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Experimental studies on rock fragmentation for the design of rock fall barriers

Giacomini A. [*], Buzzi O., Renard B. & Giani G.P.

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Centre for Geotechnical and Materials Modelling, School of Engineering, University of Newcastle, Australia

Politecnico di Milano, Milano, Italy

Abstract

Keywords

Rockfall, Impact, Energy, Fragmentation, Prediction, Design.

1 Introduction

Natural hazards involving rocks or rock slopes are responsible for loss of life and damage to infrastructure and are consequently widely studied. The theoretical and technological effort to protect urban areas, civil infrastructure from rockfall hazards is due to the need to conserve historical sites and to protect towns which continue to expand into mountainous regions. In assessing the risks associated with rockfall phenomena, it is important to consider that the velocity of rockfalls usually is much greater than the velocity of slope movements, and so they typically pose a greater risk to life. To date, research efforts have been focused on in situ rockfall tests (Ritchie, 1963; Broili, 1973; Azzoni et al., 1994; Giani et al., 2002, 2004), on barrier tests (Kane & Duffy, 1993; D.Smith & Duffy, 1990; Labiouse et al., 1996; Peila et al., 1998) and on the development of analytical and numerical models. These latter are chiefly focused on the evaluation of the trajectories of detached blocks (Piteau & Clayton, 1976; Descoeudres & Zimmermann, 1987; Pfeiffer & Bowen,

[*]Email: Anna.Giacomini@newcastle.edu.au

1989; Scioldo, 1991; Guzzetti et al., 2002; Agliardi & Crosta, 2003) for different morphological and geological conditions (Bozzolo & Pamini, 1986; Azzoni et al., 1992; Azzoni & Freitas, 1995; Giani, 1997; Giani et al., 2004).

Different protection systems have been designed against rockfall, the most common being rock restraining nets, catch walls or deformable barriers. Generally, the location of the defense system is determined on the basis of the estimated block trajectories, of their velocity and of the identified arrest areas. Most of the experimental studies carried out over the last 50 years aimed to determine the key parameters governing the rock fall phenomenon: velocity of free falling block, restitution coefficients at impact or equivalent rolling friction coefficients (Azzoni et al., 1992; Chau et al., 2002; Giani et al., 2004). Rock fall tests are usually performed in representative sites by moving a large number of block and recording the motion using high speed cameras. The kinematic motion features can then be estimated and attention is usually focused on mechanisms triggering the rock fall, on aerial phases of motion, on the impact with possible fragmentation of the block and on the velocity and kinetic energy acquired by the blocks.

Block fragmentation upon impact is usually not accounted for in the design of a defense structure because the energy lost at impact is assumed to be high enough to not generate fragment projection (REFERENCE). This lack of consideration explains why the fragmentation is still in its early age despite it is a natural and frequent phenomenon. Moreover, it is facilitated by the presence of bedding planes in the boulders and by high impacting velocities (Falcetta, 1985). The relevance of considering rock fragmentation resides in the possibility for the fragments to follow trajectories much different from that of the intact block (used to design the barrier) with the risk of traveling over the protection barrier. In particular, Agliardi & Crosta (2003) have experimentally observed that "the smaller rock fragments are characterized by observed velocities greater than the computed maximum velocities" and that "the high observed velocities could be due to the momentum increase occurring as a consequence of fragmentation at impact".

Another very significant consequence is the formation of tabular pieces of rock after impact which can travel a long way due to a higher rolling efficiency (Giani, 1992). This happens when the fragment rolls down the slope like a wheel. Giani (1992) mentions that low height of impact is enough to observe fragmentation of schistose rocks where recurrent weak planes can be found.

Several authors have raised the issue of the impact of small blocks (Giani & Cantarelli, 2006; Peila & Oggeri, 2001). It has been put in evidence that major damage can be produced in the rockfall protection systems due to smaller impacting areas and stress concentration. Projectile effect, holing the net, is even mentioned (DeCol & Cocco, 1996). Giani & Cantarelli (2006) have investigated the damage and deformation induced on a protection barrier upon impact of a spheroidal block of mass M and of an irregular shape block having minor mass $m < M$. The impacting speed was the same for both kind of blocks but, because of the different shape, the impacting area is smaller for the irregular blocks. They could demonstrate that the blocks having a much greater kinetic energy actually produce less damage on the net than the irregular block. This result is explained by the higher stress concentration that leads to a deformation of the net greater than the critical value.

Fragmentation is probably the most complicated and poorly understood aspect of a rockfall, and very few useful contributions can be found in the literature. Most of them consider the evaluation of the dynamic strength of rock materials and try to understand the effects of the loading rate on the rock fragmentation phenomenon via energetic considerations (Grady & Kipp, 1987; Zhang et al., 2000). Moreover, only a few modeling approaches taking into account of the possible breakage of the falling block could be found (Fornaro et al., 1990; Amatruda et al., 2002). Fornaro et al. (1990) proposed a rockfall model taking to account the possibility of block breakage at each impact with formation of smaller block continuing to run down the slope. The rock breakage is triggered by a fragmentation energy threshold, namely EUR, depending on the type of rock and on the geometry of the block. Moreover, it accounts for previous fragmentations of the boulder. This energy threshold, required to break the block, is based on experimental results obtained by Mancini et al. (1981)who quantified the energy required to crush blocks with a stone hammer. When the impacting kinetic energy reaches the energy required to break the block (EUR), the block is randomly divided into several fragments and the remaining kinetic energy is distributed between the fragments in proportion to the fragments volumes.

There is a real need to improve our understanding of fragmentation mechanisms in order to strengthen the protection against rockfall. In particular, predicting the possible size, shape and number of fragments generated under impact is fundamental to design more efficient protection systems. Discontinuities and schistosity planes are known to play a fundamental role in both slope stability and fragmentation problems. Firstly, they are responsible for the isolation of potentially unstable blocks, and secondly, they strongly influence the tendency for larger blocks to fragment on impact (Giani, 1992).

This paper presents the results of *in situ* free fall tests with an emphasis on fragmentation in order to improve our understanding of the phenomenon. The tests were carried out in a quarry in North-West Italy using two different kind of rocks having different schistosity. The results have been discussed considering the influence of impacting energy and the angle between bedding planes and the impact surface at impact. Indeed, these two parameters are thought to play a key role in the fragmentation. Then, energetical considerations are undertaken in order to assess whether the idea of a energy threshold can be applied to trigger fragmentation. some ideas are proposed in order to take into account the rock fragmentation in the design of protection systems.

2 Experimental facilities

2.1 Experimental set up

The rock fall tests were performed in a quarry located in Crevoladossola (Verbania, Italy) from which an orthogneiss rock called Beola is still extracted. This testing site, represented in Figure 1, was chosen because of its rocky base (impacting surface) and because of the safety conditions against rock fragment projection offered by its U shape defining a closed area. A mechanical crane anchored on the top of the rock wall (see Figure 1) was used to lift and release the rock boulders. The fall height, ranging from 10 to 40 meters, was adjusted according to the tests and to the experimental program. A detonating fuse, fixed on the hanging system, was used to release the blocks. As shown in Figure 1 (b), the angle between bedding planes and impacted surface, called impacting angle in the following, could be roughly adjusted by the position of the hanging system. The fall, impact and rebound of the blocks were fully recorded using two digital high speed cameras and two video cameras positioned in the quarry. The velocity of the block (pre-impact) and of the fragments (post-impact) was back calculated using the photographs. The accurate definitive value of the impacting angle is also measured using the photographs. Each block was painted prior testing in order to identify the fragments produced at the impact (Figure 3). For each fragment, its volume and the distance at which it was found were then measured.

(a) (b)

Figure 1: (a) Photograph of Crevoladossola quarry in Italy. (b) Schematic representation of the test site and experimental set up

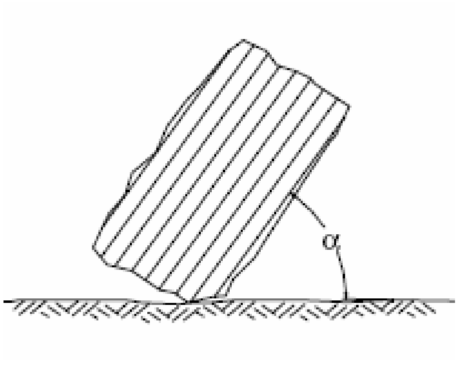

Figure 2: Schematic representation of the impacting angle defined as the angle between the bedding planes and the impacted surface.

Figure 3: View of painted blocks prior testing in order to allow proper identification of fragments.

2.2 Materials

Two ornamental stones from the Ossola Valley (Italy) were used in this experimental study in order to highlight the influence of the schistosity of the rock. The first material, commercially known as Beola, is the orthogneiss rock extracted on site. The second material, commercially known as Serizzo, was extracted in another quarry nearby and the blocks were brought to the test site. The Beola ornamental stone is a striped texture orthogneiss with heterogeneous grain, marked foliation and strong mineralogical lineation. The rock (density of 2630 kg/m^3) is characterized by a whitish background with irregular aggregates of finely grained laminar biotite. Overall, the rock has a rather even grey color. Because of the its strong anisotropy the mechanical behavior is strongly influenced by the orientation of the main foliation respect the load application direction (Cavallo et al., 2004). The second ornamental stone, Serizzo, is a granitic orthogneiss (density of 2730 kg/m^3) of pre-Triassic age extensively exploited in Ossola Valley. It has medium grain size and a generally marked planar foliation, defined by biotite millimetric plans. The rock is characterized by a white background with bright black spots. Both ornamental stones have good physical and mechanical properties and versatility of working, so they are considered a valuable material for indoor and outdoor construction in Italy and abroad.

2.3 Experimental program

As shown in Tables 1 and 2, two series of tests representing a total of twenty tests were performed. These latter are divided into ten tests of variable mass, falling height and impacting angle on each material. Note that for safety reasons and because the quarry was still in exploitation, only twenty tests coud have been performed. For the same reasons, it was not possible to study the influence of one parameter (e.g. impacting angle) keeping the other one (e.g. impacting energy) constant.

Test	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Mass [t]	1.18	1.68	1.84	2.66	2.68	1.01	2.26	3.00	1.20	1.13
Height[m]	10	10	10	10	10	20	20	20	30	40
α [°]	0	90	90	90	90	45	45	45	10	10

Table 1: Testing program for Beola.

In the following, the results will be analyzed in terms of kinetic energy just before impact (or impacting energy) which can be computed from the mass of each block and the falling height as follows:

$$E_k^{bi} = \frac{1}{2} m v_i^2 = mgh \qquad (1)$$

Test	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Mass [t]	1.58	1.91	2.46	2.13	2.13	1.99	2.43	2.18	1.15	2.29
Height [m]	10	10	10	10	10	10	20	20	30	40
α [°]	10	10	10	45	45	90	60	60	60	60

Table 2: Testing program for Serizzo.

where m is the mass of the block, v_i is the velocity at impact and h the falling height. Note that in case of free fall neglecting air friction, the velocity at impact v_i can be expressed as $\sqrt{2gh}$.

3 Results and discussion

As expected, a majority of the dropped blocks broke under impact as shown in Figures 4 (a) and (b). Some blocks broke in numerous fragments (up to 22) while others broke in limited number of fragments. One block did not even break (test S5). The smallest pieces of rock (few cubic centimeters) produced by the impact were not considered when counting the fragments.

Table 3 summarizes all the relevant data measured during the two series of tests.

Test	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
E_k^{bi} [kJ]	116	165	181	261	263	198	588	444	352	442
α_m [°]	10	75	80	80	70	60	55	75	15	30
V_o [m^3]	0.45	0.64	0.7	1.01	1.02	0.38	1.14	0.86	0.45	0.43
NF	2	20	22	9	13	7	3	14	5	8
Test	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
E_k^{bi} [kJ]	155	187	241	209	209	196	477	429	337	900
α_m [°]	10	15	15	30	45	75	70	60	80	50
V_o [m^3]	0.58	0.7	1.4	0.78	0.75	0.73	0.89	0.8	0.42	0.84
NF	8	14	8	3	1	5	2	9	4	3

Table 3: Results of free fall tests performed on Beola and Serizzo. N/A: not applicable.E_k^{bi} : kinetic energy before impact, α_m: measured impacting angle, V_o : initial volume of the block, NF: number of fragments.

(a)

(b)

Figure 4: a) test S3 post impact; b) test S6 post impact.

3.1 Influence of impacting energy and of impacting angle on the fragmentation

In rock fall studies, the energy at impact is usually retained as the key parameter for the rock fall defense design (Giani & Cantarelli, 2006; Peila et al., 1998; EOTA, 2008). With the study of fragmentation undertaken herein, the material with its inherent schisotsity and the impacting angle are two other relevant parameters. The effect of three independent variables (rock type, impacting angle and energy at impact) on one dependent variable (number of fragments) was studied by means of a generalized linear model (GLM, McCullagh & Nelder, 1989). In a GLM, the dependent variable Y is assumed to follow a given distribution, whose mean μ depends on the independent variables X as follows:

$$g(E(Y)) = g(\mu) = X\beta \tag{2}$$

In this equation, β is a vector of unknown parameters which need to be estimated, and g is the link function, which describes the relationship between the mean of the dependent variable Y and the linear predictor $X\beta$. In this study, a GLM was constructed as follows. Let $Y_{i,j}$ denotes the value of the dependent variable for experiment i ($i = 1, , 10$) and rock type j (j=1 for Beola, 2 for Serizzo). The mean of $Y_{i,j}$ is described by:

$$g(E(Y_{i,j})) = g(\mu_{i,j}) = \beta_0 + \beta_j + \gamma_j \alpha_{i,j} + \phi_j E_{i,j} \tag{3}$$

where $\alpha_{i,j}$ is the impacting angle and $E_{i,j}$ the energy at impact for experiment i and rock type j. The additional constraint $\beta_1 = 0$ was used to ensure parameters identifiability. Consequently, the GLM in equation 3 is equivalent to the use of the following two models for Beola (Equation 4) and Serizzo (Equation 5)

$$g(E(Y_{i,1})) = g(\mu_{i,1}) = \beta_0 + \gamma_1 \alpha_{1,j} + \phi_1 E_{i,1} \tag{4}$$

$$g(E(Y_{i,2})) = g(\mu_{i,2}) = \beta_0 + \beta_2 + \gamma_2 \alpha_{i,2} + \phi_2 E_{i,2} \tag{5}$$

Parameters γ_1 and γ_2 describe the effect of the impacting angle on the dependent variable for rock type Beola and Serizzo, respectively. Similarly, parameters ϕ_1 and ϕ_2 describe the effect of the energy at impact on the dependent variable for each rock type. β_0 is the intercept for rock type Beola, while $\beta_0 + \beta_2$ is the intercept for rock type Serizzo. Consequently, parameter β_2 can be interpreted as the overall effect of the rock type on the dependent variable. A t-test is performed to investigate the significance of each of these effects. The dependent variable N (number of fragments after impact) was assumed to follow a Poisson distribution with mean $\mu > 0$. A natural logarithm function was used as the link function g to ensure positivity of the mean. All other dependent variables were assumed to follow a Gaussian distribution with mean μ. The identity function was used as the link function.

Parameter	Value	Standard error	t-value	p-value
β_0	1.227	0.456	2.692	**0.007**
β_2	1.160	0.529	2.193	**0.028**
γ_1	0.022	0.005	4.283	$\mathbf{1.83 \times 10^{-5}}$
γ_2	-0.022	0.006	-2.009	**0.044**
ϕ_1	-9.08×10^{-4}	8.21×10^{-4}	-1.107	0.268
ϕ_2	-4.6×10^{-4}	7.90×10^{-4}	-0.586	0.557

Table 4: Results of the GLM analysis. Values in bold refer to significant effects at level 10%

Results of the GLM analysis for the number of fragments chosen as the dependent variable are summarized in Table 4 and the linear models are plotted together with the experimental data in Figures 5 and 6.

As shown in Table 4, the significance of the impacting energy for both Beola and Serizzo is relatively low (p values of 26.8% and 55% respectively). On the contrary, the impacting angle appears to be a significant parameter for the formation of fragments since the p values are very low (lower than 5%). The values of β_0, β_2, γ_1, γ_2, ϕ_1 and ϕ_2 in themselves are of little interest. This results is, of course, valid for these series of tests and is due to the variation of the impacting angle during the tests. Should the tests be performed at constant angle, the influence of energy would certainly be seen as in any other study. However, keeping a constant impacting angle is not representative of real rock fall events and the relevance of keeping the impacting angle constant can be questioned. Note that on figure 5, a trend is still visible: decreasing number of fragments with increasing energy. Yet, this is not incompatible with the absence of influence of energy concluded by the statistical study. It just means that not considering the energy in the model (i.e. constant value of number of fragment) would give a similar accuracy of prediction.

Fornaro et al. (1990) have used the idea of an energy threshold to trigger the fragmentation of the blocks but no threshold value could be identified from these series of tests. Indeed, fragmentation almost always occurred. Note that block S5, tested under 200 kJ, di dnot broke but others tested under lower energy did break (e.g. S1, S2, S4 and S6). This fact does not validate the idea of a threshold of impacting energy.

Regarding the influence of the impacting angle, it can be noticed in Figure 6 that the trends for Beola and Serizzo are opposite. In fact, the number of fragments for Beola tends to increase with the impacting angle. This result is consistent with results obtained on jointed rock in the literature. For example, Einstein (1973) showed that the mechanical strength of jointed rock decreases when the angle between joint set and loading direction decreases from 90° to 0°.

In particular, when looking at tests B9, B10 and B8, for which the impacting energy is around 400 kJ, the number of fragments increased with the impacting angle: 5 fragments for 15°, 8 for 30° and 14 for 75°. Moreover, the fragments produced are of similar size: for test B8, all the 14 fragments have a volume lower than 14 % of the initial volume of the block.

Block B5 (impacting angle of 70°) broke along the foliation planes as visible in Figure 7 (a). This represents a clear situation where the fragmentation at impact generates fragments of tabular shape with a significant effect on the block motion. Indeed, as shown in Figure 7 (b) (after Giani, 1992), the movement of these fragments along an hypothetic slope is naturally optimized when the maximum area section becomes vertical. The movement is then similar to that of a rolling wheel and it can induce unexpected lengths in the traveling of the blocks, even for gentle inclinations. The

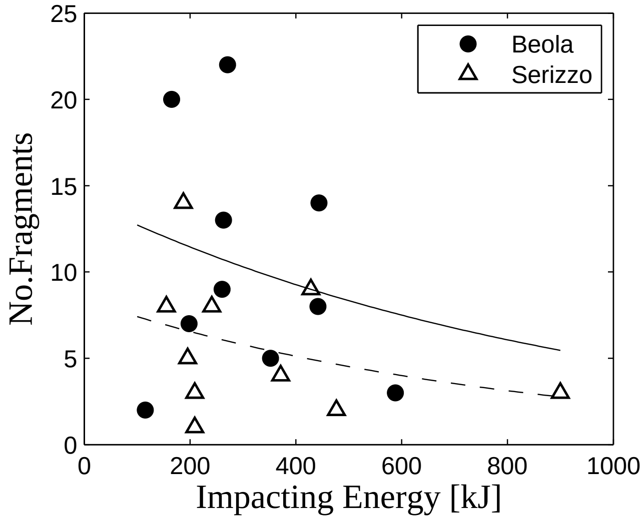

Figure 5: Results of rock fall tests: number of fragments vs. impacting energy for Beola and Serizzo. The points are the experimental results and the lines correspond to the statistical models (dashed line: Beola, continuous line: Serizzo).

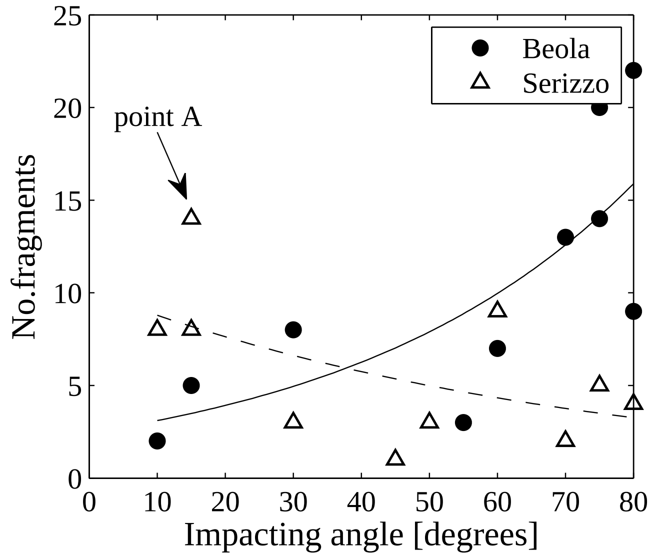

Figure 6: Results of rock fall tests: number of fragments vs. impacting angle α for Beola and Serizzo. The points are the experimental results and the lines correspond to the statistical models (dashed line: Beola, continuous line: Serizzo).

issues associated with the optimization of motion are an increase of kinetic energy and potentially higher rebounds.

Moreover, as mentioned in the introduction of this paper, Giani & Cantarelli (2006) showed that

(a) (b)

Figure 7: (a) View of broken block B5. Fragmentation occured along foliation planes forming fragments of tabular shape. (b) Optimized rolling movement of a tabular shaped block (after Giani, 1992)

a barrier can resist to a big block of regular shape without being able to resist to the impact of a smaller block having a minor kinetic energy but with a smaller contact area inducing high concentration of stress.

Unlike Beola, the statistical trend for Serizzo suggests that number of fragments decreases with increasing impacting angle. Cavallo et al. (2004) suggested that Serizzo is of slightly lower mechanical strength than Beola. Actually, it has been experimentally observed that breakage of Serizzo blocks does not occur systematically along the bedding planes but also through the rock matrix. As a result, the impacting angle has much less influence on the fragmentation. Actually, the decreasing trend comes partly from point A in Figure 6. Should this point be discarded, a much flatter trend is found (see Figure 8) and the impacting angle becomes insignificant (p value of 26.7 %). This is not the case for Beola where the trend relies on much more experimental points. The fragmentation pattern of Serizzo appears to be more sensitive to the impacting angle. When the impacting angle is low, breakage occurs mainly in the matrix producing numerous fragments of similar volume: 14, 7 and 8 fragments for S1, S2 and S3, respectively. All the fragments produced have a volume lower than 30 % of the initial volume. For higher impacting angles, more heterogeneity was observed in the volumes of fragments. It has been noticed that bigger fragments tend to be produced for impacting angle above 30°. For S7 and S6, the initial block broke in two halves (see Figure 4) with or without small fragments corresponding to the broken corners. Again, for S4, the initial block is almost intact except that the corners broke to form small fragments. Test S5 was tested under the same energy than S4 with an higher angle and it remained intact.

It has been concluded from the fragmentation pattern of the two materials that the bedding planes of Beola are mechanically weaker than that of Serizzo producing tabular fragments more systematically. The impacting angle has more influence on Beola that on Serizzo (in terms of number of fragments) and it appears more difficult to predict the number of fragments for Serizzo and, by extension, to any material which does not have a strong foliation.

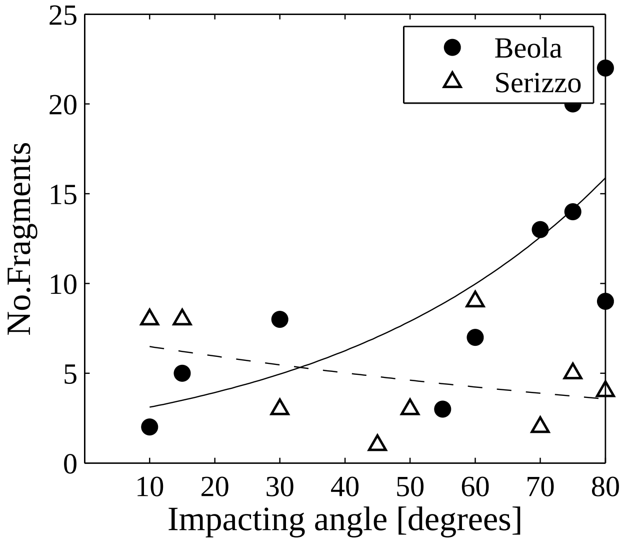

Figure 8: Partial results of rock fall tests: number of fragments vs. impacting angle α for Beola and Serizzo. The points are the experimental results and the lines correspond to the statistical models. Point A of Figure 6 has been removed.

3.2 Energetical considerations

The kinetic energy just before impact E_k^{bi} has been defined section 2.3 (Equation 1). After impact, the velocity of the most significant fragments (in terms of volume) has been back calculated using the photographs knowing the frame speed and the total kinetic energy after impact E_k^{ai} can be calculated as :

$$E_k^{ai} = \frac{1}{2} \sum_f m_f \cdot v_f^2 \tag{6}$$

where m_f is the mass of a fragment and v_f its speed. Computed values of total kinetic energy after impact are recorded in Table 5. This energy is nil for test S5 for which the block neither broke nor moved.

The conservation of energy can be written as follows:

$$E_k^{bi} = E_k^{ai} + E_f + E_d \tag{7}$$

Test	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
E_k^{ai} [kJ]	2.7	6.7	27.7	10.4	13.4	6.8	37.5	12.4	12.2	26.8
Test	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
E_k^{ai} [kJ]	7.67	10.85	37.36	8.67	0	2.26	6.79	20.65	2.50	4.30

Table 5: Values of total kinetic energy after impact for Serizzo and Beola

where E_d is the deformation energy (deformation of the ground and of the block during the impact) and E_f is the fragmentation energy. The deformation energy is not trivial to measure and it has to be estimated. This is done using the restitution coefficient k_n (for a vertical fall v_t is assumed to be nil and k_t is irrelevant). Considering a fall without fragmentation, the velocity of the block after impact can be defined as $k_n \cdot v_n$ (Giani et al., 2004). The kinetic energy of the intact block after impact is then equal to :

$$E_k^{ai(intact)} = \frac{1}{2} \cdot m \cdot (k_n \cdot v_n)^2 \tag{8}$$

so that the deformation energy E_d can then be estimated as:

$$E_d = E_k^{bi} - E_k^{ai(intact)} = E_k^{bi} \cdot (1 - k_n^2) \tag{9}$$

Obviously for the tests performed herein, fragmentation did occur and the total kinetic energy measured after impact is different from $E_k^{ai(intact)}$. With the formulation of deformation energy given in Equation 9, the fragmentation energy is expressed as:

$$E_f = E_k^{bi} \cdot k_n^2 - E_k^{ai} \tag{10}$$

As a result of the assumption made (see Equation 8), the fragmentation energy depends on the restitution coefficient k_n. Since the impacted surface in the quarry was made of hard rock, a value of 0.8 can reasonably be chosen (Piteau & Clayton, 1976). In the attempt to validate the idea of an energy threshold triggering fragmentation, the fragmentation energy E_f is plotted as a function of number of fragments in Figure 9 (a). It was concluded previously that no threshold in impacting energy triggering the fragmentation could be defined. On the same way, it is not trivial to see a threshold in fragmentation energy. Indeed, several values of fragmentation energy lead to the same numbers of fragments. However, a very interesting outcome is that the amount of impacting energy corresponding to failure is relatively constant for the twenty tests. This can be seen in Figure 9 (b) where the ratio $\frac{E_f}{E_k^{bi}}$ is plotted vs. the number of fragments. This ratio can be derived from Equation 10:

$$\frac{E_f}{E_k^{bi}} = k_n^2 - \frac{E_k^{ai}}{E_k^{bi}} \tag{11}$$

Note that the term k_n comes from the assumption made to obtain the deformation energy but both E_k^{ai} and E_k^{bi} are measured entities. It appears in Figure 9 (b) that around 60 % of the impacting energy is used in the breakage of the blocks.

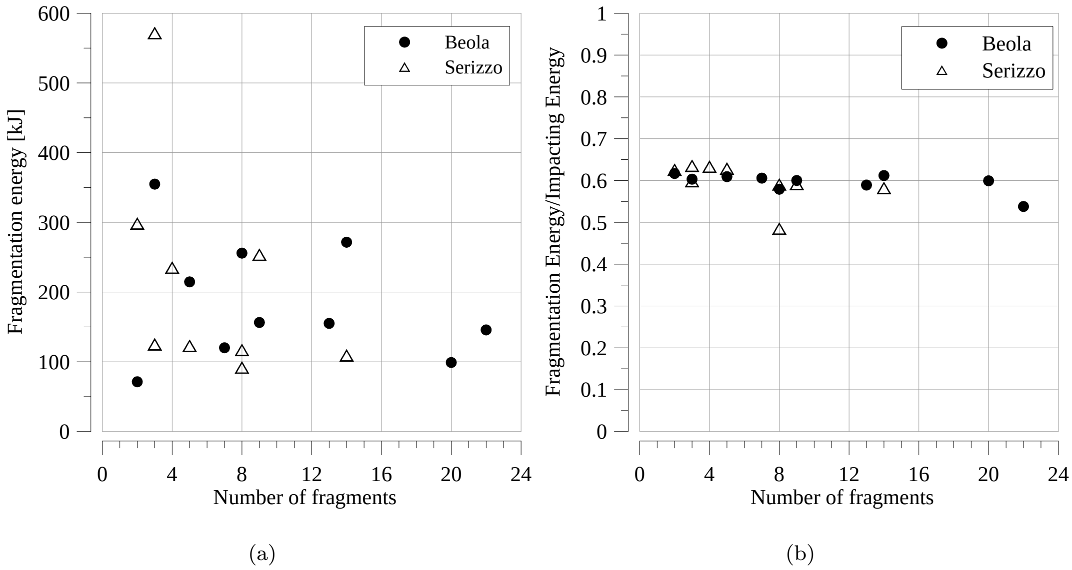

Figure 9: (a) Fragmentation energy E_f vs. number of fragments for Beola and Serizzo. (b) Ratio fragmentation energy over impacting energy vs. number of fragments for Beola and Serizzo.

4 Significance for the design of protection barriers

As mentioned previously, the fragmentation is not currently taken into account in the design of rock fall protection systems despite several authors have risen several issues associated with fragmentation (Giani et al., 2004; Giani & Cantarelli, 2006; Agliardi & Crosta, 2003; Fornaro et al., 1990; DeCol & Cocco, 1996).

In an attempt to model the fragmentation, Fornaro et al. (1990) have considered an impacting energy threshold, which is used to trigger the fragmentation. It has been shown in the present study that the sensitivity of the fragmentation phenomenon to the impacting angle tends to minimize the effect of the impacting energy so that the idea might not be valid for an anisotropic or foliated material. Actually, the results obtained herein suggest that an impacting energy threshold either does not exist or is very low. This conclusion is believed to be valid even though free fall tests are not exactly representative of real rock fall events.

Determining whether fragmentation will take place or not is far from trivial, especially if the material does not comprise weak bedding planes. It appears from the energetical considerations that the proportion of impacting energy dissipated during fragmentation appears to be quite constant and could maybe used in numerical modeling to attribute the new kinetic energy to the fragments. With the possible formation of tabular blocks upon impact, the rolling coefficient should be considered decreasing in order to capture the increasing rolling efficiency acquired by the block. Indeed, this decreasing rolling coefficient produces higher tangential velocity (Azzoni et al., 1995).

5 Conclusions

Studies on the rock fragmentation during rock fall events are rather rare in the literature because this phenomenon is not assumed to not have consequence for the design of protection barriers. Indeed, the kinetic energy of the fragments produced upon impact is assumed to be negligible. However, several authors have mentioned that this assumption is not correct and that rock fragments can cause serious damage to barriers due to projectile effect, stress concentration or very high rolling motions. Another issue is the possible projection of fragments over the fences.

The experimental study presented in this paper aimed to understand better the rock fragmentation phenomenon with an emphasis on the impacting angle in case of foliated materials. A total of twenty free fall test were performed in a quarry in Italy using two ornamental stones from the Ossola Valley (Italy) namely Beola and Serizzo. The use of high speed cameras have allowed to quantify the impacting angle, the fragments velocity and their kinetic.

The tests have shown that all the blocks except one broke in several fragments upon impact even for lowest values of impacting energy. The results have been analyzed statistically using a general linear model (GLM) to assess the significance of the impacting energy and that of the impacting angle on the number of fragments produced.

Beola appeared to be very sensitive to the impacting angle with the number of fragments produced increasing with the impacting angle. This result is mechanically consistent with the presence of weak foliation planes in the boulders. For Serizzo, this effect is less obvious. Firstly, the statistical trend showing an influence of the angle is highly affected by one specific experimental result. Then, the breakage pattern appeared to be different with fractures along bedding planes and through the rock matrix. The impact angle should in fact be introduced as a fundamental characteristic of the study only for rock comprising bedding planes of weak mechanicla properties.

The results obtained do not confirm the idea of an impacting energy threshold to trigger the fragmentation. This latter could be very low but, from a qualitative point of view, for an anisotropic material, the threshold should anyway account for the direction of loading with respect with the bedding planes. Another interesting outcome of this study is the fact that the proportion of impacting energy disspated during the fragmentation appears to be relatively constant. For a restitution coefficient $k_n = 0.8$, it represents around 60 % of the initial energy. This outcome could be of interest when trying to attribute an initial kinetic energy to the blocks formed at impact.

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