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# Dynamic fragmentation of natural ceramic tiles: Ejecta measurements and kinetic consequences

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ABSTRACT

Velocity and size measurements of ejecta derived from impacts of railgun-launched projectiles into 10 mm thick gabbro tiles are examined. Fragmentation of the target and the ejecta velocity field are found to be governed by Hertzian fracture and the transfer of kinetic energy to the target. Over 90% of the total kinetic energy is contained above the average ejecta velocity and greater than 95% in angles bounded by Hertzian fracture. Log-normal distributions of the ejecta reveal that the kinetic energy transfer from projectile to ejecta is an organized process that spans over four orders of magnitude. The ejection angle that contains the most total kinetic energy coincides with the primary ejection angle, indicating the importance of larger plate-like fragments in the fragmentation process. Approximately 11–16% of energy to the target (initial – final kinetic energy of the projectile) is converted to the kinetic energy of fragments when the projectile does not perforate the target ($\leq$52 J). The conversion to fragment kinetic energy increases near-linearly to $\sim$50% at an incoming projectile energy of 305 J. This reveals the importance of this energy conversion mechanism under these experimental conditions.

## 1. Introduction

The quasi-static fracture of linear elastic-plastic and linearly viscoelastic materials are quite well understood [1–7]. Dynamic fracture, where inertia effects are important in crack propagation mechanics, is less well understood. This is due to the complex interaction of varying spatial and temporal length scales that span many orders of magnitude. Dynamic fragmentation is a spatially and temporally discrete process governed by flaws (inherent and random), material properties (e.g., toughness, hardness) and structure (e.g., grain orientation and size) [8]. The dynamic fracture and fragmentation of solids have been areas of continued interest since the early works by Mott [9,10], and they remain active areas of research [11–18]. The dynamic fragmentation of natural brittle materials is the subject of this paper.

Impact testing has been used to study the fragmentation of brittle materials (e.g., ceramics) since the development of high-speed launchers (e.g., solid propellant launchers, light-gas guns) in the 1950's [19–24]. High-speed impact testing can be accomplished using, for example, solid propellant guns (200 m/s to 2.75 km/s [25]), single- and two-stage light-gas guns (300 m/s to 7.5 km/s [25]), and electromagnetic railguns (10 m/s to 8 km/s [26–29]). Railgun launch technology is desirable because it has a relatively low operational cost and is able to achieve higher theoretical velocities and efficiencies than conventional chemical propulsion systems [30].

Applications for impact testing include evaluating the ballistic performance of ceramic-metal shielding systems [31–35] and simulating colliding planetary bodies in small-scale laboratory experiments [36–39]. This research has yielded valuable information on the mechanisms governing fragmentation through the predominantly qualitative post-experiment analysis of fragments [13–15,18], and the examination of fracture surfaces using, for example, scanning electron microscopy [18] and transmission electron microscopy [40,41]. Real-time measurements of the dynamic fragmentation of brittle materials have been studied less due to the difficulty of collecting measurements (e.g., time resolution, triggering) [42,43]. Examples of real-time measurements include velocity interferometry (VISAR) to determine equations of state [44–46] and velocity measurements of ejected fragments [19–23,43,47–50]. In the present work, velocity and size measurements of ejecta are recorded to investigate the dynamic fragmentation of gabbro tiles.

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Ejecta are generated through the dynamic tensile failure of the target material via energy and momentum transfer from the impactor to the target. Laboratory studies concerned with ejecta velocity distribution measurements have mainly focused on planetary impact scenarios involving, for example, basalt [43,48], loose quartz and sand targets [49,50], and regolith-like powders [20]. These studies have primarily focused on quantifying crater formation [51–54], the effect of porosity [55], scaling [50–53] and corresponding ejecta size-velocity distributions [19–23,47,56–58].

Velocity measurements of ejecta have been obtained using various methods in the past. Examples include: hand-tracing vector fields onto photographs [48] and using post-experiment measurements of spatial distributions of mass to back-calculate necessary velocities [42]. While these investigations have offered insight into these catastrophic events, the ambiguity of these methods has not enabled capture of a comprehensive set of velocity-size measurements to yield reliable statistics. Knowledge of these relationships enables reconstruction of the fragmentation process through analysis of fragment velocities, and provides a deeper understanding of the underlying kinetics of, for example, impact cratering and planetary formation, ballistic protection, and the fundamentals of dynamic fragmentation in brittle materials.

More recently, particle tracking velocimetry (PTV), which is analogous to particle image velocimetry (PIV) used in fluids research, has been implemented to track the motion of multiple fragments over several high-speed image frames in highly cluttered debris fields [50]. Tracking of all individual fragments is difficult because of the cluttered nature of the debris field and the inherent difficulty in developing associated computational algorithms.

The computational modelling of the dynamic behaviour of brittle materials is widely studied. Graham-Brady [59], expanded the work by Paliwal and Ramesh [60], and developed a multi-scale model to capture microscale-localized failure in brittle materials. Finite element method-based techniques have also been used in the modelling of brittle fragmentation [61–63]. Damage laws are implemented to model scale-varying processes [64] (e.g., friction across interfaces [62,63]) and the effect of material flaw distributions are incorporated [65–67]. Models predicting fragmentation distributions based on simulations [12,68] have provided reasonable agreement with experimental works [17,69]. Challenges remain in developing criteria for identifying fragments in three-dimensional models, tracking ejection trajectories [70], and accurately modelling fragment–fragment interactions. The latter includes modelling micro-scale frictional behaviour, which has a major contribution to total energy dissipation in the form of plastic and thermal behaviour, as well as further fragmentation [18]. Facilitating improvements in these models will require increased quantitative validation via well characterized laboratory experiments.

This paper investigates ejecta velocity-size distributions and associated kinetic energy contribution resulting from low-speed impacts (26–100 m/s) into gabbro tiles (10 mm thick). An electromagnetic railgun was used as the launching platform. Low-speed tests of this kind have not received attention in the literature, but are more tractable since a lower number of distinct fragments are generated in comparison to higher energy tests. The distribution of kinetic energy among ejecta velocities, angles, sizes and kinetic energies is presented. Fragment size distributions are examined and the relationship between kinetics and damage is explored.

## 2. Experimental setup and analysis methods

The impact tests were performed at the French-German Research Institute of Saint-Louis (ISL), France. Gabbro is a coarse grained, intrusive mafic igneous rock consisting of plagioclase, pyroxene, amphibole, and olivine. The density is estimated at 3200 kg/m$^3$. Gabbro tiles (150 mm by 150 mm and 10 mm thick) were selected because they are relatively homogeneous, there is an abundant supply, and they serve well as a starting material for future tests. In addition, the material used is dark in colour, allowing the fragments to be more easily distinguished by the tracking software, as compared to lighter coloured rocks. The target configuration is shown in Fig. 1a. The tile is sandwiched between two plywood plates and is secured with four bolts on each side of the tile. The target is allowed to expand latterly and the plywood pieces are replaced after each shot. The projectile used to fragment the tile was cast from aluminium and had a mass of 62 g (Fig. 1b). The projectile was 30 mm in length and had a hexagonal cross-section with 20 mm between diagonal vertices. A single copper brush passes through the projectile to enable conduction with the rails. Impact velocities of 26–100 m/s were obtained using the SR 3/60 electromagnetic railgun [71], corresponding to kinetic energies at impact of 21–305 J. Estimates of strain rate limits (velocity/thickness) of $>2.6 \times 10^3$ indicate these tests are dynamic. Values for all trials are displayed in Table 1.

A Photron APX Ultima video camera filming at a 8 kHz frame rate captured fragment trajectories at the rear of the targets. Two high-powered lamps were used to back-illuminate the particles. Proper lighting is critical with such an experimental setup. A tracking algorithm written in Matlab [72] was implemented to track ejecta larger than 0.8 mm (length of two pixels determined by resolution of

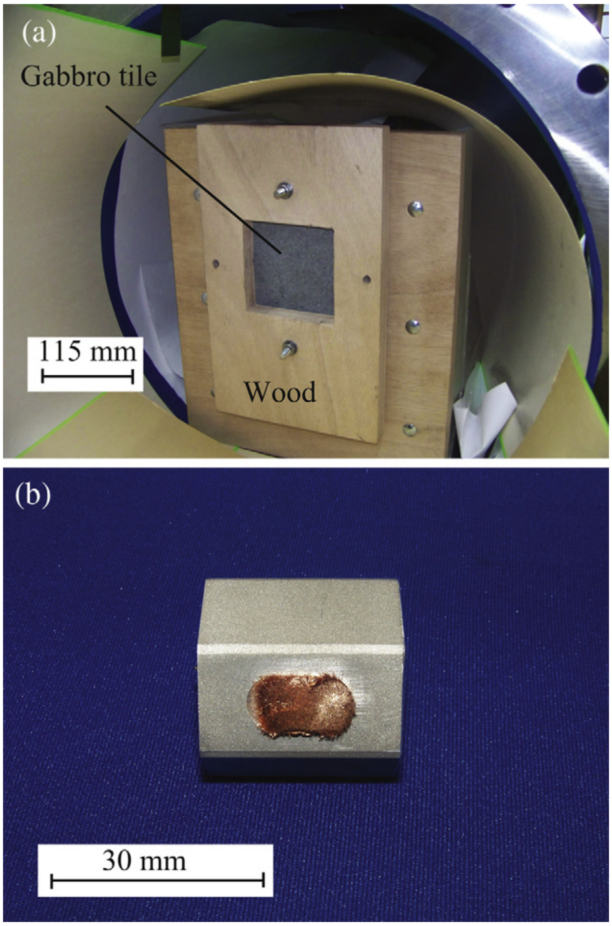

**Fig. 1.** (a) The target configuration with target and target holder materials labelled, and (b) the aluminium projectile used in these trials. There is a single copper brush passing through the aluminium projectile.