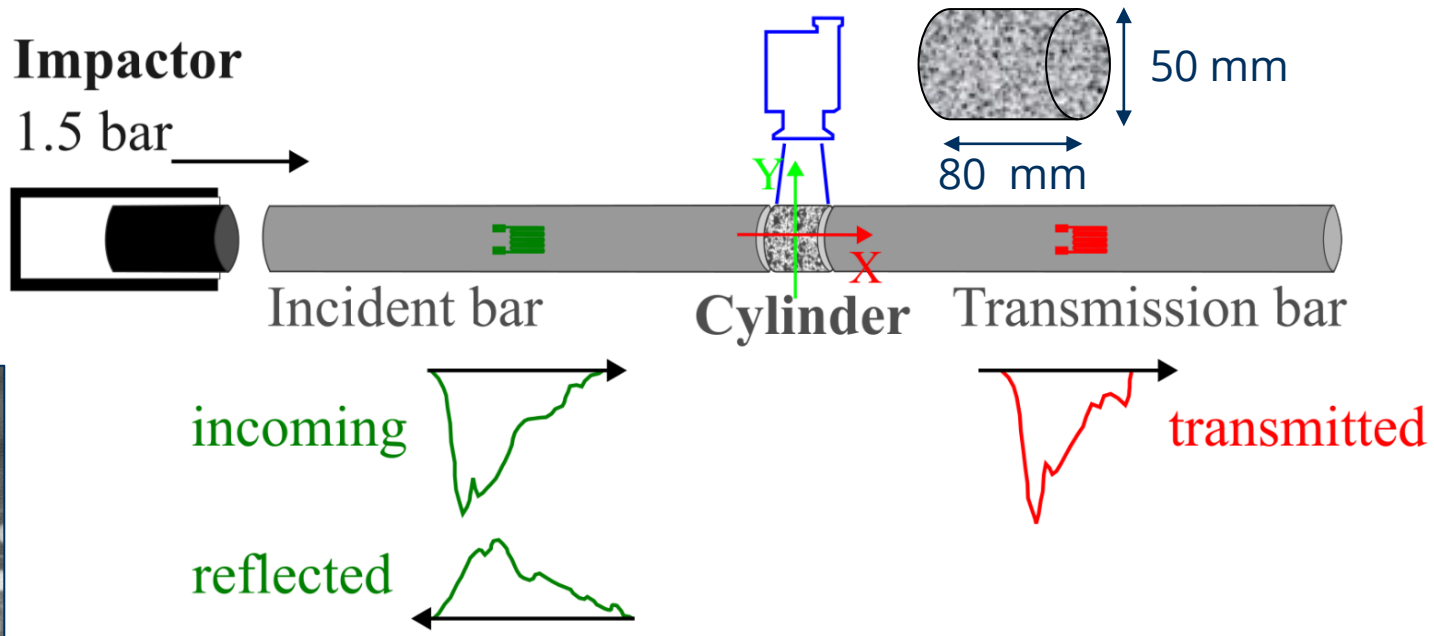
High impact load accelerations

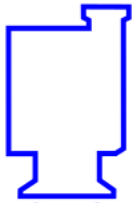
$\dot{\varepsilon} = (10^2 s^{-1}, 10^6 s^{-1})$



Photron SA5 $1024 \times 640\ px$ at $70.000\ fps$

Split Hopkinson Pressure Bar





The Focal Encyclopedia of Photography, 2007

High Speed	$50 - 500\ fps$
Very High Speed	$500 - 100\ kfps$
Ultra High Speed	$100\ kfps - 10\ Mfps$
Super High Speed	$>> 10\ Mfps$

Material properties

$$\varepsilon = \frac{\partial u}{\partial x}$$

$$v = -c_L \varepsilon$$

$$\sigma = -\rho c_L v$$

u *displacement*
x *reference lenght*
v *particle velocity*
c_L *wave velocity*
ρ *mass density*
ε *strain*
σ *stress*
$\dot{\varepsilon}$ *strain rate*

Sensor Operation
CMOS vs. ISIS

$$Fill\ factor = \frac{photodiode\ size}{pixel\ size}$$

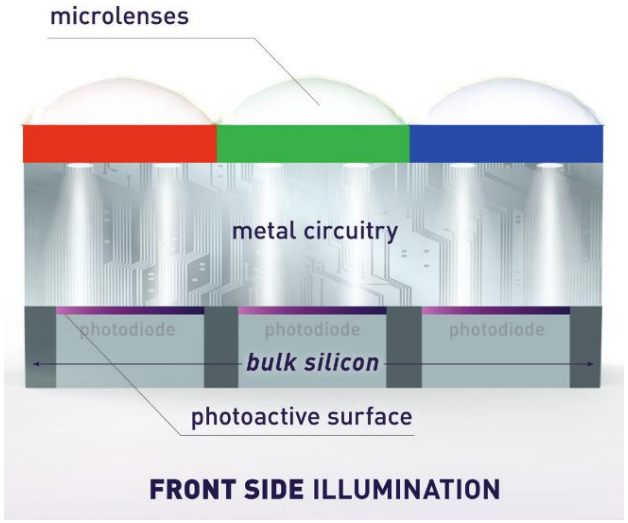
CMOS: Complementary Metal Oxide Semi-conductor

Photron SA-X2 - 480K - 8GB

px size: 20 µm

$128 \times 48\ px$
at $480{,}000\ fps$

$1{,}95\ sec$



Fill factor
$50 - 60\%$

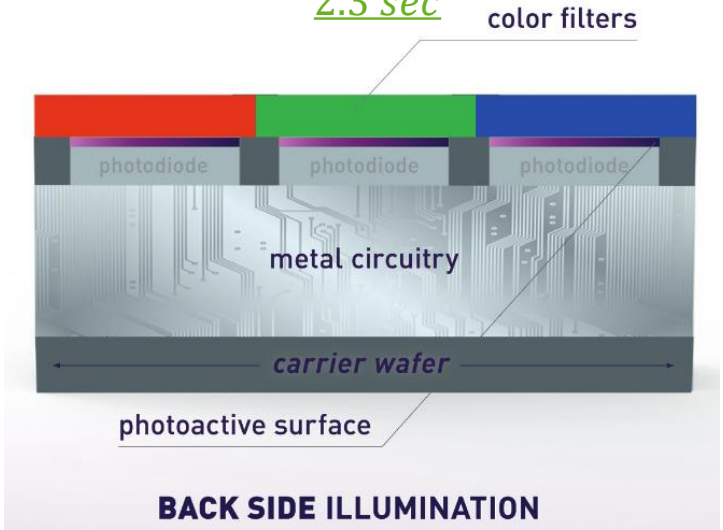
@Phantom BSI

Phantom TMX 7510

px size: 18.5 µm (binned 37 µm)

$1280 \times 32\ px$ or
$640 \times 64\ px$ (binned)
at $1{,}750{,}000\ fps$

$2.3\ sec$



Fill factor
$\approx 100\%$

@Phantom BSI

Sensor Operation
CMOS vs. ISIS

ISIS: In Situ Storage Image Sensor
- **CMOS:** Complementary Metal Oxide Semi-conductor
- **CCD:** Charge Coupled Device

Kirana7M - uCMOS

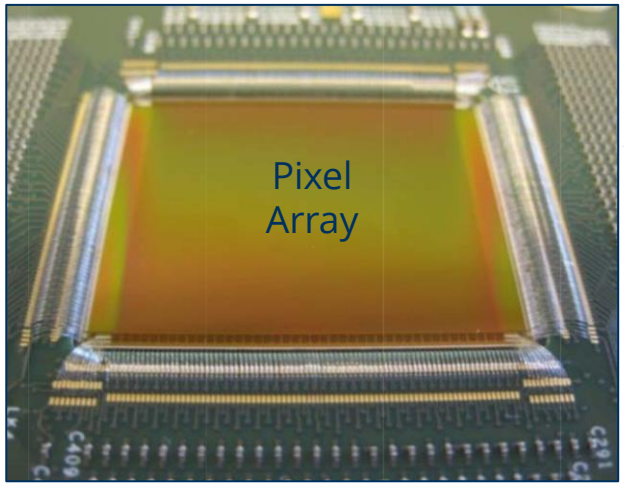
px size: 30 µm

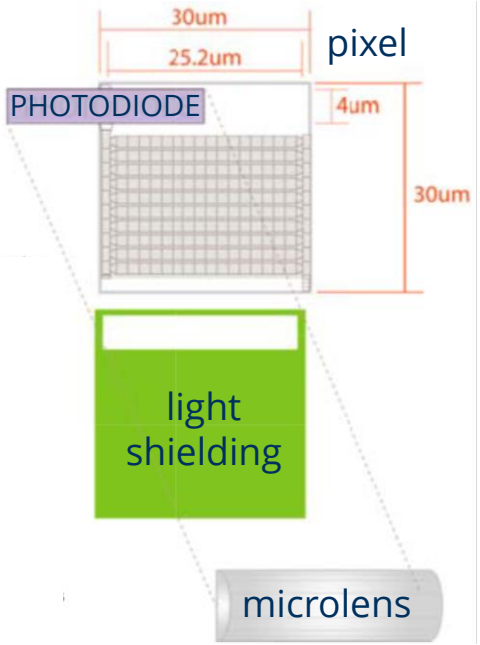
$924 \times 768\ px$

up to $7{,}000{,}000\ fps$

180 frames

Fill factor $\approx 11\ \%$





@Crooks et al. 2013

Shimadzu HPV-X2 - FTCMOS

px size: 32 µm

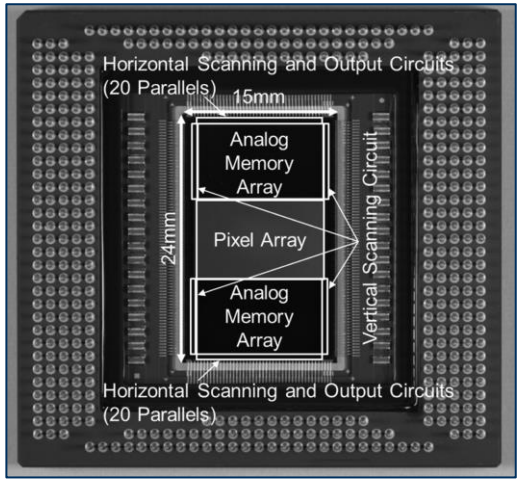
$400 \times 250\ px$

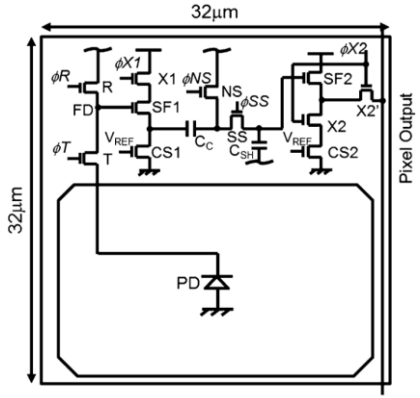
Fill factor $= 55\%$

FP: up to $5{,}000{,}000\ fps$

HP: up to $10{,}000{,}000\ fps$

FP: 128 frames HP: 256 frames



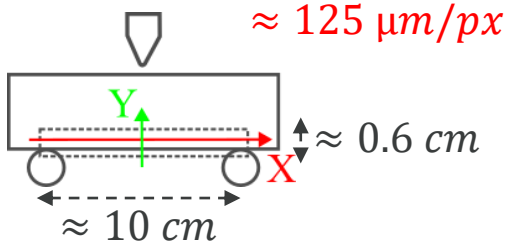


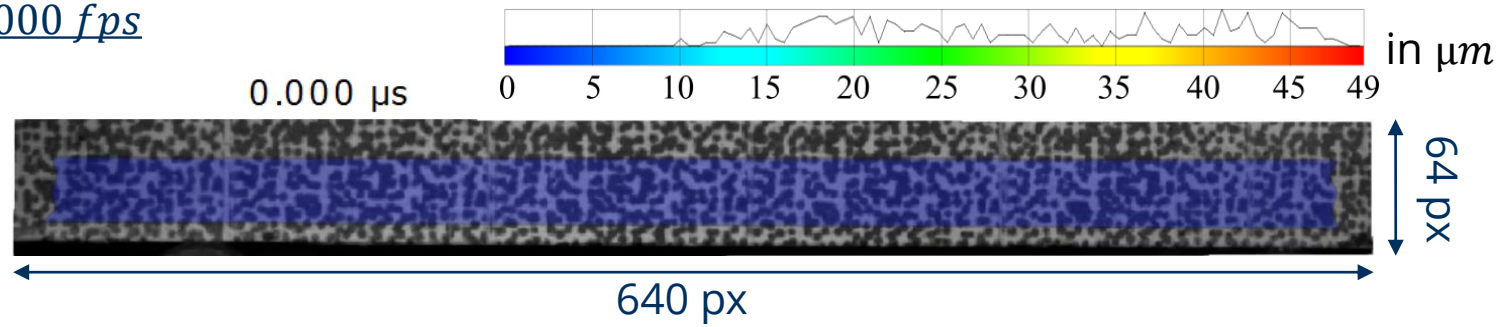
@Tochigi et al. 2013; @ Kuroda et al. 2016

High-impact load application
3 Point Bending Test: in-plane displacement

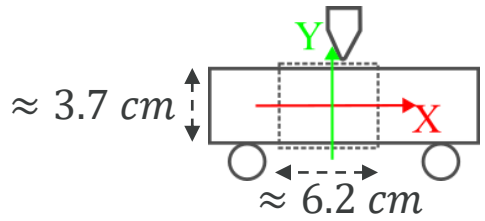
Software: GOM Correlate Pro

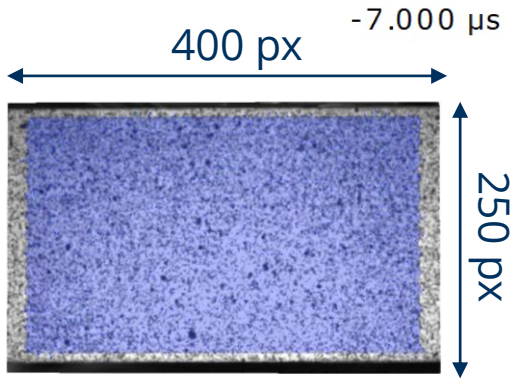
Phantom TMX 7510 binned at 1,700,000 fps

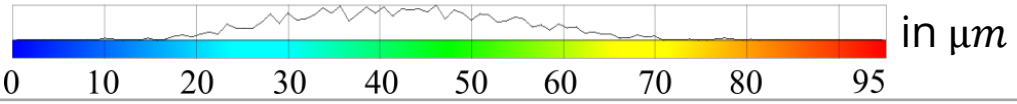


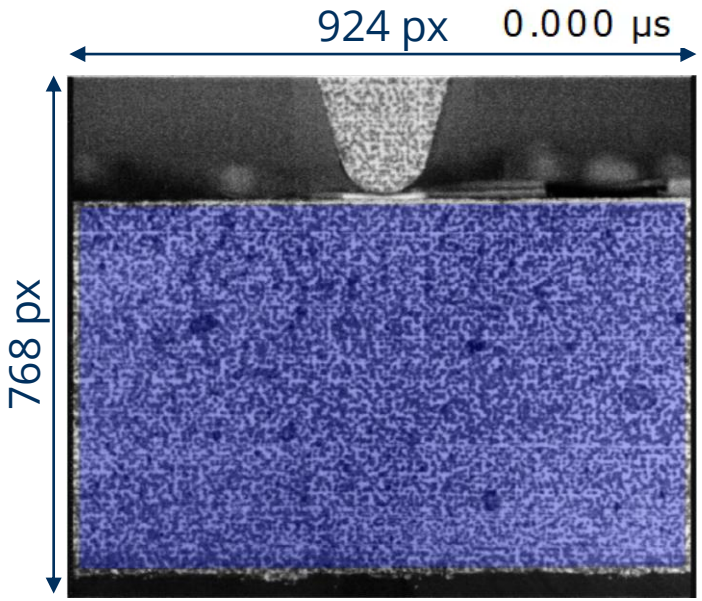


Shimadzu HPV-X2 HP at 1,000,000 fps



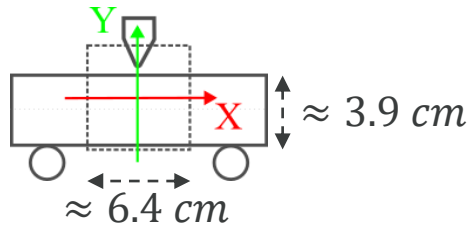






Kirana7M
at 1,500,000 fps

≈ 70 µm/px



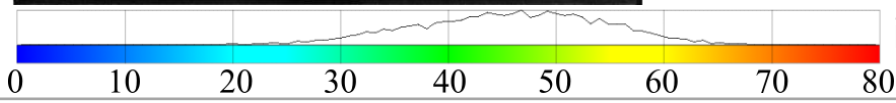
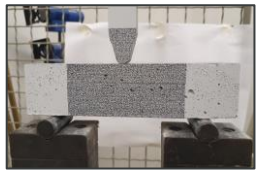


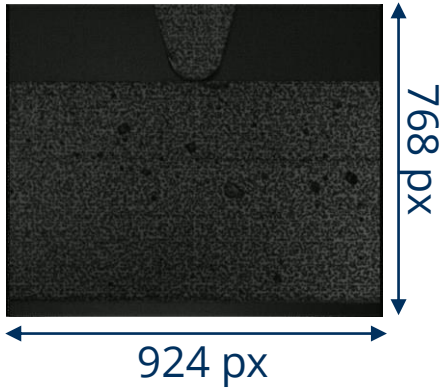
Image acquisition challenges
I. Sensor sensitivity

RIGID-BODY MOTION-BASED PROCEDURE

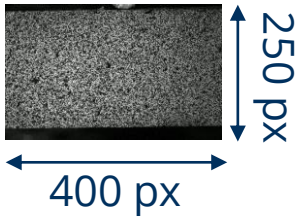
- Static recordings at different frame rates
- Surface coordinates
- Plane Similarity Transformations:
  - Between 2 consecutive stages
  - 4 transformation parameters
  - Result: $(n-1)$ plane mapping errors s_0



Kirana7M
at 1,500,000 fps



Shimadzu HPV-X2
at 2,000,000 fps



Phantom TMX 7510
at 875,000 fps

Rigid
Body
Transformation

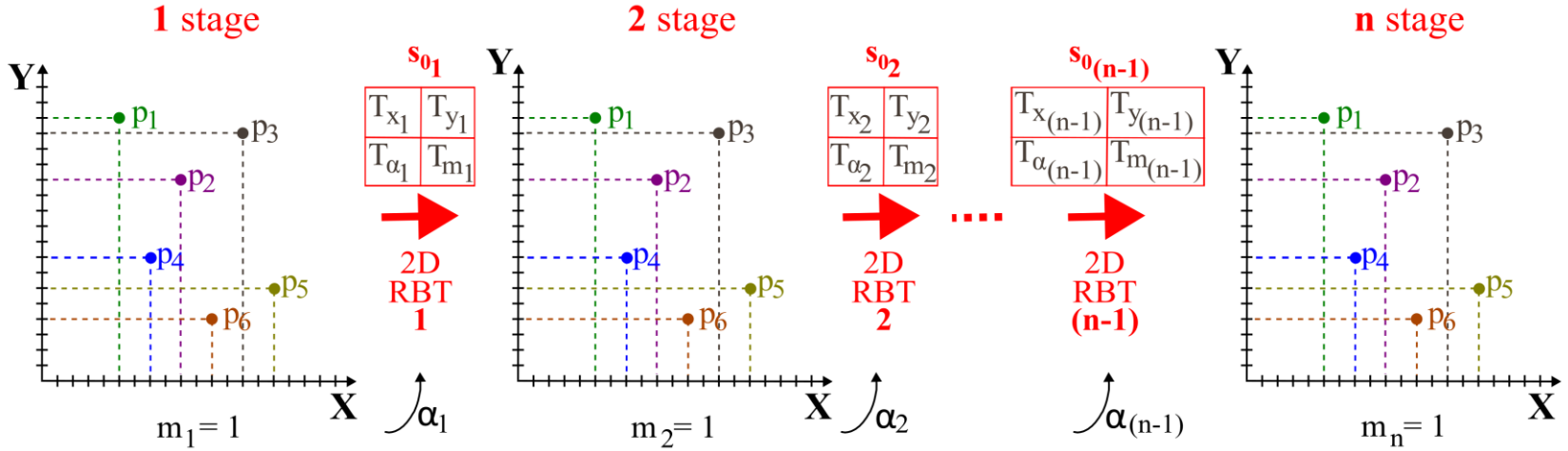
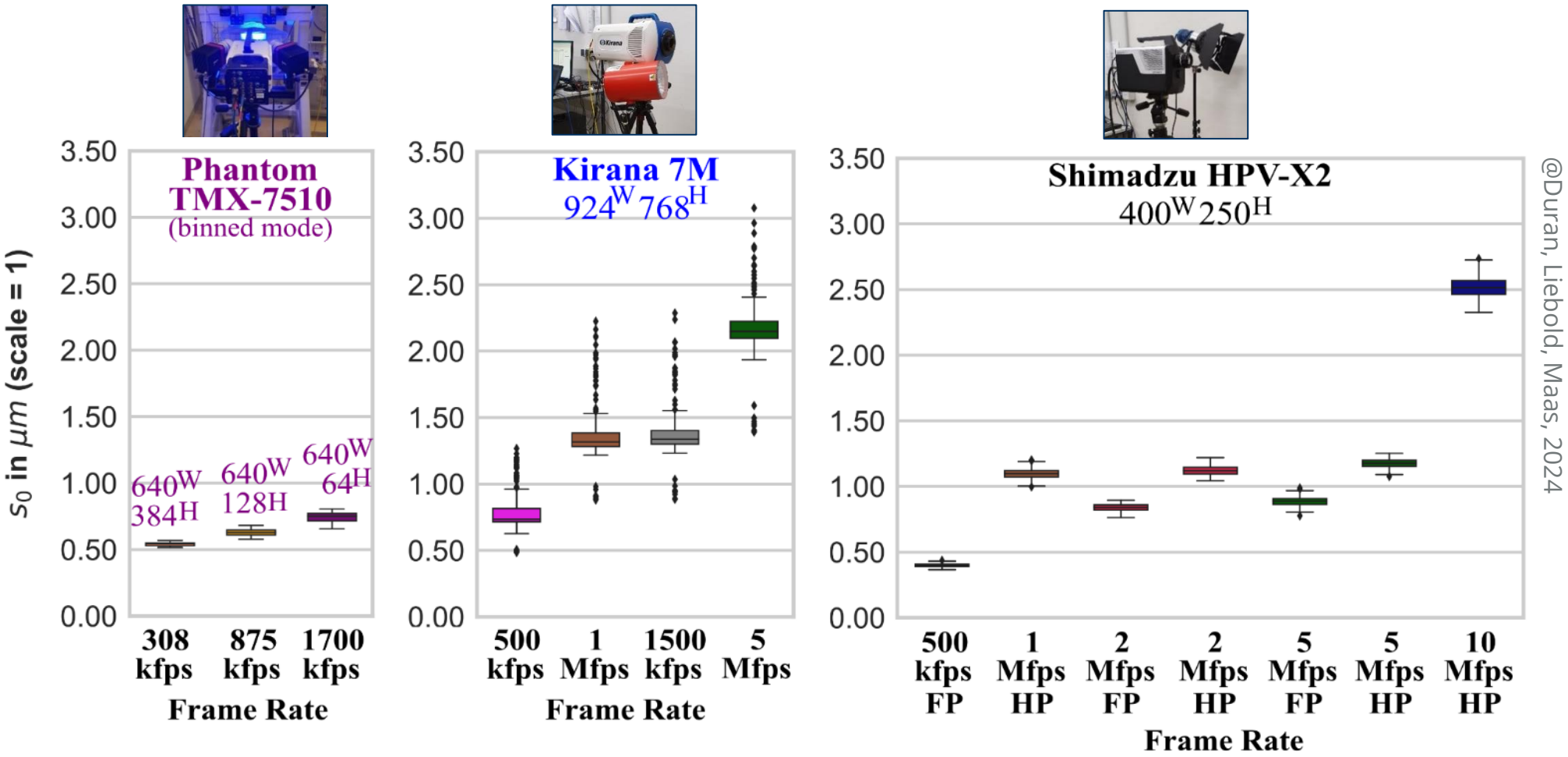


Image acquisition challenges

I. Sensor sensitivity



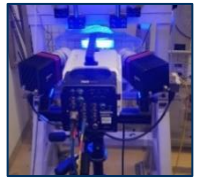
Boxplots of plane mapping errors s_0 obtained from static tests recorded at different frames rates with the three cameras

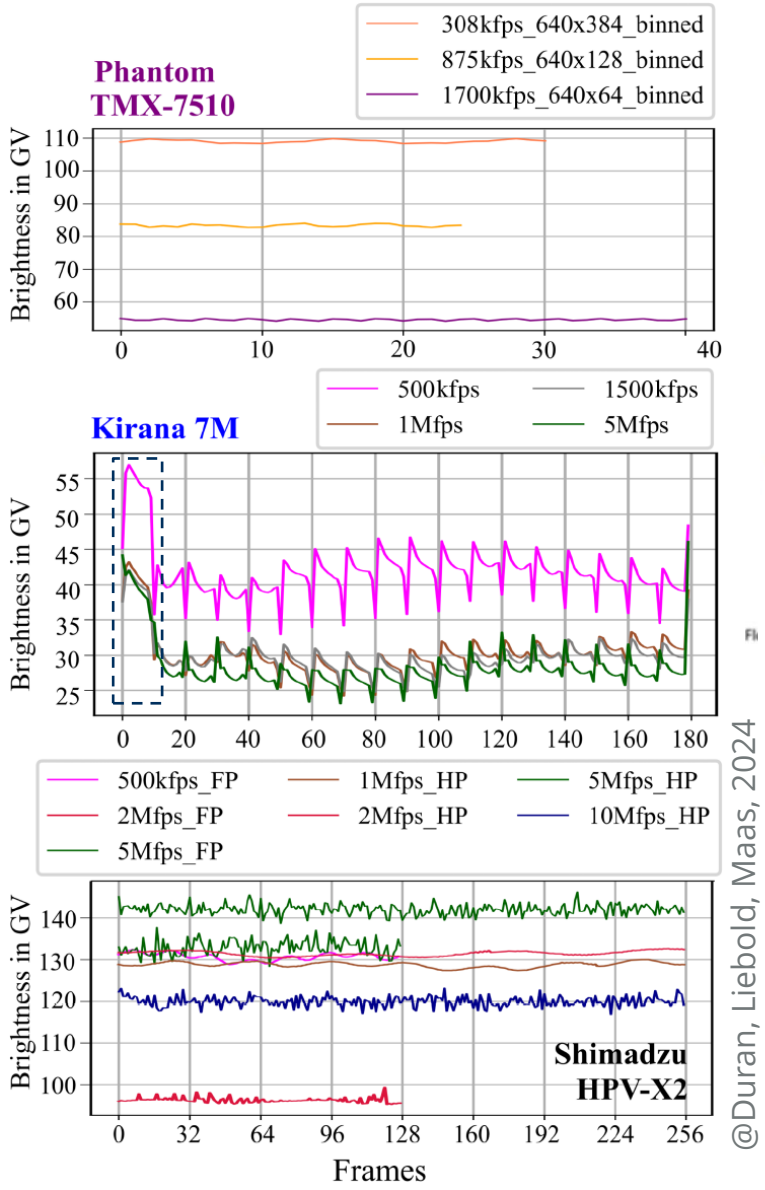
Image acquisition challenges
II. Image Lag

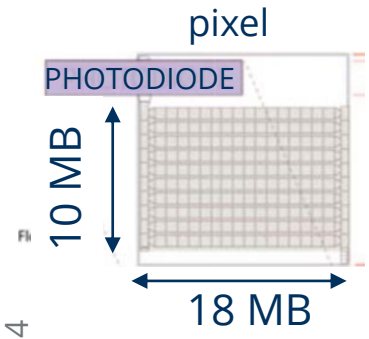
$$B_I = \frac{1}{m * n} \sum_{x=0}^{m-1} \sum_{y=0}^{n-1} I(x, y)$$

@Luhmann, 2023

B	Brightness
I	Image
$m * n$	# pixels (m rows and n columns)
(x, y)	Pixel coordinate Position







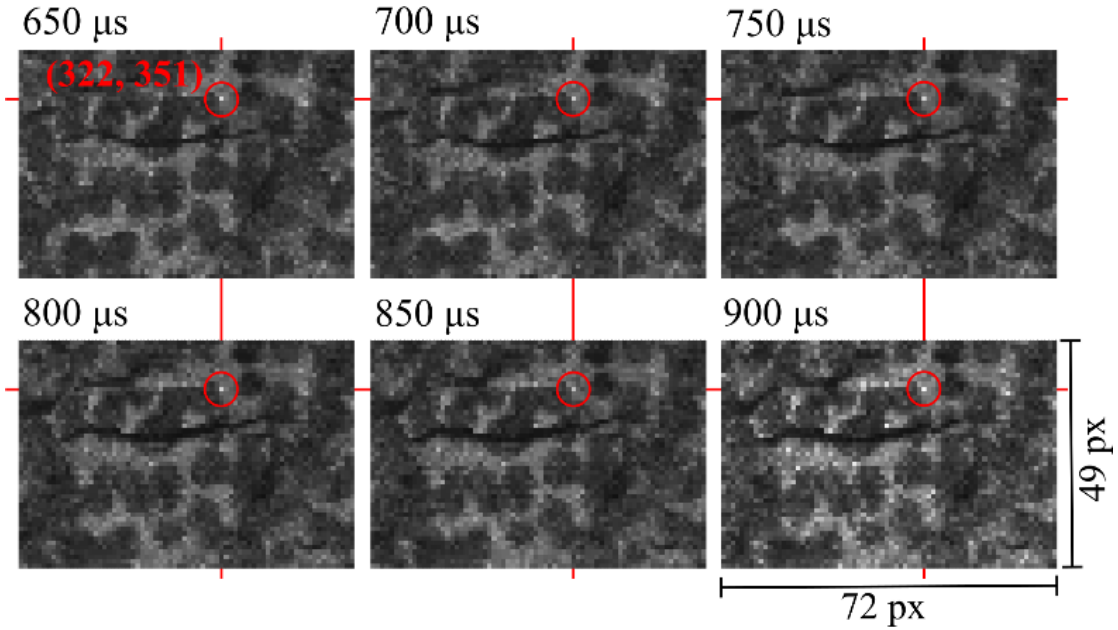
@Duran, Liebold, Maas, 2024

Brightness variations of static recordings

Image acquisition challenges
III. Fixed Pattern Noise

- Radiometric distortions caused by variations in the semiconductor
- Digital compensation to correct the spatial non-uniformity of the intensities
- More visible at high light levels

Kirana7M



@Duran, Liebold, Maas, 2024

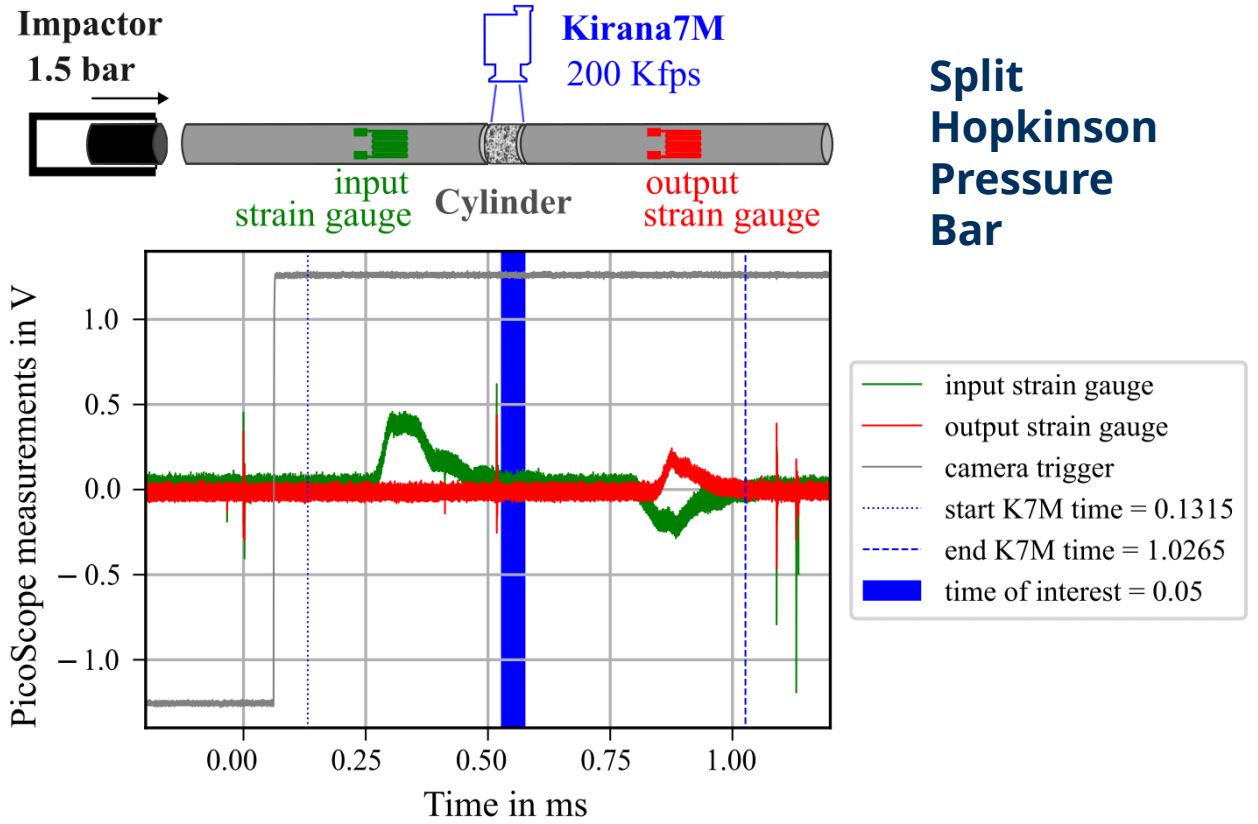
Kirana 7M image section sequence without applying the *Session Black* correction. A red circle around an apparently stationary pixel illustrates this effect.

Image acquisition challenges
IV. Recording Capacity

- Relevant for ISIS sensors due to the limited expansion of the number of cells

Shimadzu HPV-X2	Kirana7M
128 memories	180 memories
	

- A reliable trigger system is required to benefit from the full recording capacity



Split Hopkinson Pressure Bar

Kirana 7M Triggering process system using the strain gauge signals connected to the oscilloscope PicoScope4000Series. A consistent trigger delay of $\boxed{61.559\ \mu s\ \pm 0.012\ \mu s}$ was obtained from this set of experiments

1. Evaluation of different ultra-high speed cameras
Conclusion

Image acquisition challenges

I. Sensor Sensitivity

II. Image Lag

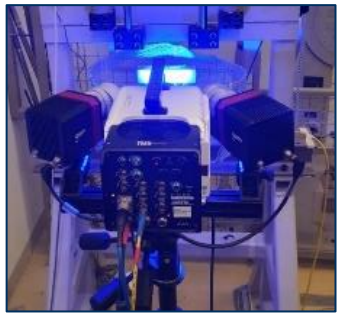
III. Fixed Pattern Noise

IV. Recording Capacity

Measurement potential

High impact load application

Phantom TMX 7510



Shimadzu HPV-X2 - FTCMOS

Kirana7M

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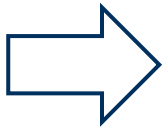

Acquistion of a new camera with high spatio-temporal resolution

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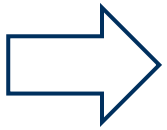
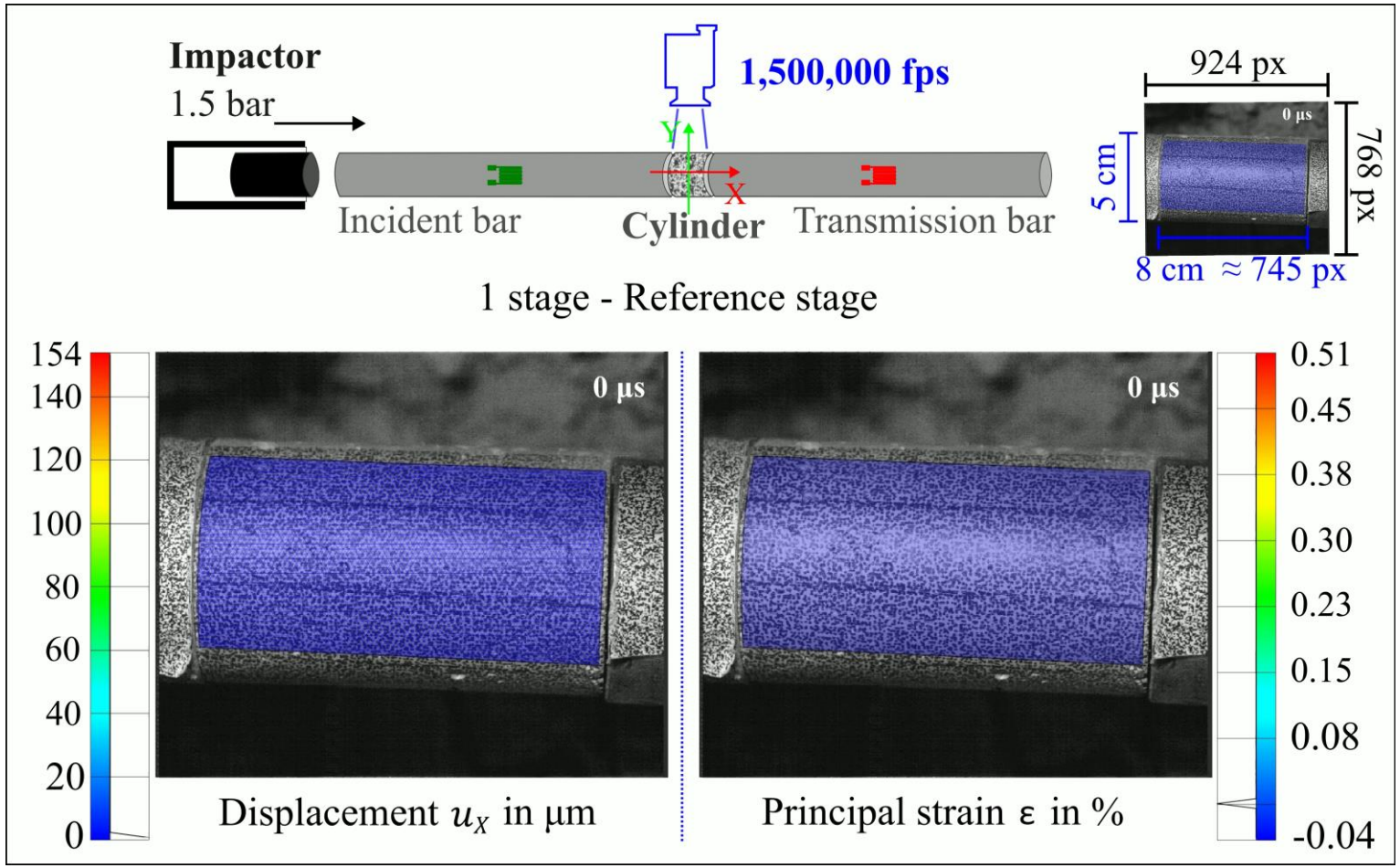


Impact wave propagation velocity

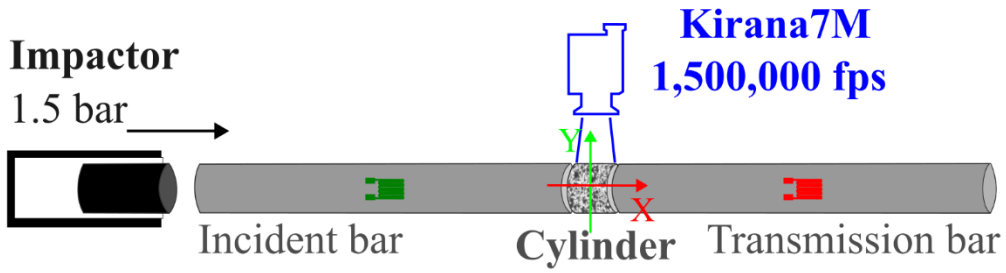
High-impact load application

Ultrahigh-speed imaging in pre- and post cracking stages

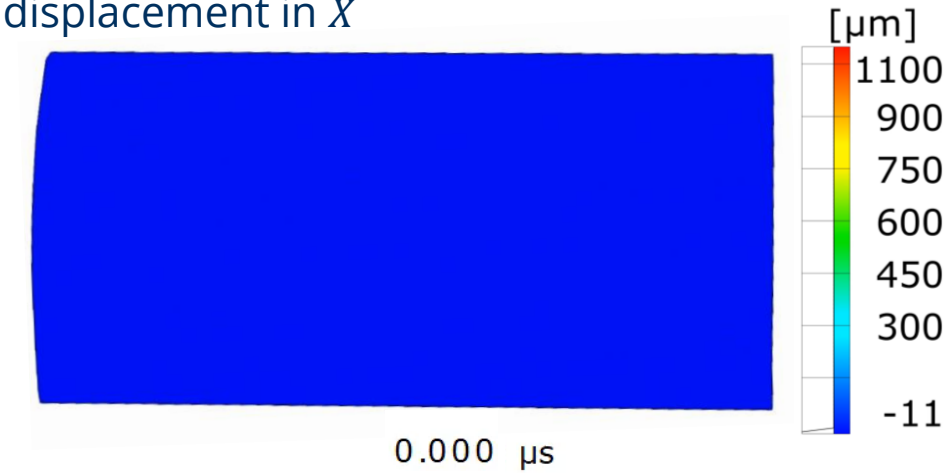


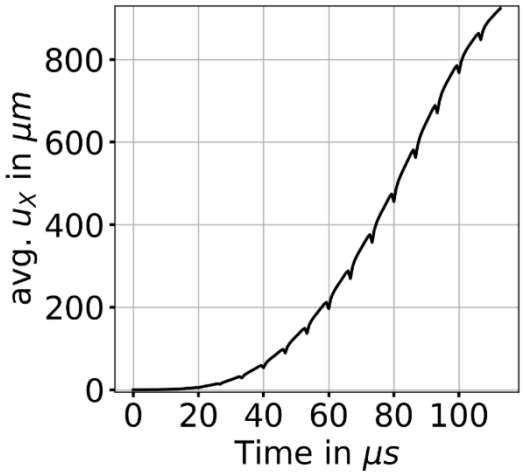
Deformation in the impact direction of a compression test before and after the main crack formation. The test was processed with the GOM Correlate Pro Software.

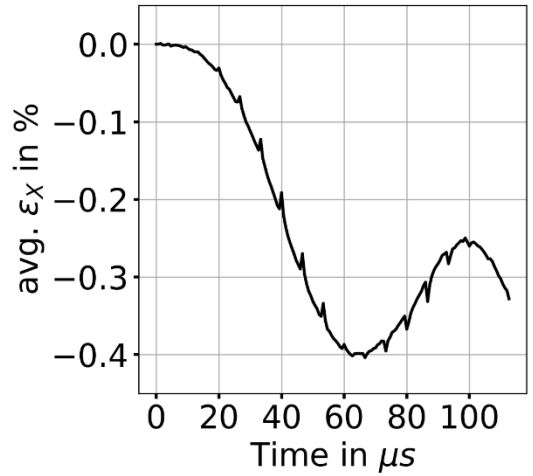
Longitudinal Wave Velocity
Initial results

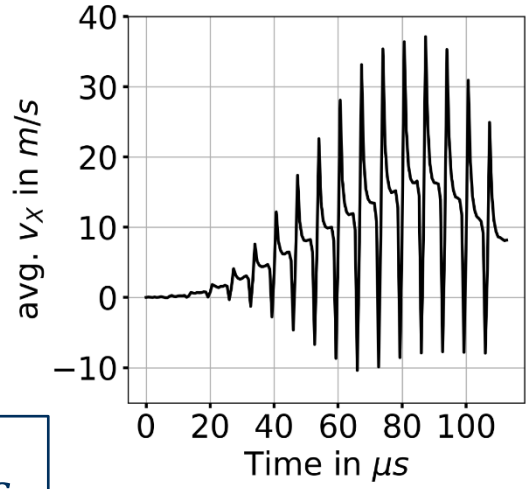


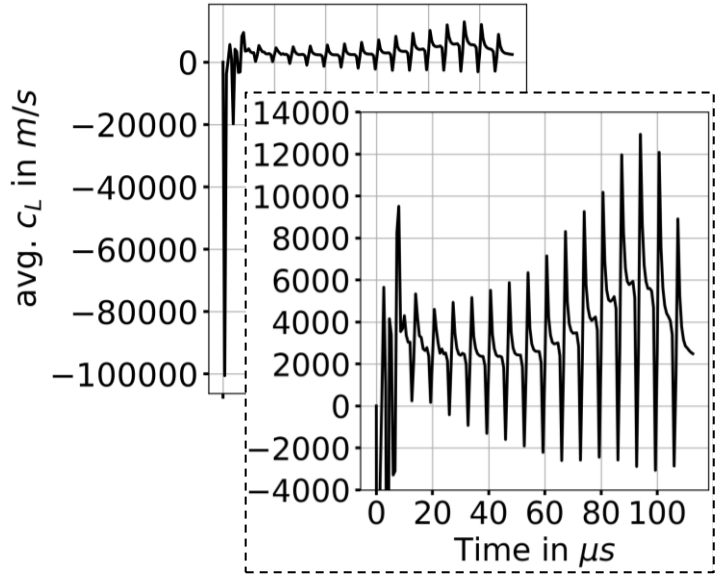
displacement in $\vec{X}$







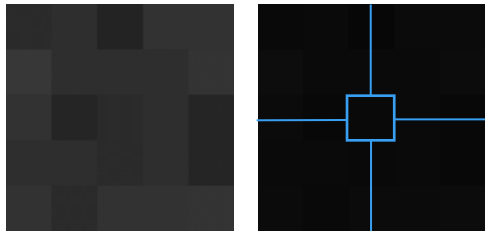


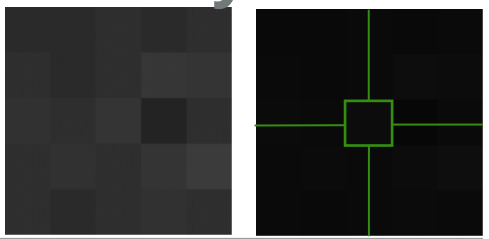


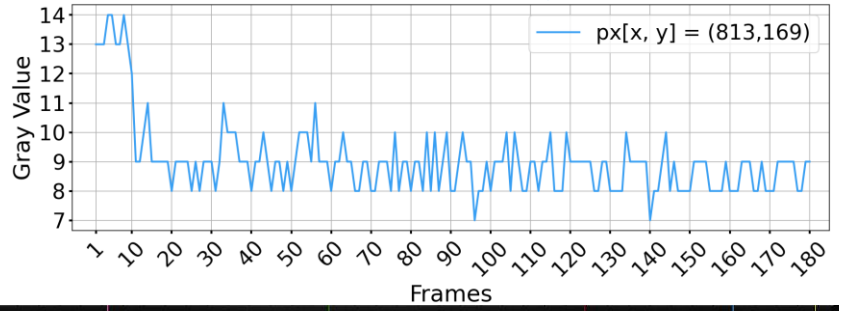
u_X *displacement*
t *time*
v_X *particle velocity*
$\boldsymbol{c_L}$ ***longitudinal wave velocity***
ε_X *strain*

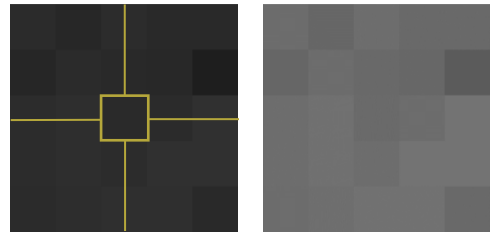
$$\frac{\delta u_X}{\delta t} = v_X = -\boldsymbol{c_L} * \varepsilon_X$$

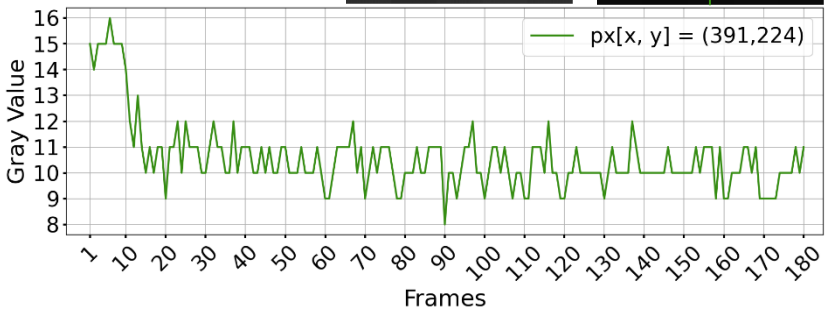
Temporal Image Analysis
Pixel intensity variations

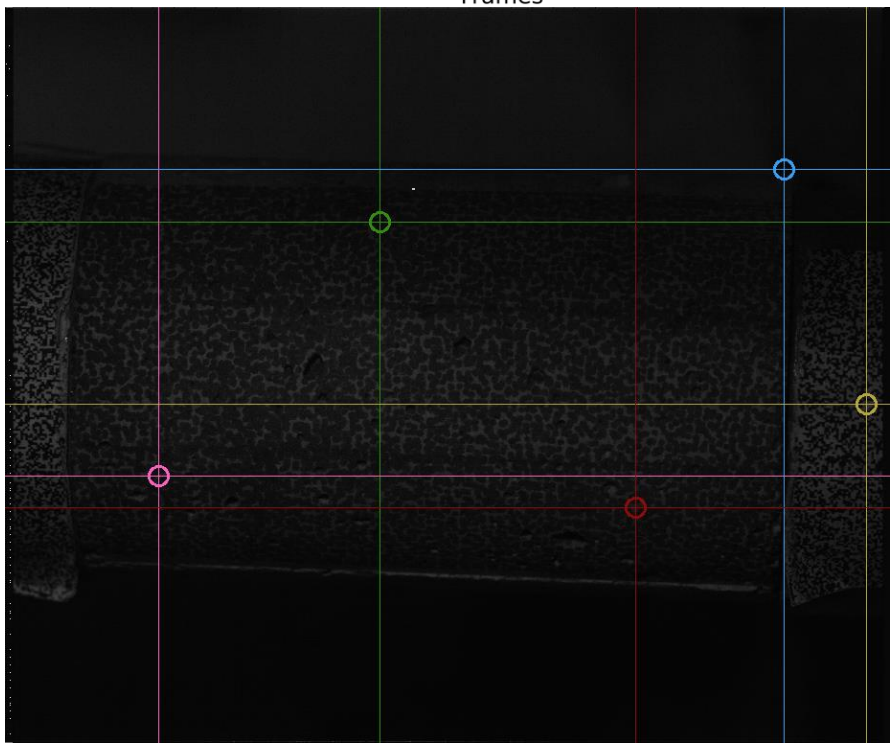


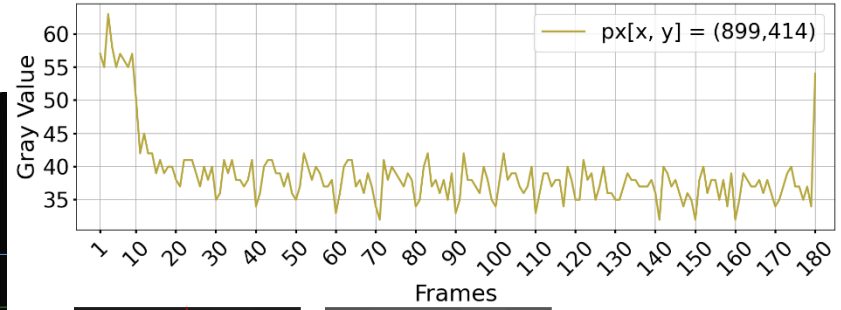


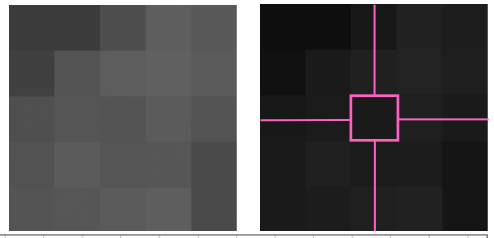


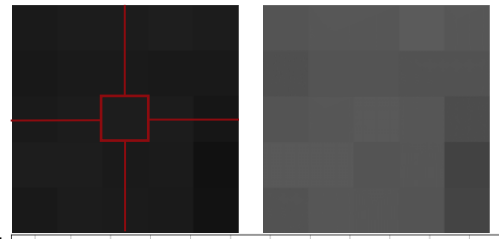


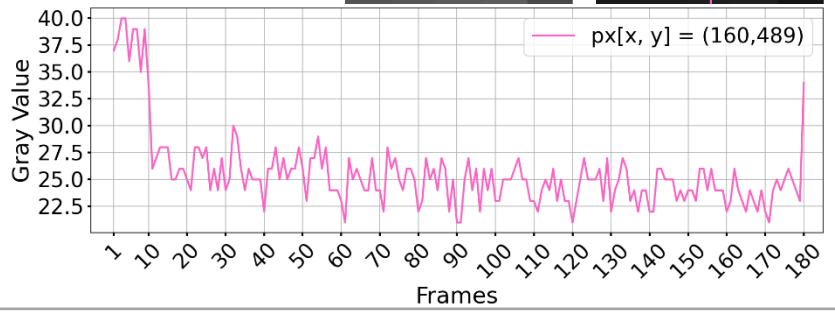


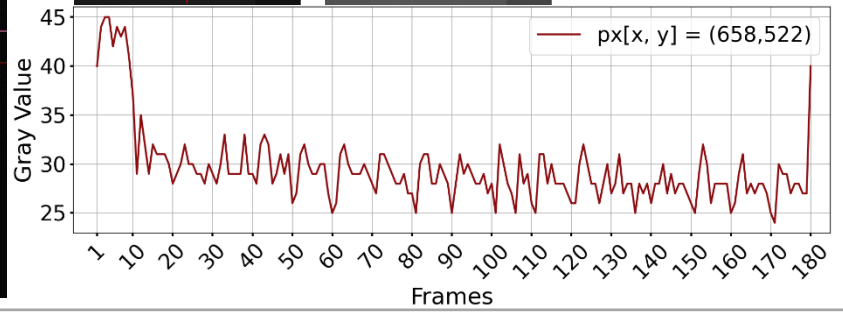








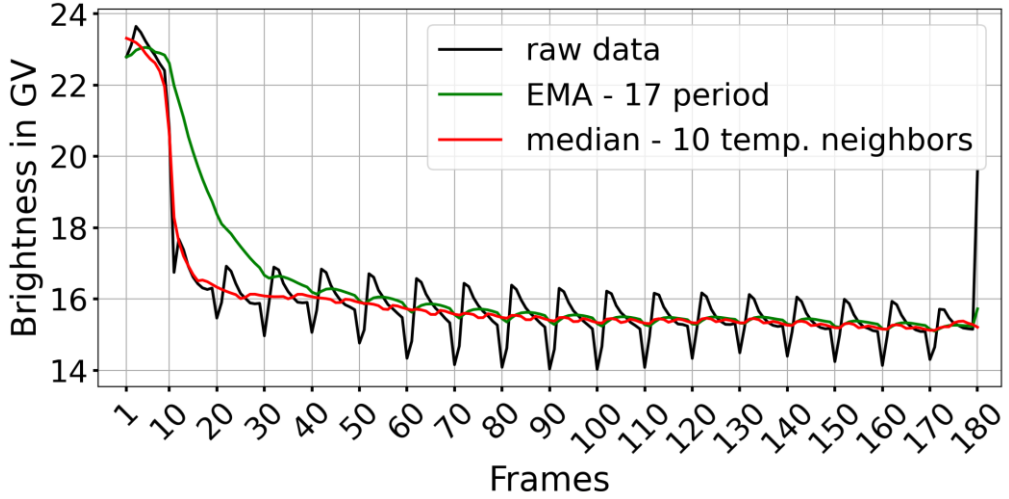


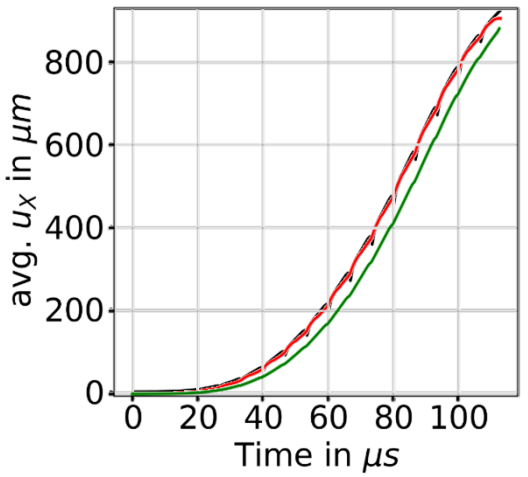


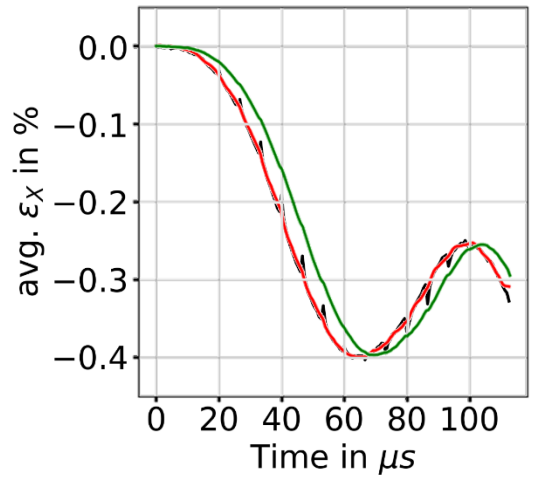
Temporal Image filtering

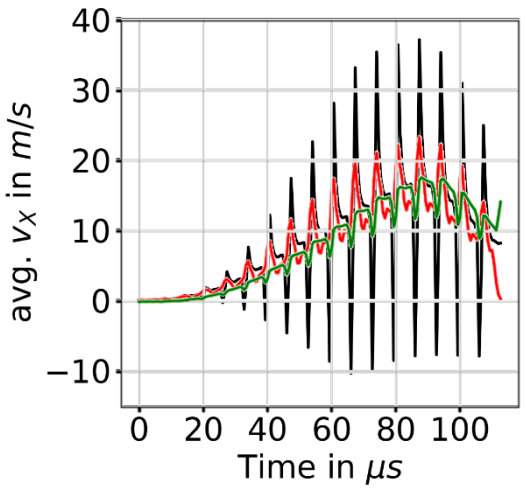
Image signal filtering

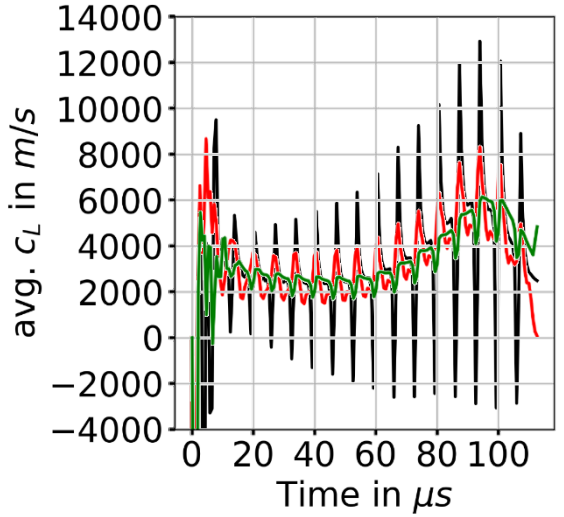
$1.500.000\ fps$











2. Research application case
Conclusion

Kirana7M

High spatial-temporal resolution

Estimation of the material properties with high redundancy

Temporal image filtering

Unsatisfactory correction of image lag using conventional filtering methods.

Most likely due to:

- Varying light intensity of flash lamps
- Object velocity

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