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# Experimental studies on fragmentation of rock falls on impact with rock surfaces

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## ABSTRACT

Rock fall is a common natural hazard causing significant damage to infrastructure and loss of life. Rock fragmentation is frequently observed during rock fall events and several authors have raised issues related to the impact of fragments on the protection structure. However, this phenomenon is not accounted for when designing the protection barriers. The paper presents the results of 20 rockfall tests performed in a quarry in Italy to provide new insight into the fragmentation phenomenon, especially in the case of foliated materials. The results have shown that the impacting angle plays a key role in the fragmentation of foliated rocks whereas the effect of the impacting energy tends to be of second order. No threshold in impacting energy could be defined to explain what triggers the fragmentation. It has been noticed that the proportion of impacting energy dissipated during fragmentation is relatively constant and depends on the choice of the normal restitution coefficient.

## 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 and civil infrastructure from rockfall hazards is due to the need to protect 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 [1–4], on barrier tests [5–8] and on the development of analytical and numerical models. The latter are chiefly focused on the evaluation of the trajectories of detached blocks [9–14] for different morphological and geological conditions [15–19].

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 rockfall phenomenon: velocity of free falling block, restitution coefficients at impact or equivalent rolling friction coefficients [16,20,19]. Rockfall tests are usually performed in representative sites by moving a large number of blocks 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 rockfall, 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. This lack of consideration explains why the study of fragmentation is still in its early age despite it being a natural and frequent phenomenon. Moreover, fragmentation is facilitated by the presence of discontinuities in the boulders and by high impacting velocities [21]. 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 and Crosta [14] 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".

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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 [22]. This happens when the fragment rolls down the slope like a wheel. Giani [22] 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 [23,24]. There is evidence to suggest that major damage can be produced in the rockfall protection systems due to smaller impacting areas and stress concentration. Projectile effect, that could hole the net, is even mentioned [25,26]. Cantarelli and Giani [23] 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 kinds of block but, because of the different shape, the impacting area is smaller for the irregular blocks. The authors 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 energy considerations [27,28]. Moreover, only a few modeling approaches taking into account the possible breakage of the falling block can be found [29,30]. Fornaro et al. [29] proposed a rockfall model taking into account the possibility of block breakage at each impact with formation of smaller blocks 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. [31] 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 volume of fragments.

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 [22].

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 kinds of rock having different schistosity. The results are discussed considering the influence of impacting energy and the angle between bedding planes and the impact surface at impact on the number of fragments. Indeed, these two parameters are thought to play a key role in the fragmentation. Then, energy considerations are undertaken in order to assess whether the idea of an 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 Fig. 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 Fig. 1) was used to lift and release the rock boulders. The fall height, ranging from 10 to 40 m, 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 Fig. 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 (see Fig. 2). Each block was painted prior testing in order to identify the fragments produced at the impact (Fig. 3).

### 2.2. Materials

Two kinds of 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 gray color. Because of its strong anisotropy the mechanical behavior is strongly influenced by the orientation of the main foliation with respect to the load application direction

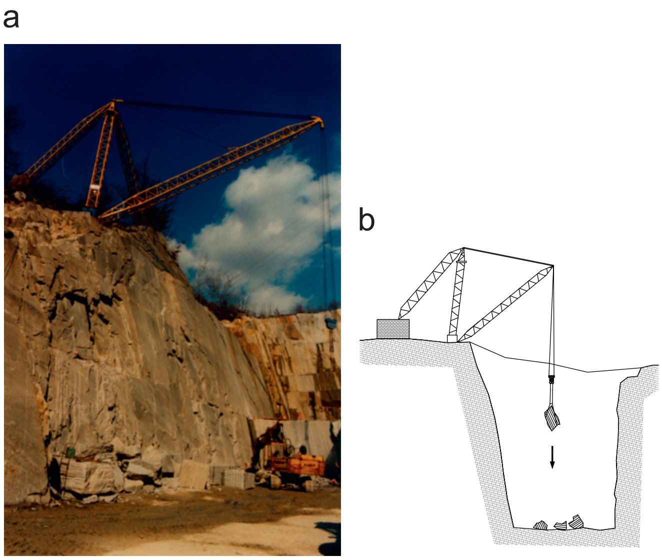

**Fig. 1.** (a) Photograph of Crevoladossola quarry in Italy. (b) Schematic representation of the test site and experimental set up.

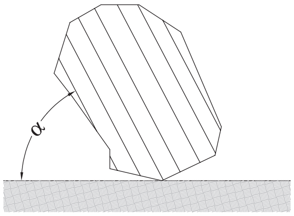

**Fig. 2.** Schematic representation of the impacting angle defined as the angle between the bedding planes and the impacted surface.

**Fig. 3.** View of painted blocks prior testing in order to allow proper identification of fragments.

[32,33]. 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 planes. 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 Table 1, two series of tests representing a total of 20 tests were performed. Each test series included 10 tests of variable mass, falling height and impacting angle on each material. 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:

$$E_k^{\mathrm{bi}} = \tfrac{1}{2}mv^2 = mgh \quad (1)$$

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

## 3. Results and discussion

As expected, a majority of the dropped blocks broke under impact as shown in Fig. 4(a) and (b). Some blocks broke into numerous fragments (up to 22) while others broke into a limited number of fragments. One block did not break (test S5). The smallest pieces of rock (less than 0.001 m$^3$) produced by the impact were not considered when counting the fragments.

**Table 1**
Testing program for Beola and Serizzo

| 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 |
| **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 |

**Fig. 4.** (a) Block S3 just after impact. (b) Block S6 just after impact.

Table 2 summarizes all the relevant data measured during the two series of tests.

### 3.1. *Influence of impacting energy and of impacting angle on the fragmentation*

In rockfall studies, the energy at impact is usually considered as the key parameter for the rock fall defense design [23,8,34]. 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 impacting energy) on

**Table 2**
Results of free fall tests performed on Beola and Serizzo

| 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 |
| $\alpha_m$ (°) | 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 |
| $\alpha_m$ (°) | 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 |

$E_k^{bi}$: kinetic energy before impact, $\alpha_m$: measured impacting angle, $V_o$: initial volume of the block, $NF$: number of fragments.

one dependent variable (number of fragments) was studied by means of a generalized linear model (GLM) [35]. In a GLM, the dependent variable $\boldsymbol{NF}$ is assumed to follow a given distribution, whose mean $\boldsymbol{\mu}$ depends on the independent variables $\boldsymbol{X}$ as follows:

$$g(E(\boldsymbol{NF})) = g(\boldsymbol{\mu}) = \boldsymbol{X\beta} \quad (2)$$

In this equation, $\boldsymbol{\beta}$ 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 $\boldsymbol{NF}$ and the linear predictor $\boldsymbol{X\beta}$. In this study, a GLM was constructed as follows. Let $NF_{i,j}$ denotes the number of fragments for experiment $i$ ($i = 1\ldots10$) and rock type $j$ ($j = 1$ for Beola, 2 for Serizzo). The mean of $NF_{i,j}$ is described by:

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

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

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

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

Parameters $\gamma_1$ and $\gamma_2$ describe the effect of the impacting angle on the number of fragments for rock type Beola and Serizzo, respectively. Similarly, parameters $\phi_1$ and $\phi_2$ describe the effect of the impacting energy on the number of fragments for each rock type. $\beta_0$ is the intercept for rock type Beola, while $\beta_0 + \beta_2$ is the intercept for rock type Serizzo. Consequently, parameter $\beta_2$ can be interpreted as the overall effect of the rock type on the number of fragments. A $t$-test was performed to investigate the significance of each of these effects. The 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.

Results of the GLM analysis are summarized in Table 3 and the linear models are plotted together with the experimental data in Figs. 5 and 6. Linear models are more than a "best fit curve" since they incorporate several independent variables (here impacting energy and impacting angle). Conclusions about the relevance of the model do not have to be drawn only from a graphical point of view (impression of "good fit") but considering the results of the $t$-tests. The values of $\beta_0$, $\beta_2$, $\gamma_1$, $\gamma_2$, $\phi_1$ and $\phi_2$ are of interest when using the general linear model for prediction. This is not the case herein since attention is focused on significance of the key parameters. Consequently, the values in themselves will not be discussed.

**Table 3**
Results of the GLM analysis

| Parameter | Value | Standard error | $t$-Value | $p$-Value |
|---|---|---|---|---|
| $\beta_0$ | 1.227 | 0.456 | 2.692 | **0.007** |
| $\beta_2$ | 1.160 | 0.529 | 2.193 | **0.028** |
| $\gamma_1$ | 0.022 | 0.005 | 4.283 | $\mathbf{1.83} \times 10^{-5}$ |
| $\gamma_2$ | −0.012 | 0.006 | −2.009 | **0.044** |
| $\phi_1$ | $-9.08 \times 10^{-4}$ | $8.21 \times 10^{-4}$ | −1.107 | 0.268 |
| $\phi_2$ | $-4.6 \times 10^{-4}$ | $7.90 \times 10^{-4}$ | −0.586 | 0.557 |

Values in bold refer to significant effects at level 10%.

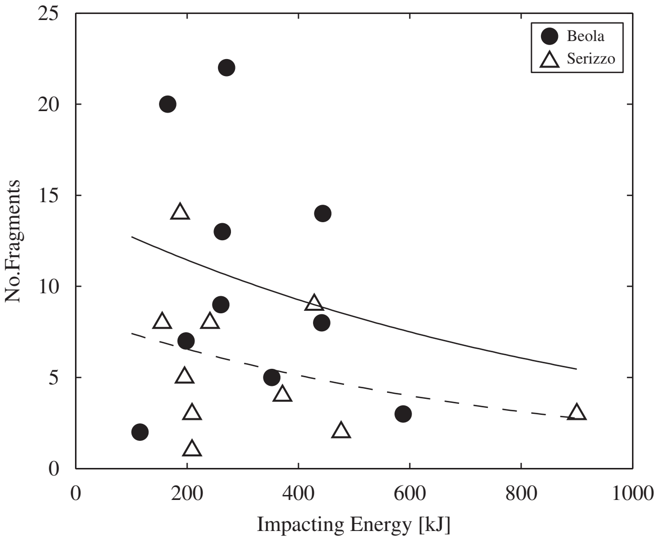

**Fig. 5.** Results of rockfall tests: number of fragments vs. impacting energy for Beola and Serizzo. The points are the experimental results and the lines correspond to the statistical models (continuous line: Beola, dashed line: Serizzo).

As shown in Table 3, the significance of the impacting energy for both Beola and Serizzo is 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%). This result 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 probably be seen as in any other study. However, keeping a constant impacting angle is not representative of real rockfall events and the relevance of keeping the impacting angle constant can be questioned. Note that in Fig. 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 would give a similar accuracy of prediction. In other words, the effect of energy is of second order compared to the effect of impacting angle for the two rock types considered.

Fornaro et al. [29] have used the idea of an energy threshold to trigger the fragmentation of the blocks but no threshold value could be identified from the series of tests presented herein. Indeed, fragmentation almost always occurred. Note that block S5, tested under 200 kJ, did not break 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 Fig. 6 that the trends for Beola and Serizzo are opposite.

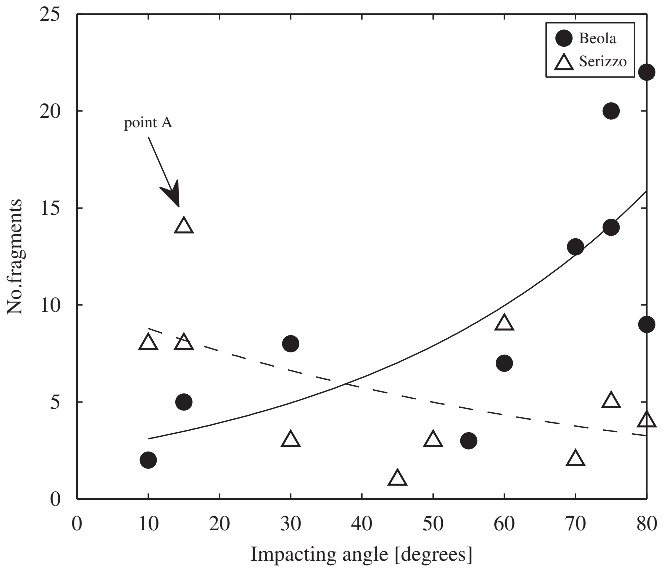

**Fig. 6.** Results of rockfall tests: number of fragments vs. impacting angle $\alpha$ for Beola and Serizzo. The points are the experimental results and the lines correspond to the statistical models (continuous line: Beola, dashed line: Serizzo).

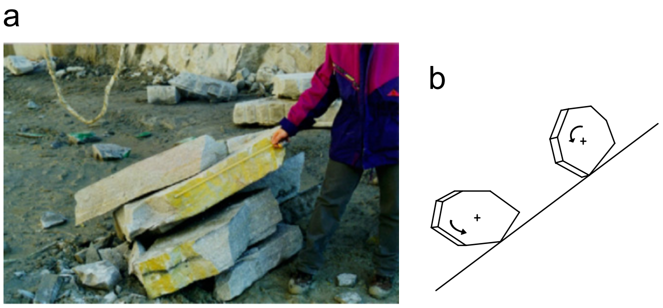

**Fig. 7.** (a) View of broken block B5. Fragmentation occurred along foliation planes forming fragments of tabular shape. (b) Optimized rolling movement of a tabular shaped block after [22].

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 [36] showed that the mechanical strength of jointed rock decreases when the angle between joint set and loading direction decreases from 90° to 45°.

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 Fig. 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 Fig. 7(b) after [22], the movement of these fragments along an hypothetical 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 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, Cantarelli and Giani [23] showed that a barrier can resist the impact of large block of regular shape without being able to resist 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 the number of fragments decreases with increasing impacting angle. Cavallo et al. [33] 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 Fig. 6. Should this point be discarded, a flatter trend is found (see Fig. 8) and the impacting angle becomes insignificant ($p$ value of 26.7%). This is not the case for Beola where several experimental points tend to show the increase of number of fragments with the impacting angle.

The relationship between the impacting angle and the number of fragments is therefore weaker for Serizzo than for Beola. However, it was qualitatively observed that 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 Fig. 4) with or without small fragments corresponding to the broken corners. Again, for S4, the initial block remained almost intact except that the corners broke to form small fragments. Test S5 was tested under the same energy as 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 those 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 strongly foliated material.

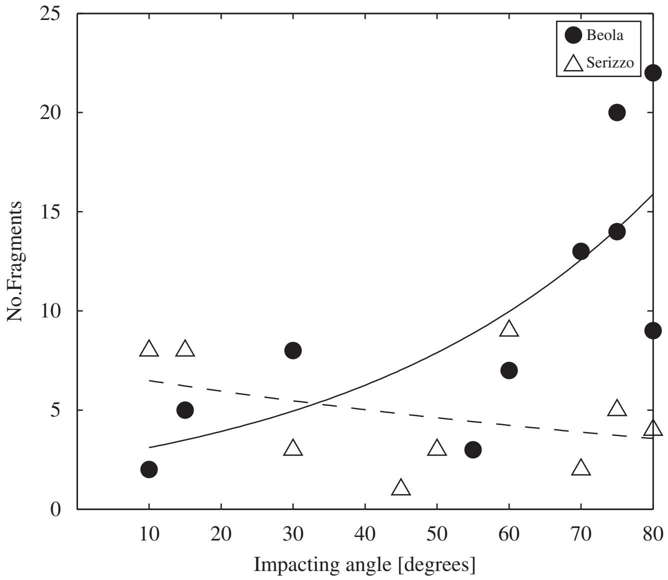

**Fig. 8.** Partial results of rock fall tests: number of fragments vs. impacting angle $\alpha$ for Beola and Serizzo. The points are the experimental results and the lines correspond to the statistical models. Point A of Fig. 6 has been removed (continuous line: Beola, dashed line: Serizzo).

An attempt has been made to quantify the homogeneity of fragment volumes in order to correlate the volume of the fragments produced to the impacting angle and impacting energy. However, the average fragment volume and standard deviation of the fragment volumes are not suitable for this purpose. No simple index could be found to describe the heterogeneity of the fragments and further research has to be done on this specific point.

### *3.2. Energy considerations*

The kinetic energy just before impact $E_k^{\mathrm{bi}}$ has been defined in Section 2.3 (Eq. (1)). After impact, the velocity of the fragments has been back calculated using the photographs and knowing the frame speed. The total kinetic energy after impact $E_k^{\mathrm{ai}}$ can be calculated as:

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

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 4. This energy is nil for test S5 for which the block neither broke nor moved.

The conservation of energy can be written as follows:

$$E_k^{\mathrm{bi}} = E_k^{\mathrm{ai}} + E_f + E_{\mathrm{d}} \tag{7}$$

where $E_{\mathrm{d}}$ 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. The normal and tangential velocities after impact ($v_{\mathrm{n}}^{\mathrm{ai}}$ and $v_{\mathrm{t}}^{\mathrm{ai}}$) are usually defined by means of restitution coefficients ($k_{\mathrm{n}}$ and $k_{\mathrm{t}}$) applied to the normal and tangential velocities before impact ($v_{\mathrm{n}}^{\mathrm{bi}}$ and $v_{\mathrm{t}}^{\mathrm{bi}}$) [11]:

$$v_{\mathrm{n}}^{\mathrm{ai}} = k_{\mathrm{n}} \cdot v_{\mathrm{n}}^{\mathrm{bi}} \tag{8}$$

$$v_{\mathrm{t}}^{\mathrm{ai}} = k_{\mathrm{t}} \cdot v_{\mathrm{t}}^{\mathrm{bi}} \tag{9}$$

In case of a vertical fall, only the normal component of velocity is considered. The tangential velocity is assumed to be nil and $k_{\mathrm{t}}$ becomes irrelevant. Considering a fall without fragmentation, the kinetic energy of the intact block after impact is then equal to:

$$E_k^{\mathrm{ai(intact)}} = \tfrac{1}{2} \cdot m \cdot (k_{\mathrm{n}} \cdot v_{\mathrm{n}}^{\mathrm{bi}})^2 \tag{10}$$

so that the deformation energy $E_{\mathrm{d}}$ can then be estimated as:

$$E_{\mathrm{d}} = E_k^{\mathrm{bi}} - E_k^{\mathrm{ai(intact)}} = E_k^{\mathrm{bi}} \cdot (1 - k_{\mathrm{n}}^2) \tag{11}$$

Obviously for the tests performed herein, fragmentation did occur and the total kinetic energy measured after impact is different from $E_k^{\mathrm{ai(intact)}}$. With the formulation of deformation energy given in Eq. (11), the fragmentation energy is expressed as:

$$E_f = E_k^{\mathrm{bi}} \cdot k_{\mathrm{n}}^2 - E_k^{\mathrm{ai}} \tag{12}$$

**Table 4**
Values of total kinetic energy after impact and ratio total kinetic energy after impact over impacting energy for Serizzo and Beola

| Test | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $E_k^{\mathrm{ai}}$ (kJ) | 2.7 | 6.7 | 27.7 | 10.4 | 13.4 | 6.8 | 37.5 | 12.4 | 12.2 | 26.8 |
| $E_k^{\mathrm{ai}}/E_k^{\mathrm{bi}}$ | 0.023 | 0.041 | 0.102 | 0.040 | 0.051 | 0.034 | 0.064 | 0.028 | 0.035 | 0.061 |

| Test | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $E_k^{\mathrm{ai}}$ (kJ) | 7.67 | 10.85 | 37.36 | 8.67 | 0 | 2.26 | 6.79 | 20.65 | 2.50 | 4.30 |
| $E_k^{\mathrm{ai}}/E_k^{\mathrm{bi}}$ | 0.049 | 0.058 | 0.155 | 0.042 | 0 | 0.012 | 0.014 | 0.048 | 0.007 | 0.005 |

As a result of the assumption made (see Eq. (10)), the fragmentation energy depends on the restitution coefficient $k_{\mathrm{n}}$. According to the literature data, this coefficient can range from around 0.4 [11] to around 0.8 [9] for an impacted surface made of hard rock. An additional value of 0.53 [37] has also been considered.

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 Fig. 9(a). It was concluded previously that no threshold in impacting energy triggering the fragmentation could be defined. Furthermore, it is not trivial to see a threshold in fragmentation energy. Indeed, several values of fragmentation energy lead to the same numbers of fragments.

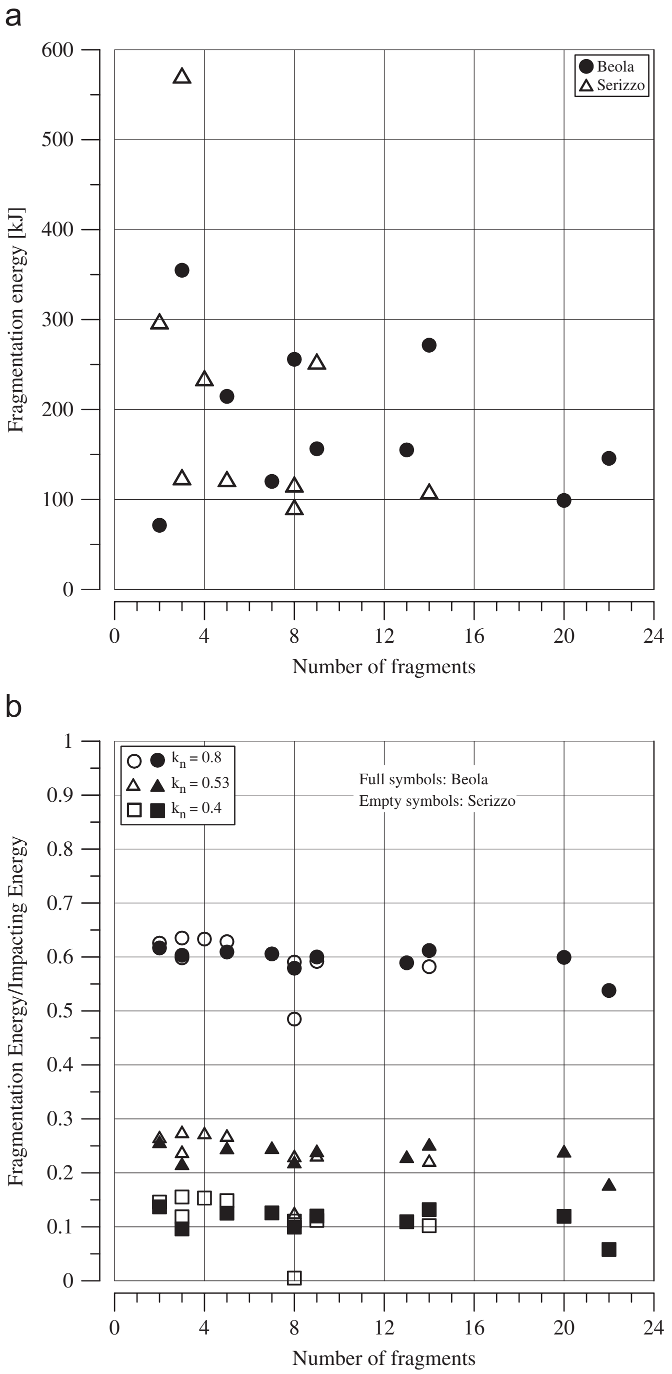

**Fig. 9.** (a) Fragmentation energy $E_f$ vs. number of fragments for Beola and Serizzo. (b) Ratio fragmentation energy over impacting energy vs. number of fragments for Beola and Serizzo. Values plotted for $k_{\mathrm{n}} = 0.4$ [11], $k_{\mathrm{n}} = 0.53$ [37] and $k_{\mathrm{n}} = 0.8$ [9].

However, a very interesting outcome is that the amount of impacting energy corresponding to failure is relatively constant for the 20 tests. This can be seen in Fig. 9(b) where the ratio $E_f/E_k^{\mathrm{bi}}$ is plotted vs. the number of fragments. This ratio can be derived from Eq. (12):

$$\frac{E_f}{E_k^{\mathrm{bi}}} = k_{\mathrm{n}}^2 - \frac{E_k^{\mathrm{ai}}}{E_k^{\mathrm{bi}}} \tag{13}$$

Note that the term $k_{\mathrm{n}}$ comes from the assumption made to obtain the deformation energy but both $E_k^{\mathrm{ai}}$ and $E_k^{\mathrm{bi}}$ are measured entities.

Consistent with Eq. (13), the amount of impacting energy used in the breakage of the blocks depends on $k_{\mathrm{n}}$. It varies from 60% for $k_{\mathrm{n}} = 0.8$ to around 10% for $k_{\mathrm{n}} = 0.4$ (Fig. 9(b)).

## 4. Significance for the design of protection barriers

As mentioned previously, the fragmentation is not currently taken into account in the design of rockfall protection systems despite several authors having raised several issues associated with fragmentation [14,19,23,25,29].

In an attempt to model the fragmentation, Fornaro et al. [29] 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 rockfall events.

Determining whether fragmentation will take place or not is far from trivial, especially if the material does not contain weak bedding planes. It appears from the energy considerations that the proportion of impacting energy dissipated during fragmentation is quite constant and could possibly be used in numerical modeling to attribute the new kinetic energy to the fragments.

Moreover, the formation of tabular blocks can be critical for the impact on barriers since their specific shape can allow them to reach very high speed by an optimized rolling motion [22]. The relevant motion parameters for a rolling movement is the rolling coefficient, which is usually considered equal to the sliding friction coefficient between the rock and the surface [38]. As explained in Azzoni et al. [17], the roughness of the slope also affects the rolling motion. However, generally, the lower the rolling coefficient, the further the boulder travels [22]. Consequently, a solution to capture the more efficient rolling motion due to the tabular shape is to reduce the rolling coefficient.

## 5. Conclusions

Studies on the rock fragmentation during rockfall events are rather rare in the literature because this phenomenon is assumed to have no 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 the case of foliated materials. A total of 20 free fall tests 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 allowed the quantification of the impacting angle, the fragments velocity and their kinetic energy.

The tests have shown that all the blocks except one broke into several fragments upon impact even for the 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 increasing with this latter. 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 impacting 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 impacting angle should in fact be introduced as a fundamental characteristic of the study only for rock comprising bedding planes of weak mechanical 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 in any case 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 dissipated during the fragmentation appears to be relatively constant. For a restitution coefficient $k_{\mathrm{n}} = 0.8$, 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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