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Experimental study on influence of impact angle on fragmentation of brittle blocks upon dynamic impact

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ABSTRACT: Falling rocks commonly break up on impact, and the change in size, shape and energy of falling blocks can drastically change the outcome of rockfall risk assessments. However, fragmentation of falling blocks is poorly understood and often ignored. The current study presents the results of an experimental campaign aiming at investigating the influence of the impact angle on the fragmentation of homogenous prismatic blocks upon impact. More than 120 brittle masonry blocks were released from the same height to impact on a horizontal concrete slab with a wide variety of impacting angles. High-speed video recordings were used to determine the actual impact angle in each case. The results show that likelihood of fragmentation decreases when the impacts is directly on a face, and increases when the impact is on a corner or an edge.

1 INTRODUCTION

Rockfall is a natural phenomenon occurring on artificial or natural slopes and creating a very significant hazard in both natural and built environments. Rock fragmentation has been ignored in existing rockfall simulations as it has been considered more conservative when calculating energy (Ashayer, 2007). However, it has been observed that fragmentation throughout rockfall leads to higher fragment velocities and greater runout lengths (Agliardi & Crosta, 2003) possibly leading to chosen protection mechanisms being unsuitable for purpose. The key factors influencing fragmentation in a rockfall event include discontinuities and their orientation at impact, the rigidity of the ground, the impacting angle and velocity and the energy at impact. (Ruiz-Carulla et al., 2017). Both experimental studies (e.g. Giacomini et al., 2009) and DEM simulations (Liu et al. 2010, Wang & Tonon 2011) showed that impact angle influences the fragmentation outcome of a falling block.

This present study aimed to develop an understanding of the effects of impact angle on fragmentation, which was achieved by releasing bricks - objects of controlled shape and material - from a given height and recording their impact with high speed cameras.

The paper first presents the testing methodology before presenting and discussing the results of this preliminary fragmentation testing campaign.

2 METHODOLOGY

2.1 *Experimental set-up*

A specific fragmentation testing cell has been developed at the University of Newcastle (Australia) in which test blocks can be dropped to impact in a controlled way on a concrete slab (compressive strength of 60 MPa). The fragmentation cell comprises alternate plywood and transparent polycarbonate sides to allow impact capture with high speed cameras located outside the cell. A system of pulleys and ropes are used to lift and release device are used to lift and release blocks, which were 75mm x 109mm x 229mm concrete masonry rectangular prisms for this study.

For this campaign two high speed cameras were used to capture details of the bricks' orientation at impact. The cameras were Optronis CamRecord CR600x2 with a resolution of 1280x1024 pixels. Each camera has a Nikkor AF 35mm f/2D Lens. The frame rate used was 500 fps with a shutter speed 1/2000s and aperture of 2.8mm. Each camera was connected to a laptop with an Ethernet cable and the software CamControl v6.10 was used to save and manage images. An array of bright lights were used to achieve a high shutter speed and therefore reduce blurring of the brick within the frame while retaining a reasonable depth of field and image quality.

2.2 *Drop tests*

Before each test, the brick to be dropped was marked to allow easy face identification during the video analysis. Then, the brick was weighed to obtain its pre-impact mass. To ensure that a variety of impact angles was achieved, the holding position of the brick was adjusted as per Figure 1. 120 blocks were dropped to ensure a good spread of impact angles. The drop height was 3.580 m ± 0.05 m for all tests.

After the drop tests, the images were saved and significant fragments (arbitrarily defined as > 1% of the initial mass) were weighed and photographed.

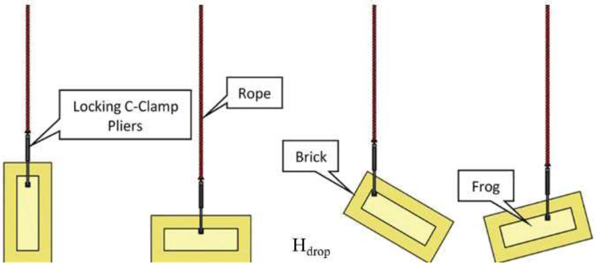

Figure 1. Various clamping arrangements adopted.

2.3 *Data analysis*

To define the position of the brick at impact, the recorded images were processed to allow each corner to be defined by (x,y,z) coordinates. This required 3D coordinates to be derived from 2D images.

During the analysis process, there needed to be a method to identify each corner of the brick according to a consistent geometric reference. Figure 2 illustrates the corner and plane identities on a particular brick. The length of the edges along with their corresponding corner identities are provided in Table 1, the subscript B is for base and T is for top (see Figure 2).

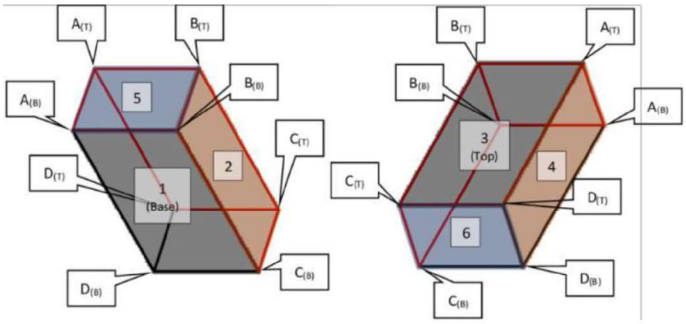

Figure 2. Corners and plane identities.

Table 1. Distance between corner identities

Edge	Length (mm)	From	To
Short (S)	75	A_B	A_T
		B_B	B_T
		C_B	C_T
		D_B	D_T
Medium (M)	109	A_B	B_B
		A_T	B_T
		C_B	D_B
		C_T	D_T
Long (L)	229	A_B	D_B
		A_T	D_T
		B_B	C_B
		B_T	C_T

The first step of image processing was to identify which camera would provide the most suitable perspective to analyse. This was determined by looking at the number of planes clearly identifiable. The image sequence was then processed in "Tracker", a free video analysis and modelling tool built on the Open Source Physics (OSP) Java framework. The frame just before impact was used to identify edges and 2D coordinates of corners assuming that the change in positioning between two frames was negligible. The impact point was always set as origin of the coordinates with x-axis aligned parallel to the edge of the slab. An example of tracker analysis is represented in Figure 3, with annotations available in Table 2.

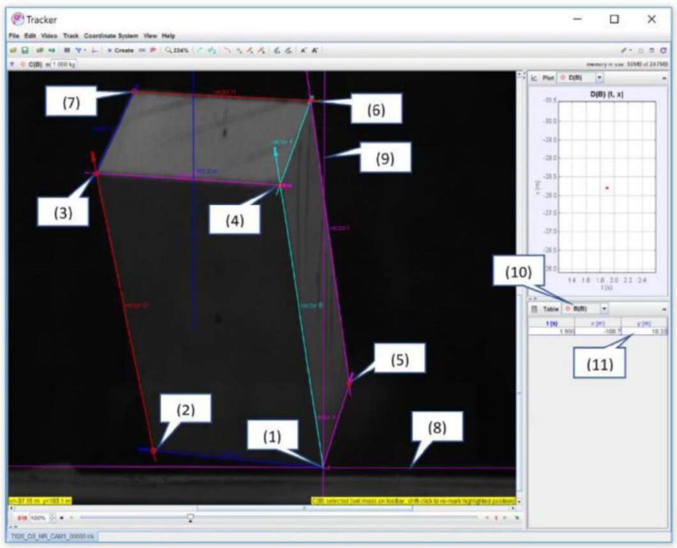

Figure 3. Example of image analysis with Tracker; for annotation see Table 4

Table 2. Tracker key features - Annotations for Figure 3

ID Number	Details	ID Number	Details
(1)	A_B, impact point	(7)	C_T
(2)	B_B	(8)	x-axis
(3)	C_B	(9)	y-axis
(4)	D_B	(10)	Point inspected
(5)	A_T	(11)	x,y coordinates
(6)	D_T		

The 2D coordinates of each corner, and the known true lengths of the brick's edges were used to determine the Cartesian coordinates of each corner at impact using a spreadsheet in Excel. This spreadsheet requires the impact point to be defined as (x,y,z) = (0,0,0), and two heights of corners on the same face/plane. Using just two heights would successfully define a brick that had landed in the centre of the slab, however slight variations in the impact point could not be avoided, which required a scaling correction. To overcome this scaling issue, a third height from a corner on the plane parallel was used, which allows the scaling adjustment to be determined. A visual inspection was also carried out using three views of the brick, an x-y plot (top view), x-z plot and a y-z plot.

An impact can always be defined by three angles:

- θ_S: angle between the impact plane (z=0) and the vector containing the short (75mm) edge of the brick
- θ_M: angle between the impact plane (z=0) and the vector containing the medium (109mm) edge of the brick
- θ_L: angle between the impact plane (z=0) and the vector containing the long (229mm) edge of the brick

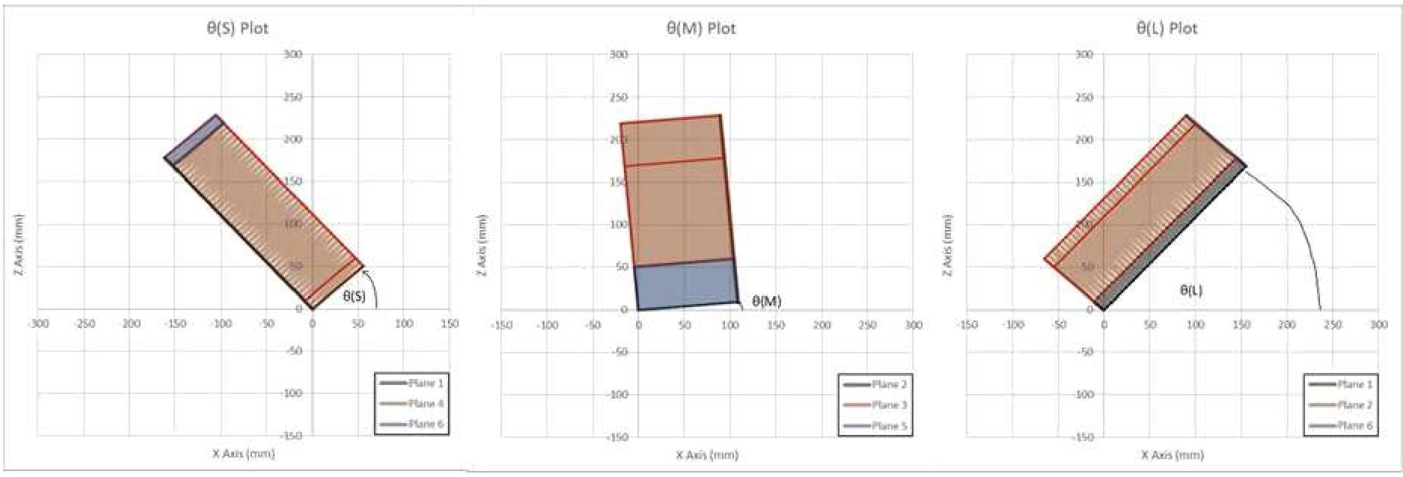

Figure 4. Angle defining an impact (Test 20)

The three angles defined are shown in Figure 4, where the brick has been rotated around point A_B such that y=0 for the vector defining the corresponding edge. To determine the three angles the following equation was used

$$\theta = \tan^{-1} (z/\sqrt{(x^2 + y^2)}) \tag{1}$$

where x,y,z are the Cartesian coordinates of the corner point defining the edge which is at angle θ to the horizontal.

To display the results of each drop in a consistent and consolidated way, so that a relationship between impact angle and fragmentation characteristics could be established, a plot showing all three angles was developed. It was decided that the best way to achieve this was a ternary plot, which would allow the identification of regions of similar fragmentation. However, a typical ternary plot has a linear scale from 0-100 in its three principal directions, and the centroid of the plot represents 33.3% of each quantity. For the representation of three inclination angles, θ_S, θ_M and θ_L, each principal direction needed to range between 0 and 90 degrees. Furthermore, for a perfect corner impact (where all edges extending from the corner make the same angle with the impacted surface), the common angle is $\theta_S = \theta_M = \theta_L = 35.26°$ (ie, the sum of these angles is 105.8°; not 90°, as it is everywhere around the perimeter of the triangle). This required the development of a customised non-linear ternary diagram with appropriately distorted graduation lines such that a valid sum was achieved for all possible values of three angles.

The resulting plot is shown in Figure 5 where the angles defining Test 20 (θ_S, θ_M, θ_L) = (42, 5, 47)° have also been plotted to illustrate how the plot should be interpreted. Using a VBA (Visual Basic for Application) code to plot the points has led to errors of a few degrees in some cases, which was considered acceptable for the purposes of this experiment.

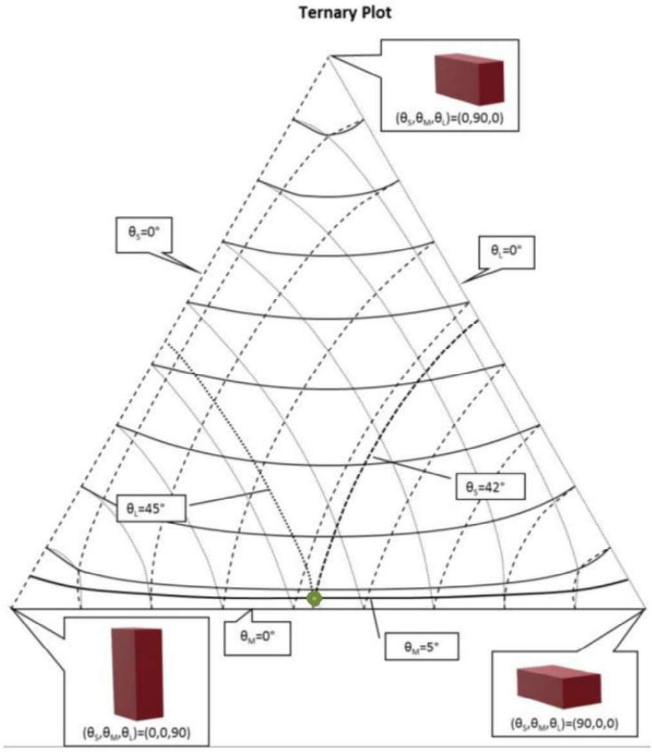

Figure 5. Ternary plot with sample datum point (Test 20)

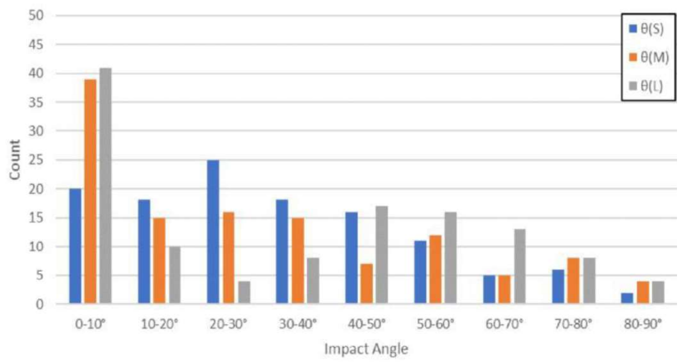

Figure 6. Bar chart of impact angle distribution

3 RESULTS AND DISCUSSION

A total of 122 drop tests were carried out and were processed using the methodology outlined in Section 2.3 to determine the three defining angles θ_S, θ_M and θ_L. The data spread of the experiments has been plotted in Figure 6 where there is a clear bias towards impact angles in the 0-10° range for θ_M and θ_L. It is also apparent that the range of θ_S has a much more even distribution for the range 0-60°.

As mentioned in Section 2.2, the mass of the brick pre-test and the mass of the fragments after impact were recorded. The mass of the pre-dropped brick varied and therefore, to compare the results, the mass of fragments was normalised as a percentage of the initial brick mass. All test results were categorised into one of four types of fragmentation:

- No Significant Fragmentation: tests with one fragment larger than 75% of the initial mass;
- Fragmentation - 1 large: tests with one fragment of between 50-75% of the initial mass and no more than 3 small fragments (each one less the 25% of the initial mass);
- Fragmentation - many small: tests with 3 or more fragments of less than 25% of the initial mass;
- Fragmentation - medium and small: all remaining tests.

The results of this fragmentation pattern analysis are plotted with unique symbols on the ternary plot.

The ternary plot of Figure 7 suggests that there is a correlation between the impact angle and the fragmentation outcome of a dropped object. Indeed, it was found that high fragmentation (i.e. many small fragment) is associated with a shallow impact angle

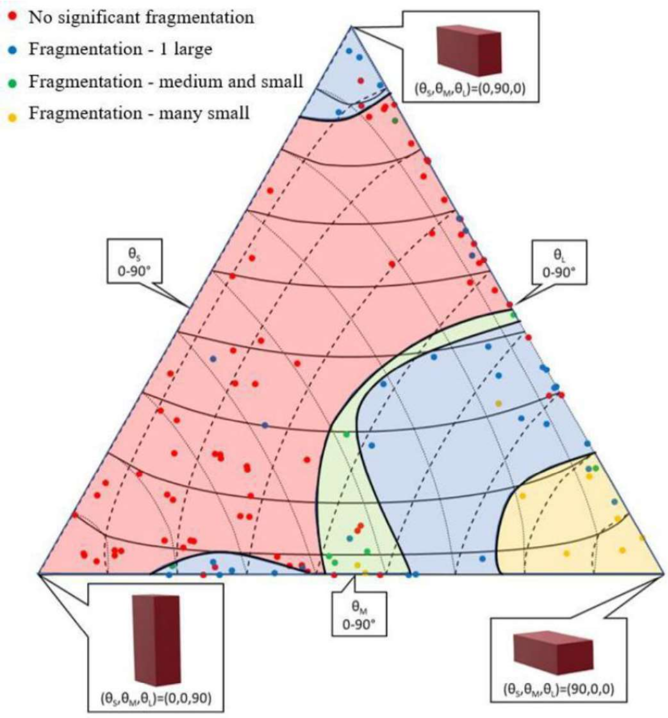

Figure 7. Ternary plot with fragmentation region identified

to a large surface area face, with fragmentation decreasing as this angle increases. For a brick, this occurs as the impact angles approach (θ_S, θ_M, θ_L) = (90, 0, 0)° with a secondary region as they approach (θ_S, θ_M, θ_L) = (0, 90, 0)°. This relationship is consistent with the findings of DEM simulations performed on cubes (Liu et. al, 2010), where larger contact areas led to greater fragmentation. Research on this topic is still ongoing.

4 CONCLUSION

Utilising the fragmentation cell developed at the University of Newcastle, it was possible to conduct 122 drop tests of brittle prisms from a constant height but with varying impact angles. The key finding of this investigation is that the impact angle does influence the fragmentation characteristics of an irregularly shaped object and therefore shape effects must be considered if accounting for fragmentation during impact in a rockfall. Although this may seem intuitive, there are no consistent and comprehensive datasets in the literature demonstrating this effect. The key relationship that was found was that fragmentation is more likely to occur when the angle between the impact surface and a face of the dropped object is small. Specifically, fragmentation is more likely to occur when impact is onto a larger face, and it is most likely to be more severe when the block impacts on, or almost on, its largest face.

REFERENCES

Agliardi, F., & Crosta, G. B. 2003. High resolution three-dimensional numerical modelling of rock-falls. *International Journal of Rock Mechanics and Mining Sciences, 40(4), 455-471.*

Ashayer, P. 2007. Application of rigid body impact mechanics and discrete element modeling to rock-fall simulation. *Ph.D. Thesis, University of Toronto, Dept Civil Engineering, Ontario, Canada.*

Giacomini, A., Buzzi, O., Renard, B., & Giani, G. P. 2009. Experimental studies on fragmentation of rock falls on impact with rock surfaces. *International Journal of Rock Mechanics and Mining Sciences, 46(4), 708-715.*

Liu, L., Kafui, K. D., & Thornton, C. 2010. Impact breakage of spherical, cuboidal and cylindrical ag-glomerates. *Powder Technology, 199(2), 189-196.*

Ruiz-Carulla, R., Corominas, J., & Mavrouli, O. 2017. A fractal fragmentation model for rockfalls. *Landslides, 14(3), 875-889.*

Tracker 2018 (version 4.11), https://phys-lets.org/tracker/, (25 September 2018).

Wang, Y., & Tonon, F. 2011. Discrete element modeling of rock fragmentation upon impact in rock fall analysis. *Rock Mechanics and Rock Engineering, 44(1), 23-35.*