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HIGH-SPEED X-RAY IMAGING FACILITIES FOR IMPACT DYNAMICS AT INTERMEDIATE AND HIGH STRAIN RATES

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Abstract: *This paper presents two advanced in-situ X-ray imaging facilities developed for studying material behavior under dynamic loading conditions at both intermediate and high strain rates. The first facility, optimized for intermediate strain rate testing using an apparatus based on linear motors, utilizes continuous axial X-ray radiography to capture internal material processes during impact testing, with frame rates ranging from* 100 fps *to* 500 fps *using a laboratory camera, and up to* 2000 fps *using a high-speed camera. The second facility, designed for high strain rate testing, integrates a flash X-ray system capable of capturing ultra-high-speed events with frame rates in the tens of thousands of frames per second. This imaging system is coupled with modular Split Hopkinson Bar (SHPB), Direct Impact Hopkinson Bar (DIHB), and Open Hopkinson Pressure Bar (OHPB) devices for dynamic material testing, enabling precise measurements of force, velocity, and displacement. The facilities have enabled successful visualization and analysis of complex deformation and failure mechanisms in various materials, providing significant insights into deformation response under dynamic conditions. Despite challenges related to resolution, frame rates, and contrast, these systems offer valuable insights with the potential for further optimization and comparison with particle-accelerator based results.*

Keywords: high-speed X-ray imaging, impact dynamics, intermediate strain rate, high strain rate, split Hopkinson bar

1. Introduction

In-situ high-speed X-ray imaging is a technique that enables the observation of internal processes in materials during dynamic impacts. It involves the use of X-ray radiation to capture rapid sequences of projections at very high frame rates, enabling the observation of short-duration events comprising various phenomena (Paulson et al., 2020). Such an advanced imaging technique combines the matter penetration ability of X-ray radiation with high temporal and spatial resolution, allowing real-time observation of dynamic events. In this context, the imaging techniques are divided into two main categories: in-situ X-ray radiography and computed tomography. As the observation of dynamic events requires high frame rates, the required high photon flux from the radiation source used to be typically achieved only in particle acceleration facilities, such as synchrotrons (Jakkula et al., 2022; Chen et al., 2014; Hudspeth et al., 2013; Cohen et al., 2019), where frame rates can reach dozens of thousands of frames per second, or even higher (Olbinado et al., 2018). However, the research conducted at experimental impact dynamics laboratory DynLab, Faculty of Transportation Sciences, Czech Technical University in Prague (DynLab FTS CTU), aims to perform similar experiments using laboratory-based setups while maintaining high versatility, flexibility, and in-house nature of measurements. Even though image quality and other measurement parameters are inevitably inferior in comparison to particle accelerators, the results remain invaluable for analysis and understanding the internal processes in heterogeneous materials subjected to complex deformation modes during dynamic loading. Moreover, the developed methods can be tested, optimized, and subsequently applied in synchrotron experiments with higher imaging speed and resolution.

This paper introduces two X-ray imaging facilities developed in recent years at DynLab FTS CTU. It provides detailed descriptions of their typical performance in mechanical testing and X-ray imaging, and presents representative results. One facility equipped with in-house designed LIMA device (Linear Motor

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Impact Testing Actuator) is optimized for experiments conducted from the quasi-static regime to intermediate strain rates (with typical loading velocities up to a few meters per second) and allows continuous X-ray imaging using a sealed high-power X-ray tube. The second facility is designed for high-speed experiments conducted at high strain rates (with typical loading velocities reaching a few dozen meters per second) with imaging based on a flash X-ray source (FXR).

2. Materials and Methods

2.1. In-situ X-ray Radiography and Computed Tomography

In-situ X-ray radiography provides 2D X-ray images of the internal structure of materials, capturing cracks, porosity, voids, and other defects, as well as their evolution during loading. While it does not produce 3D images like computed tomography, radiography is easier to implement, less sensitive to image noise, and allows higher frame rates. At DynLab FTS CTU, two in-situ imaging setups have been established: one for intermediate strain rate testing using the LIMA device, and one for high strain rate testing using split Hopkinson pressure bar (SHPB), direct impact Hopkinson bar (DIHB), and open Hopkinson bar (OHPB) devices. Computed tomography (CT) enables 3D imaging by rotating the specimen during X-ray exposure and reconstructing its volume from 2D projections. As high-speed in-situ CT is not currently available at DynLab, this method is limited to pre- and post-mortem scans. These are used for subtraction tomography analysis (see (Šleichrt et al., 2021)) and provide reference data for assessing total damage or constructing numerical models via finite element simulations.

2.2. Facility for In-situ X-ray Imaging at Intermediate Strain Rates

The X-ray laboratory for in-situ X-ray imaging of experiments at intermediate strain rates was established in 2022. The facility consists of an X-ray shielded bunker housing a high-power X-ray tube (HP225, Comet X-ray, Switzerland) and an imaging system comprising a scintillation panel (CsI, Hamamatsu, Japan) and a laboratory optical camera (Kiralux CS135, Thorlabs, USA). The scintillation panel converts X-rays to visible light, which is then recorded by the laboratory camera. The X-ray tube operates at a maximum voltage of $225\,\mathrm{kV}$ and a power of $1800\,\mathrm{W}$, with a focal spot size of $1\,\mathrm{mm}$. This setup allows for a typical frame rate ranging from $100\,\mathrm{fps}$ to $500\,\mathrm{fps}$ during continuous X-ray radiography, with no limitation on the maximum number of frames. The imaging parameters must be optimized to balance image quality, resolution, contrast, and motion blur effects. This challenge can be mitigated by using a high-speed camera capable of capturing up to $2000\,\mathrm{fps}$, while minimizing the radiation exposure of the camera to extend its lifetime and also reduce the stochastic effects arising from interactions of the intensive radiation with the CMOS chip represented typically by occurrence of zingers in the acquired projections.

The imaging system is coupled with an in-house designed LIMA device, a high-performance linear motor-based device for dynamic impact testing. The device features two linear sledges driven by high-thrust iron-core linear motors (LMSA34G, HIWIN, Taiwan) on a shared guidance framework, allowing independent or synchronized motion, which effective doubles the impact velocity and acceleration. The load bearing structure of the system includes parallel linear rails (SNS size 35, Bosch GmbH, Germany) and high-strength aluminum alloy sledges (EN-AW-6082-T6). Force measurements are carried out using strain-gauge load-cells (LCF450, FUTEK, USA) or piezoelectric load-cells (CFT, HBM, Germany). Position and velocity are monitored by high-precision optical encoders (Renishaw, UK). The device is equipped with impact dampers (ACE GmbH, Germany) for energy dissipation and supports various test configurations, including compressive, tensile, and bending tests, with adaptable ballast for varying impact velocities. This system performs dynamic experiments within a velocity range from the quasi-static regime to intermediate strain rates. The facility has been successfully used for experiments with various materials over the past two years ranging from 3D printed lattices to ultra-high performance fiber reinforced concrete.

2.3. Facility for In-situ Flash X-ray Radiography at High Strain Rates

The X-ray laboratory for in-situ X-ray imaging at high strain rates was established in 2021, with the first impact experiments successfully completed in 2023 (Fíla et al., 2024). The facility is equipped with a FXR system MAT 300-4C (Scandiflash, Sweden) for ultra-high-speed X-ray imaging using a multi-anode FXR tube with four individual anodes and an acceleration voltage in the range of $100 - 300\,\mathrm{kV}$. The FXR device

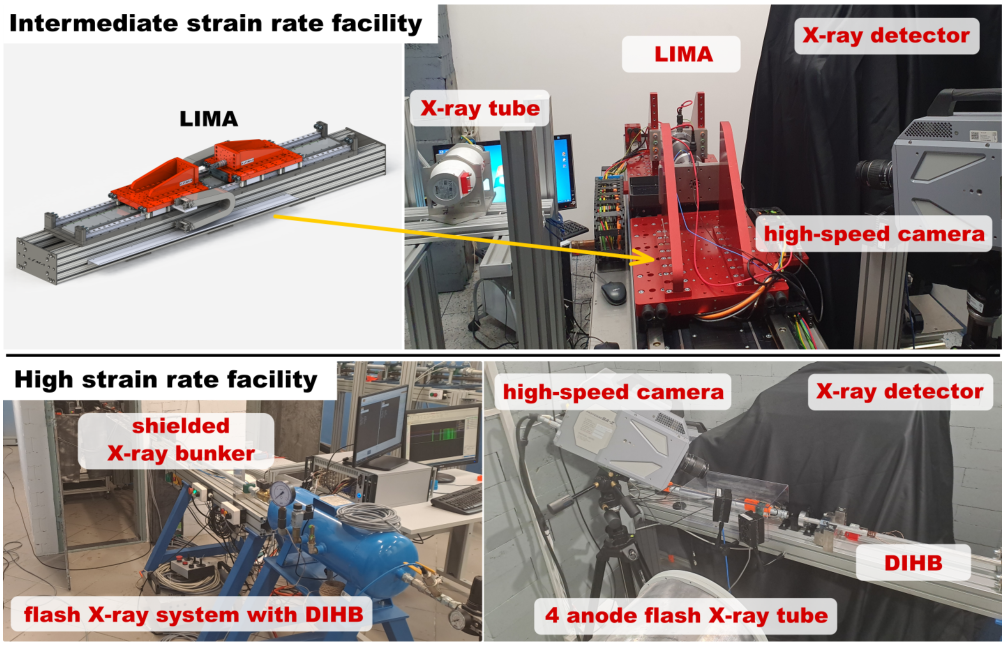

Fig. 1: Intermediate and high strain rate testing facility with in-situ high-speed X-ray imaging.

generates extremely short, high-intensity bursts of X-rays (flashes) by rapidly discharging high-voltage energy into the X-ray tube. These X-rays pass through the object, and a detector on the opposite side captures the transmitted X-rays to create an image. The synchronization and timing of the flash pulses are crucial to capture the X-ray image at the precise moment of the studied event. Due to the architecture of the system, the discharge current of $10\,\mathrm{kA}$ and exposure time of $20\,\mathrm{ns}$ are constant and cannot be changed. A large-area scintillating screen (CsI, Hamamatsu, Japan) coupled with a high-speed camera is used for acquisition of projections, capable of capturing images at a nominal frame rate of tens of thousands of frames per second. However, as the flash X-ray system is equipped with four imaging channels, only four projections can be captured during the experiment. A high-precision mirror and additional lead lining is employed to avoid radiation exposure of the high-speed camera.

The DynLab FTS CTU high strain rate testing facility integrates the FXR system with modular SHPB, DIHB, and OHPB systems for dynamic material testing. The SHPB setup uses a gas-driven striker bar to generate the strain waves, with strain gauges on the incident and transmission bars to establish the force and velocity data. The DIHB configuration involves a projectile ($100-1000\,\mathrm{mm}$ in length) directly impacting the specimen, achieving velocities of up to $50-200\,\mathrm{m\cdot s^{-1}}$ for more uniform loading and accurate measurements. The OHPB arrangement minimizes wave dispersion by unconstrained boundary conditions on the bar faces, enabling longer measurement time windows ideal for testing of complex materials such as cellular structures. Strain gauges and high-frequency data acquisition systems are used for precise measurements, while digital image correlation (DIC) and laser velocimetry can be used to track specimen deformation. This combination of advanced instrumentation provides a robust platform for high-precision, high-strain-rate testing. Since the exposure time of the X-ray flashes is very short and extremely intensive, the frame rate, signal-to-noise ratio, and motion blur do not present significant challenges. The focal spot size of the tube is $1\,\mathrm{mm}$, ensuring image quality comparable to the system used for intermediate strain rates. However, problems related to electromagnetic pulses generated during discharges have caused noise peaks in the measured data. Moreover, the timing of the individual flashes requires careful adjustment, often necessitating the use of additional specimens to identify optimal projection timings based on the mechanical response. The facility has been employed in several experimental campaigns with various materials over the past two years. Both testing facilities (intermediate and high strain rates) are shown in Figure 1.

3. Results

To demonstrate the capabilities of both facilities, sandwich panels filled with shear thickening fluid (STF) were tested under dynamic penetration across a broad range of strain rates. The force-displacement curves

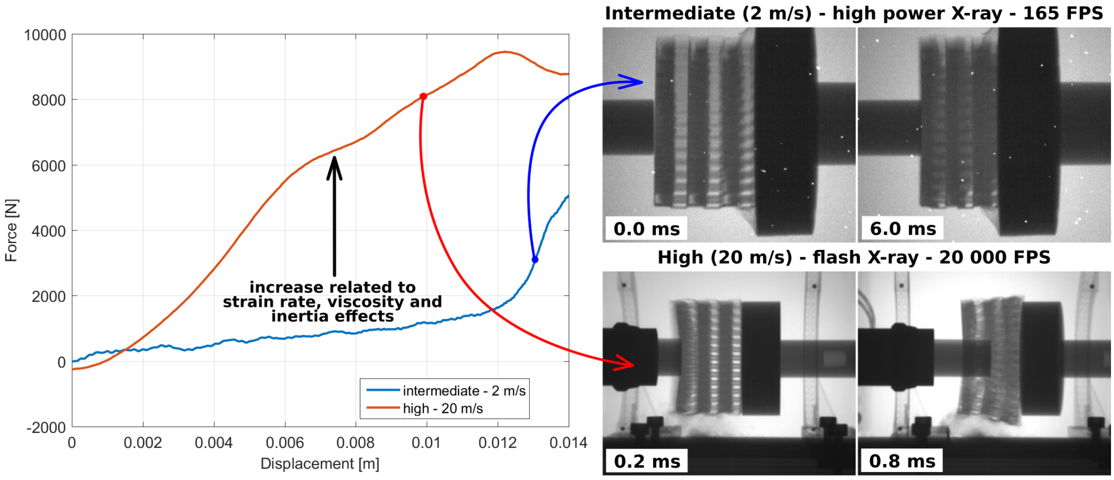

Fig. 2: Force-displacement diagrams (left) and X-ray images (right) of an additively manufactured sandwich panel filled with shear thickening fluid at different velocities.

exhibited a more gradual deformation at intermediate strain rates, whereas a sharp force increase accompanied by localized damage was observed at high strain rates. X-ray imaging confirmed uniform damage at intermediate strain rates and concentrated damage at the impact site at high strain rates, illustrating the influence of strain rate on material behavior. The results are presented in Figure 2.

4. Conclusions

This paper presented two in-situ X-ray imaging facilities developed at DynLab FTS CTU for the study of materials under dynamic loading conditions at intermediate and high strain rates. Both facilities have been successfully utilized in numerous impact dynamics studies, providing valuable insights into internal material processes during dynamic loading. The intermediate strain rate facility, employing continuous X-ray radiography, and the high-speed flash X-ray system for high strain rate testing have both proven effective in capturing critical events and contributing to the understanding of failure mechanisms and material behavior. Despite certain limitations related to resolution and frame rates, these systems have significantly advanced the analysis of dynamic processes in materials and can be further optimized for future synchrotron experiments.

Acknowledgments

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