# Inertial impact tests to characterize the high strain rate response of PMMA

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**Abstract.** PMMA is frequently used in applications where it may be subjected to impact loads. This manuscript proposes a new experimental technique to identify the material properties of glassy polymers at high strain rates. First, the virtual fields method, the inverse technique used to determine the material parameters, is presented. Next, the experimental protocol for performing inertial impact tests is described. Finally, the results of the test campaign and parameter identification are discussed.

## Introduction

PMMA is frequently used a glass substitute in windows due to its low density and transparency. These polymer windows must be able to resist impact loads, and as a result, are often subjected to strain rates exceeding 100 $s^{-1}$. PMMA is viscoplastic material, with its modulus, yield stress, and post-yield behavior changing with increasing strain rate. While the mechanical response of PMMA has been extensively studied at low strain rates, far fewer studies have quantified its response at high strain rates. In this manuscript, a new method for characterizing the high strain rate response of PMMA is presented. The technique can be broadly applied to characterize the elasto-plastic response of glassy polymers. The grid method and an ultra-high-speed camera are used to obtain time resolved displacement fields on the surface of a PMMA specimen during an inertial impact test. The virtual fields method (VFM) is then used to inversely identify the Young's modulus, Poisson's ratio, and yield stress of PMMA from the collected full-field data.

## Virtual Fields Method

The VFM is an inverse technique for the identification of material properties based on the weak form of the equilibrium equation. For the specific case of plane stress, the principle of virtual work can be written as:

$$-\int_S \sigma(x,y,t)\cdot\varepsilon^*(x,y,t)\,dS+\int_{\partial S}\mathbf{T}\cdot\mathbf{u}^*(x,y,t)\,dL=\int_S \rho\,\mathbf{a}(x,y,t)\cdot\mathbf{u}^*(x,y,t)\,dS \tag{1}$$

where $\sigma$ is the stress tensor, $\varepsilon^*$ and $\mathbf{u}^*$ are the virtual displacement and associated virtual strain, respectively, $\mathbf{T}$ is the traction vector on the boundary of the body, $\rho$ is the density of the material, and $\mathbf{a}$ is the acceleration, $S$ is the surface of the solid, and $\partial S$ is the edge of the solid where tractions are applied. The VFM has been well developed for linear elastic problems and the material parameters will be identified using noise-minimizing virtual fields for elasticity [1]. The yield stress will be identified using the stress gauge virtual fields, which enable the average stress at any vertical section to be calculated from the acceleration.

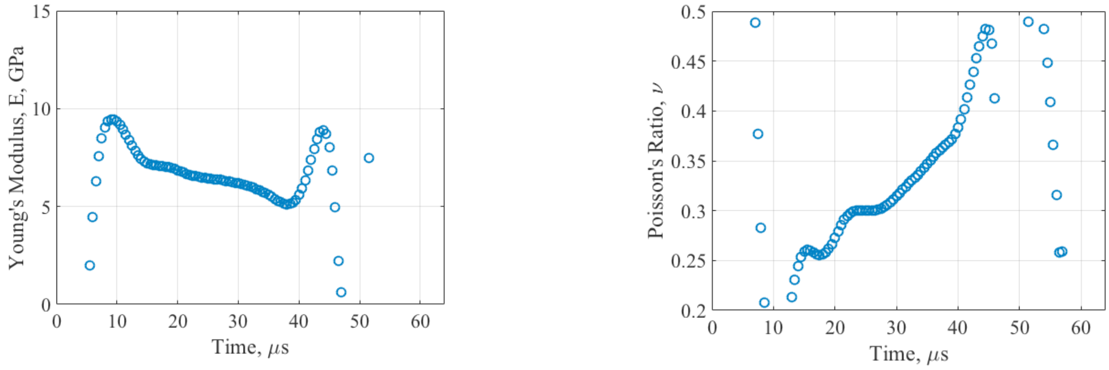
## Experimental Protocol

The gas gun facilities at the University of Southampton were used to perform the inertial impact tests. Each specimen was L=70 mm long by H=45 mm tall with a thickness of 4 mm. A gas gun is used to fire a cylindrical aluminum projectile towards the waveguide and specimen. A grid with a pitch of 1 mm was applied to the specimen using transfer paper. An ultra-high-speed camera (HPV-X, Shimadzu) was used to image the sample during the impact test. A total of 128 frames were recorded at a rate of 2 Mfps. Using the grid method [2], the collected images were analyzed to produce time-resolved displacement maps. To minimize the influence of measurement noise, the displacement field at each pixel was filtered in time using a Savitzky–Golay filter. The displacement was then numerically differentiated twice to produce maps the acceleration. Before calculating the strain, the displacement was spatially smoothed using a Gaussian filter.

## Results and Discussion

Four PMMA specimens were impacted at a nominal speed of 25 m/s. The maximum strain rate attained in the tests was approximately 1000 $s^{-1}$. Using the noise optimized virtual fields for elasticity, the value of the Young's Modulus and Poisson's ratio can be identified as a function of time. Fig. 1 shows the evolution of the elastic parameters for a representative sample. While the modulus is relatively stable overtime, Poisson's ratio is far more sensitive to measurement noise leading to oscillations in the identified value. Averaging the identified values from 12 – 35 $\mu$s where the identification is stable, the mean values Young's modulus and

Poisson's ratio calculated are E = 6.2 GPa and $\nu = 0.32$. The identified values correspond well the values reported in literature for PMMA [3] where E and $\nu$ were reported to be 6 GPa and 0.33, respectively, at strain rates near 1000 $s^{-1}$. Similar values and trends were identified for the remaining three samples where the average values for all four samples are E = 5.82 ± 0.26 GPa and $\nu$ = 0.32 ± 0.013.




(a) (b)

Fig. 1 Identified values of (a) Young's Modulus and (b) Poisson's ratio as a function for time for sample 1

An additional four samples were impacted at 50 m/s and are being analyzed to identify the rate-dependent yield stress. The stress gauge virtual fields enable to the average stress in any vertical section along the specimen length to be calculated. These average stress-strain curves will be used to identify the yield stress for each sample. In Fig. 2, the average stress along a vertical section approximately 35 mm from the impact edge is presented. The yielding response of the PMMA is clearly observed followed by elastic unloading. To identify the yield stress a cost function which includes each vertical section is built. The stress calculated from acceleration using the stress gauge virtual fields is subtracted from the stress calculated from the constitutive equation. The cost function is iteratively evaluated for different values of the yield stress until the cost function reaches a minimum.

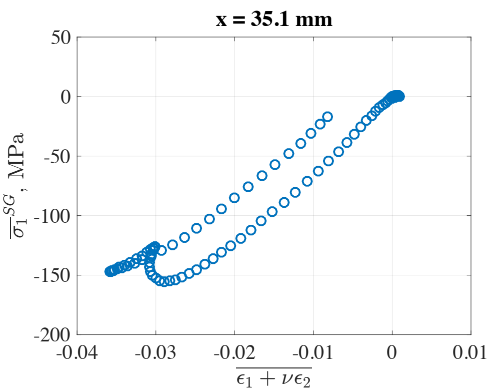



Fig. 2 Average stress in a vertical section 34.9 mm from the impact edge for a sample impacted at 50 m/s.

In summary, full-field deformation data was obtained from the images collected using an ultra-high-speed camera. This full-field data was then used as an input to the VFM to perform an inverse identification of the material parameters. Currently, work is underway to analyze the results of second test campaign where the impact speed was increased to 50 m/s and identify the rate-dependent yield stress of PMMA.

## References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