



**HAL**  
open science

# Fast x-ray radiography to study the dynamic compaction mechanisms in a rigid polyurethane foam under plate impact

P Pradel, F Malaise, T. de Resseguier, M Olbinado, A Rack, D Eakins

## ► To cite this version:

P Pradel, F Malaise, T. de Resseguier, M Olbinado, A Rack, et al.. Fast x-ray radiography to study the dynamic compaction mechanisms in a rigid polyurethane foam under plate impact. shock compression of condensed matter, Jun 2019, Portland, United States. 10.1063/12.0000941 . hal-03428494

**HAL Id: hal-03428494**

**<https://hal.science/hal-03428494v1>**

Submitted on 15 Nov 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Fast x-ray radiography to study the dynamic compaction mechanisms in a rigid polyurethane foam under plate impact

Cite as: AIP Conference Proceedings **2272**, 110010 (2020); <https://doi.org/10.1063/12.0000941>  
Published Online: 04 November 2020

P. Pradel, F. Malaise, T. de Rességuier, et al.



View Online



Export Citation

## ARTICLES YOU MAY BE INTERESTED IN

[Ultra-high-speed x-ray imaging of shock-induced cavity collapse in a solid medium](#)

AIP Conference Proceedings **2272**, 110003 (2020); <https://doi.org/10.1063/12.0000933>

[Effect of texture on elastic precursor decay in magnesium alloy AZ31B](#)

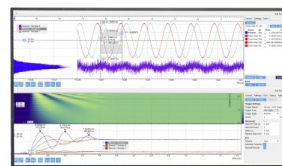
AIP Conference Proceedings **2272**, 120009 (2020); <https://doi.org/10.1063/12.0000818>

[Shock structure and spall behavior of porous aluminum](#)

AIP Conference Proceedings **2272**, 120015 (2020); <https://doi.org/10.1063/12.0000913>

Challenge us.

What are your needs for  
periodic signal detection?



Zurich  
Instruments



# Fast X-ray Radiography to Study the Dynamic Compaction Mechanisms in a Rigid Polyurethane Foam Under Plate Impact

P. Pradel<sup>1, a)</sup>, F. Malaise<sup>1</sup>, T. de Ressaiguiet<sup>2</sup>, M. Olbinado<sup>3</sup>, A. Rack<sup>3</sup>, and D. Eakins<sup>4</sup>

<sup>1</sup>CEA CESTA, 15 avenue des Sablières CS60001, 33116 Le Barp Cedex, France

<sup>2</sup>Institut Pprime UPR3346 CNRS-Université de Poitiers-ENSMA, 11 boulevard Marie et Pierre Curie, 86962 Futuroscope Chasseneuil Cedex, France

<sup>3</sup>European Synchrotron Radiation Facility CS40220, 38043 Grenoble Cedex 9, France

<sup>4</sup>University of Oxford, Oxford OX1 2JD, United Kingdom

<sup>a)</sup>Corresponding author: pierre.pradel@cea.fr

**Abstract.** This article presents results of plate impact experiments coupled to in situ X-ray radiography, performed on a polyurethane foam, to visualize its deformations during the propagation of a stress wave. A two-wave structure associated with the propagation of an elastic precursor and pores compaction has been observed. A phenomenological compaction model, implemented in a dynamic explicit one-dimensional hydrocode, was used to simulate the dynamic macroscopic response of the foam. By using this model, which has previously been calibrated and validated by performing dedicated dynamic experiments, it is possible to compare calculated and experimental waves velocities and improve interpretations. Quasi-static tests coupled to in situ X-ray tomography have also been performed to study the mechanical behavior under low strain rates. Experimental results show that the compaction is due to bending and buckling of cell edges, and then matrix failure. Strain rate dependence of the foam behavior has been observed.

## INTRODUCTION

Polymeric foams are commonly used in aerospace, automotive, marine and military industries for the protection against crashes or high velocity impacts [1-2]. Their light weight and their energy absorption abilities are of great interest to develop efficient systems that mitigate effects of intense (several GPa) and brief (1-1000 ns) stress wave loadings. At the CEA CESTA, these loadings are representative of the ones that are carried out with the Laser MégaJoule (LMJ), in France. Effective protection systems against laser irradiation or very high velocity impacts of small debris must be developed to protect some diagnostics or samples support devices.

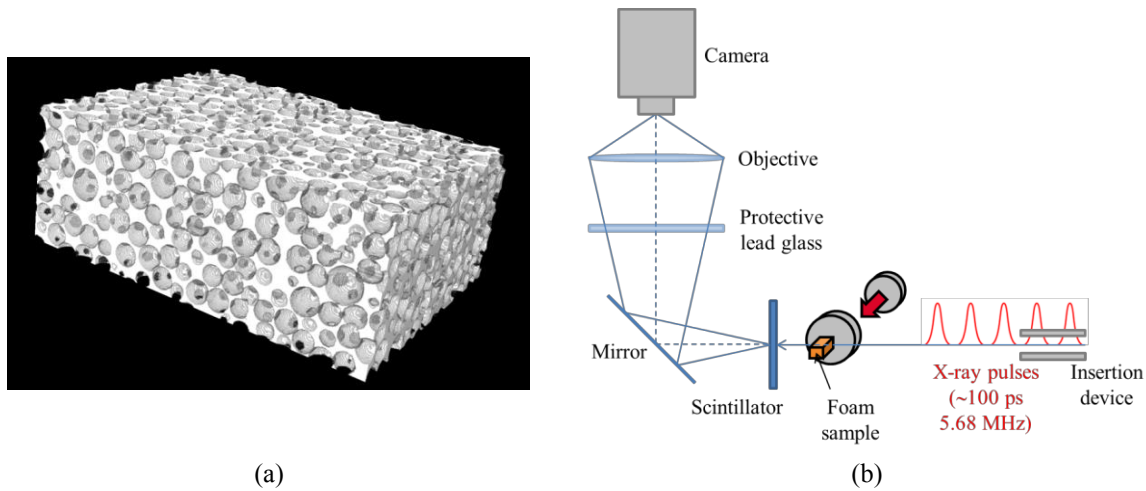
Expected devices consist of a metal shield, to interact with the laser beam or debris, and a mitigator layer, to reduce the intensity of stress waves transmitted to the component to protect. A rigid closed cell polyurethane foam (320 kg/m<sup>3</sup>) has been chosen for its energy absorption abilities. Quasi-static and dynamic experiments (magnetic pressure, plate impact, electron beam and laser-driven shock experiments) have already been performed to provide valuable data [3-5] for the development and validation of a constitutive model.

The objective of this paper is to visualize deformation mechanisms into the foam during the propagation of a stress wave. Plate impact experiments coupled to in situ X-ray radiography have been performed at the European Synchrotron Radiation Facility (ESRF). Quasi-static tests coupled to in situ X-ray tomography have also been performed at the Institut Pprime to study the mechanical behavior under low strain rates.

# PLATE IMPACT EXPERIMENTS COUPLED TO IN SITU X-RAY RADIOGRAPHY

## Experimental set-up

A 3D X-ray tomographic view of the foam is shown in Fig. 1.a. Porosities are mainly around 100  $\mu\text{m}$  of diameter, and cell walls thicknesses are about a few dozen of micrometers. A schematic overview of the experimental set-up is shown in Fig. 1.b. Experiments have been performed at the microtomography beamline ID19 of the ESRF. On this facility, X-ray phase-contrast imaging (XPCI) process is used. Compared to hard X-ray radiography based on attenuation-contrast, this technique permits to enhance the visibility of discontinuities, such as density variations due to the propagation of a shock wave [5-6]. The 16-bunch filling mode of the storage ring is used. Each X-ray pulse has a duration of around 100 ps HWHM; the time between X-ray flashes is 176 ns. After having penetrated the foam sample, X-ray pulses are captured by using a LYSO:Ce scintillator and a HPV-X2 Shimadzu fast camera. 128 images are stored in one recording sequence with an effective pixel size of 8  $\mu\text{m}$ . In order to avoid empty frames and achieve a full exploitation of the 128 images, an inter-frame of 530 ns is used in experiments, which means that one in three X-ray pulses is captured.



**FIGURE 1.** 3D X-ray tomographic view of the polyurethane foam (a), and experimental configuration of plate impact experiments coupled to in situ X-ray radiography (b).

The gas gun used is a 25 mm bore single stage gas gun from the University of Oxford, which is able to achieve impact velocities from 100 m/s to 800 m/s. Two plate impact experiments have been performed at two impact velocities: 182 m/s and 600 m/s. Shots characteristics are shown in Tab. I. The sabot is made of polycarbonate. For the shot #1, as the X-rays beam center was 3 mm away from the front surface of the foam sample, a 2 mm-thick glass has been added between the driver made of aluminum and the foam. Foam samples are cubes of  $5 \times 5 \times 5 \text{ mm}^3$ .

**TABLE I.** Characteristics of plate impact experiments.

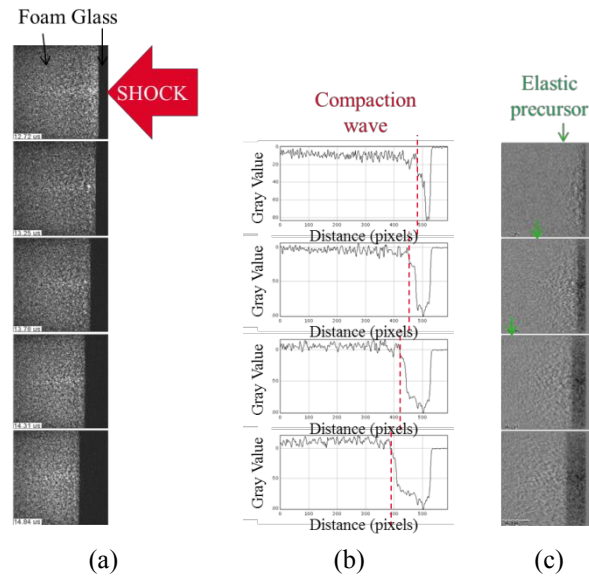
Shot	Impact velocity (m/s)	Projectile	Target	Camera	
				Field of view (mm <sup>2</sup> )	Exposure (ns)
#1	182	PMMA (6 mm)/Al (6 mm)	Al (3 mm)/Glass (2 mm)/Foam (5 mm)	$2 \times 2$	176
#2	600	PMMA (6 mm)/Al (6 mm)	Al (3 mm)/Foam (5 mm)	$3.2 \times 2$	200

## Experimental results

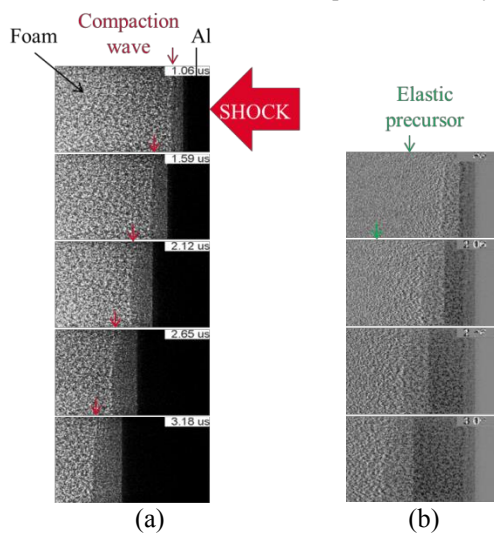
X-ray phase-contrast images obtained during experiments are shown in Fig. 2.a and Fig. 3.a. The impact of the projectile on the aluminum driver generates a shock, which propagates from the right to the left in radiographs. For the shot #2, one can clearly see the propagation of a wave, with a phase-contrast modification. It is the compaction

(plastic) wave, which involves a high augmentation of density. When the shock wave propagates, pores partially or fully close, and dense matter thickness crossed by X-rays is higher, which explains changes in image contrast, as it absorbs more. Knowing dimensions of the field of view and the inter-frame, waves velocities can be calculated. For the shot #2, compaction wave velocity is about  $752 \pm 38$  m/s. For the shot #1, as the compaction wave might propagate at nearly the front surface speed, it is quite hard to see it in radiographs. The gray value as a function of distance (Fig. 2.b) shows a decrease just before the one due to the presence of the glass. This is due to the compaction wave propagation. The compaction wave velocity deduced for the shot #1 is about  $204 \pm 10$  m/s.

The elastic precursor propagates at a higher velocity than the compaction wave. Thus, it is the first wave to propagate into the foam but as it barely changes the density, it is quite difficult to see it directly in radiographs. By subtracting each image to the first one, it is possible to visualize the propagation of this wave (Fig. 2.c and Fig. 3.b). On these images, one can see the elastic wave propagation, and deduce its velocity with some error bars. For the shot #1, the elastic precursor velocity calculated is around  $1198 \pm 120$  m/s; for the shot #2, it is around  $1322 \pm 130$  m/s. For both tests, the resolution is not high enough to quantify wave fronts thicknesses.



**FIGURE 2.** X-ray phase contrast images for the shot #1 ( $V = 182$  m/s) (a). Compaction wave propagation is shown in (b), demonstrating the gray value of images as a function of distance. The compaction wave velocity is around  $204 \pm 10$  m/s. Elastic precursor propagation is shown in (c), where images are subtracted to the first one. The elastic precursor velocity is about  $1198 \pm 120$  m/s.

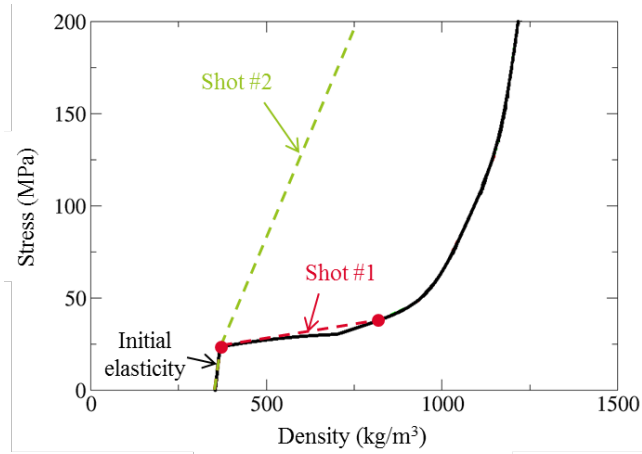


**FIGURE 3.** X-ray phase-contrast images for the shot #2 ( $V = 600$  m/s) (a). The compaction wave velocity is around  $752 \pm 38$  m/s. Elastic precursor propagation is shown in (b), where images are subtracted to the first one. The elastic precursor velocity is about  $1322 \pm 130$  m/s.

By performing experimental reference measurements of gray value (without sample), it is possible to calculate the evolution of the material density – and of the pressure using simulations – along the shock propagation axis, knowing the foam initial density. This study was not realized, but will be the aim of future works.

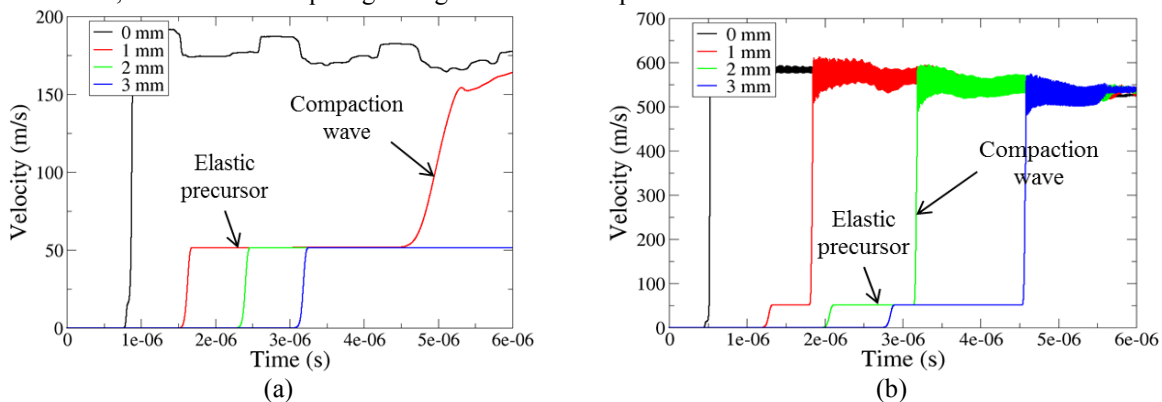
## MODELLING

The dynamic behavior of the foam is represented by a phenomenological model, developed by the Stanford Research Institute [7], and implemented in a 1D hydrocode of the CEA. As the mechanical loading in these experiments can be considered 1D in the direction of waves propagation, the use of a 1D hydrocode for calculations is justified. Model parameters have previously been calibrated and validated by performing dedicated dynamic experiments (magnetic pressure, plate impact, electron beam and laser-driven shock experiments) on polyurethane foam [3-4]. In this model, the bulk modulus, on which depends the elastic precursor velocity, is taken equal to 500 MPa, and the Hugoniot Elastic Limit (HEL) is equal to 21 MPa. Fig. 4 shows the evolution of stress in the foam as a function of density, implemented in the model.



**FIGURE 4.** Stress-density curve corresponding to the model used. The local curve slope is linked to waves velocity, which explains why the wave splits in two: first the elastic precursor, due to the foam elastic behavior, and then a compaction wave, whose propagation velocity depends on the pressure reached. For the shot #1, the pressure reached into the foam is about 38 MPa ; for the shot #2, it is around 530 MPa.

For both shots, velocity profiles calculated into the foam for different distances (0 mm, 1 mm, 2 mm and 3 mm) are shown in Fig. 5. As explained, the first wave to propagate into the foam is the elastic precursor, which propagates faster than the compaction wave, whose velocity depends on the pressure reached into the foam. In this model, the elastic precursor velocity is not dependent on the pressure, and is equal to 1250 m/s, which is close to the ones deduced from experiments. The compaction wave velocity calculated is 226 m/s for the shot #1, and 741 m/s for the shot #2, which is also in quite good agreement with experiments.

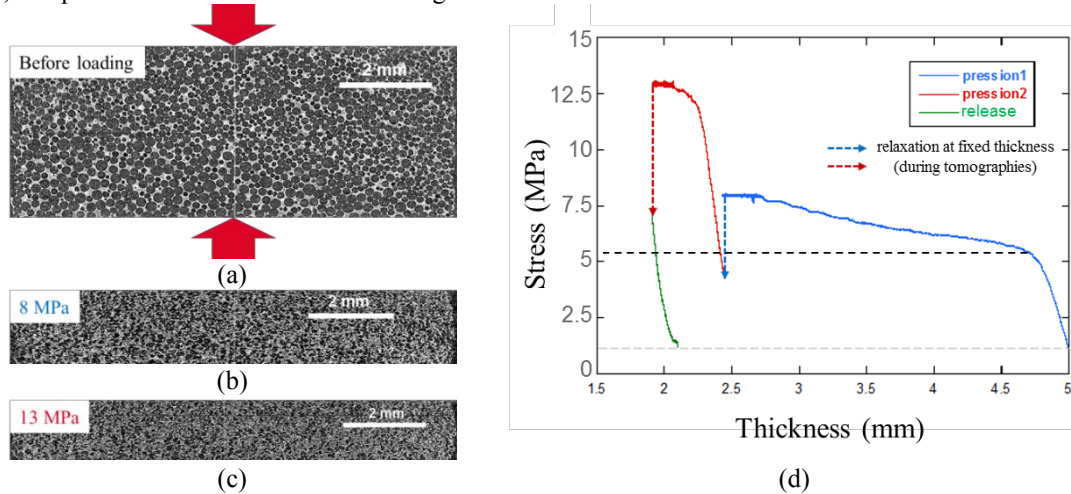


**FIGURE 5.** Velocity profiles calculated at different distances into the foam sample for the shot #1 ( $V = 182$  m/s) (a), and the shot #2 ( $V = 600$  m/s) (b).

## IN SITU QUASI-STATIC TESTS

Quasi-static compression tests coupled to in situ X-ray tomography have been performed at the Institut Pprime to study the mechanical behavior of the foam under low strain rates. The effective pixel size is  $4\ \mu\text{m}$ . An entire test has been performed on a unique foam sample (10 mm diameter, 5 mm thick), without lateral confinement. After having reached a stress of 8 MPa, the compression test is stopped at constant strain, and a tomography of the foam is made. The same procedure is reproduced after having reached 13 MPa. In Fig. 6.d, one can see that during the tomography step, the stress relaxes, which shows the viscous behavior of the foam under quasi-static loading.

2D tomographies, represented in Fig. 6.a, Fig. 6.b and Fig. 6.c, show that the foam compaction is due to bending and buckling of cell edges, and then matrix failure. As the spatial resolution of the Shimadzu fast camera is not high enough, this phenomenon is not observed for high strain rates.



**FIGURE 6.** 2D tomographies of the foam sample subjected to a quasi-static loading, before loading (a), under 8 MPa (b) and under 13 MPa (c). Stress-thickness curve of the foam under quasi-static loading (d).

Fig. 6.d shows that the compaction threshold is around 5 MPa, which is much lower than the HEL of 21 MPa used in the dynamic model. This underlines the strain rate dependence of the foam from quasi-static to plate impact experiments, which can be an explanation of differences observed on deformation mechanisms between low and high strain rates.

## CONCLUSION AND PERSPECTIVES

Plate impact experiments coupled to in situ X-ray radiography have been conducted to investigate the dynamic behavior of a polyurethane foam. A phenomenological model fairly reproduces propagation velocities of both elastic and compaction waves. Quasi-static tests show that deformation mechanisms are quite different if the foam is subjected to low or high strain rates.

Future works will consist in developing a mesoscopic model to better understand phenomena observed and to optimize mechanical properties of the foam (nature of the matrix, pore size...).

## REFERENCES

1. L.J. Gibson and M. F. Ashby, *Cellular Solids: Structure and Properties – Second Edition* (Cambridge University Press, 1997).
2. L. Di Landro et al., *Polym. Test.*, **21**, 217-228 (2002).
3. P. Pradel et al., *AIP Conference Proceedings*, **1979**, 110015 (2018).
4. P. Pradel et al., *Eur. Phys. J. Special Topics*, **227**, 3-16 (2018).
5. M.P. Olbinado et al., *J. Phys. D: Appl. Phys.*, **51**, 055601 (2018).
6. M.P. Olbinado et al., *Opt. Express*, **25**, 13857 (2017).
7. L. Seaman et al., Technical report, Stanford Research Institute, 1974.