Dynamic finite element analysis of interceptive devices for falling rocks

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Abstract

The widespread use of net barriers, which are flexible, as opposed to rigid, devices for intercepting falling rocks has led to the need for rigorous design criteria based on safe and sound theoretical methods. Consistently with current practice, full-scale experimental tests are necessary in order to assess the reliability of any such barrier. Here, a new simulation approach based on numerical methods is presented: the analysis of a complete typical falling-rock event has been performed, to study the response of these interceptive devices. A commercial finite element code featuring explicit dynamic capabilities, particularly useful when modelling high-speed phenomena has been used. The simplifying assumptions along with the model geometrical and mechanical data are discussed. Both single net panel and complete barrier simulations are presented. In the latter case, the results are compared with some experimental data obtained from in situ testing. The results of the numerical simulations highlight some limitations in the testing methods which are currently accepted, and suggest the use of new parameters to more precisely characterize the behaviour of such interceptive devices for falling rocks. The benefits of numerical simulations as supplements to or substitutes for full-scale crash tests are emphasized particularly for design or parametric studies. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Rocks falling from cliffs or slopes may cause great damage to underlying construction. Several methods have been developed to prevent or reduce the social and economic costs involved. Net barriers are widely used to intercept and hopefully arrest the falling blocks: a typical installation experiencing the impact of a falling block is presented in Figs. 1 and 2, taken during a recent in situ crash test.

In the past, researchers have concentrated on the simulation of the rockfall phenomenon and, in particular, the prediction of the block trajectory, velocity and energy (see, for instance, the references cited in the introduction by [1]).

Indeed, when the most common protection against rockfall consisted of rigid structures like concrete rockfall shelters, it was sufficient, for analysis and design purposes, to know the trajectory, velocity and energy of the falling block, since the task of dissipating the energy produced by the impact was left to some absorbing material such as soil backfill surrounding the structure, which was itself considered a perfectly rigid body.

In recent times, the widespread use of net barriers (especially in France, Switzerland and Italy), which are flexible devices for intercepting falling rocks requires the consideration of the deformation of the structure during the impact, along with its resistance and ductility.

Of course, when involved with net barrier design, issues like rock stability assessment, rock fall analysis and the modelling of rock fall trajectories are still very important, but cannot solve, by themselves, the problem. Indeed, some theoretical or physical modelling of the catch fence is required at the design stage, in order to predict its behaviour during rock impact.

The present conventional methods of net barrier design are based on oversimplified theoretical models. Normally, assuming a given duration of impact, the force applied to the barrier can be evaluated from the estimated kinetic energy of block. Then, the forces
induced in the cables can be determined from a static analysis.

Alternatively, crash tests are performed on full-scale physical models to determine the maximum impact energy sustainable by the net barrier. The tests are generally carried out using large natural or artificial regular-shaped blocks, which collide with the centre of the net. As it will be shown later, an upper bound for the impact energy is obtained. It should be emphasized that, notwithstanding the very particular nature of the test conditions, the barrier is certified for this value of energy, without taking into account the size and the impact point of the blocks of rock.

A more accurate approach has been adopted by [1], who took the experimental data recorded by some dynamometers during a crash test and applied them as static loads to the deformed configuration of the barrier, in order to evaluate the forces acting on the structure.

The results provided by this method are limited, however, to the particular crash test recorded and do not take into account all possible impact conditions.

In this paper, a different approach is adopted, which is based on numerical simulations, performed by means of a finite element code, involving a typical dynamic event of a rock fall against a net barrier. Such an approach, to the best of the authors’ knowledge, has not been used yet in catch fence design. Its suitability for design or redesign purposes or for parametric analyses will be shown.

In particular, the authors’ objectives are:

1. To show that a finite element model of the rock-block impact against a net barrier can be formulated in the dynamic range. It turns out, moreover, that such a model is schematic and simple enough to require a reasonable amount of computing resources but, at the same time, retains the fundamental characters of the observed physical phenomena.

2. To assess the reliability of the above-mentioned model by comparing its results with those provided by real size tests.

3. To emphasize the ability of the model to investigate the effects of impact conditions, such as size, shape, translational and rotational velocity components and the impact point of the block.

4. To propose the adoption of numerical simulations as a cheap new tool for the design of catch fences. These can usefully supplement real-scale crash tests when parametric analyses are required or the effects of minor—or even major—design changes need to be investigated.

As a final remark, emphasis is placed here more on methodology (i.e. on how the proposed method can be applied to the dynamic analysis of a net barrier hit by a rock block) rather than on the detailed problem-solving techniques for design purposes. The authors are aware, for instance, that simulations performed at 1 m/s intervals might not be precise enough when large boulders or low velocities are involved. On the other hand, their interest was more in providing parametric studies based on numerical simulations, rather than in pushing the results to a higher precision level.

2. Finite element explicit dynamic analysis

The problem of modelling the impact of a rock block against a catch fence requires the consideration of the dynamic characteristics of impact phenomena and the large displacements which develop. If this task must be performed by numerical simulation based on the finite element method, a non-linear code is needed. Indeed, to correctly predict the response of a net barrier during the impact, both non-linear geometrical and mechanical
behaviour should be considered, along with appropriate contact conditions.

Developing from scratch a new computer program, merely for analyzing the proposed problem, would be an immense and highly time-consuming task, and even a pointless one, if the resulting code were not submitted to extensive debugging and tuning.

For this reason, the study was carried out by using a program which is commercially available, namely ABAQUS/Explicit (version 5.7). This program (implemented by Hibbitt, Karlsson & Sorensen Inc.) is a general purpose one, and features fully non-linear geometrical, mechanical and contact behaviour in the structural dynamic range. Its suitability for fast dynamics applications (e.g. crash tests, impacts, explosions, etc.) is undisputed. It has been used to model the impact of falling rocks against typical interceptive devices. By the way, the choice of this code was mostly dictated by its availability on some workstations of the computing centre (similar simulations could have been carried out, of course, by using another dynamic explicit code, for instance, one belonging to the DYNA-3D family).

When both the falling rock and the interceptive device are modelled by finite elements, they are split in many little portions, having small but still finite dimensions, and therefore called finite elements. These portions are supposed to be connected together only at particular points, called nodes. The behaviour of each element is then supposed to be completely specified by its material and geometrical parameters and by the motion of the nodes to which it is attached.

The behaviour of the assembly of all elements modelling the structure and the boulder can then be expressed by the usual equation of motion (see, for further details [2, pp. 490–493]):

\[ M \ddot{d} + C \dot{d} + K d = F, \]

where \( M, C \) and \( K \) denote, respectively, the mass, viscous damping and stiffness matrices of the system; vector \( F \) collects externally applied loads, while vectors \( d, \dot{d} \) and \( \ddot{d} \) represent displacements, velocities and accelerations of all nodes.

The motion of the system, i.e. of the net barrier and of the rock block, is known if the nodal displacements \( d \) are evaluated as a function of time, \( t \),

\[ d = d(t) \]

satisfying Eq. (1) and the given initial values:

\[ d(0) = d_0, \]
\[ \dot{d}(0) = v_0 \]

which specify the initial position and velocity (at time \( t = 0 \)) of all nodal points.

To calculate the solution, the following strategy is implemented: first, the equation of motion is rewritten for a sequence of time steps, i.e. of time values equally spaced by the same amount \( \Delta t \), \( t_0 = 0 \), \( t_1 = t_0 + \Delta t \), ..., \( t_n = t_0 + n \Delta t \), \( t_{n+1} = t_n + \Delta t \), etc.; for instance, at \( t = t_{n+1} \), Eq. (1) becomes

\[ M a_{n+1} + C r_{n+1} + K d_{n+1} = F_{n+1}, \]

where \( a_{n+1}, r_{n+1} \) and \( d_{n+1} \) are, respectively, the approximations of the accelerations, \( \dot{d}(t_{n+1}) \) of the velocities, \( \ddot{d}(t_{n+1}) \) and of the displacements, \( \dot{d}(t_{n+1}) \) while \( F_{n+1} \) coincides with \( F(t_{n+1}) \).

Next, these update formulae are adopted:

\[ d_{n+1} = d_n + v_n \Delta t + a_n \Delta t^2 / 2 = \dot{d}_n^* \]
\[ v_{n+1} = v_n + (a_n + a_{n+1}) \Delta t / 2 = v_n^* + a_{n+1} \Delta t / 2. \]

At this point, at any time step, Eqs. (5), (6) and (7) form a system of simultaneous linear algebraic equations which, once \( a_n, v_n \) and \( d_n \) are known from the previous step’s calculations, can be solved for \( a_{n+1}, v_{n+1} \) and \( d_{n+1} \), and so on.

However, since \( M \) and \( C \) are diagonal matrices a so-called explicit method is obtained (see [3, p. 770]), and the simultaneous linear algebraic equations turns out to be particularly easy to solve. Indeed, by substituting Eqs. (6) and (7) into Eq. (5) one gets

\[ (M + C \Delta t/2) a_{n+1} = F_{n+1} - C v_n^* - K d_n^* \]

which can be solved immediately for \( a_{n+1} \) without requiring any factorization, i.e. any inversion, of the stiffness matrix \( K \).

There is, therefore, a significant reduction of computational effort per time step, partially balanced by the requirement of very small time increments \( \Delta t \) to achieve stability (as shown in [4, pp. 2.4.5–2], and [5, p. 65]). The need for small time steps is not, however, a big issue in the framework of a typical rock fall phenomenon, where the time scale of the whole simulation, from the first block-net collision to the complete catch, is of the order of a few seconds. In contrast, the corresponding time interval during which the forces, the accelerations or the velocities can vary significantly or during which contacts between moving/deforming surfaces can be established or released, amounts to a few nanoseconds, i.e. is \( 10^{-9} \) times smaller. Therefore, the need to accurately model rapidly varying forces, accelerations, velocities and contact conditions can be easily achieved within the explicit dynamic method presented above.

3. Basic assumptions

The scope of the present work is limited to the analysis of interceptive devices consisting of deformable rock restraining net barriers, i.e. of metal cable nets,
supported by steel posts and equipped with energy-dissipating devices systems also known as friction brakes.

These devices can undergo large displacements and are used as a passive protection against rockfalls, as they are able to dissipate a part of the kinetic energy of the falling boulders by both friction and/or by the permanent deformation of their own structure.

The actual behaviour of these interceptive devices during rockfall events results from the combination of several concurrent phenomena whose complex interaction is not well known. The task of analyzing them can be accomplished by means of numerical simulations only at the expense of some simplifying assumptions, based mostly on engineering judgement.

For instance, the typical behaviour of a net cable during a standard static tensile test is sketched in Fig. 3. It can be seen that the load vs. displacement diagram exhibits first (from point O to point A in Fig. 3) a non-linear stiffening, mostly due to some thread rearrangement. Then (between points A and B) the curve is almost linear, but for load levels exceeding that of point B, the stiffness begins to decrease, and is probably associated with the development of some permanent deformation. However, when failure point (R) is reached, the load cannot be further incremented and the limit resistance is attained. As threads begin to break, the active cross-section of the cable decreases; displacement can still be incremented, but only at the expense of a reduction in the applied load.

Similarly, a typical static tensile test on a friction brake yields the curve presented in Fig. 4. Again, an initial non-linear stiffening effect can be seen (between points O and A), but is then followed by an irreversible flow (from point A to point B) at a pretty constant load level. It is only after reaching point B that stiffness starts to increase significantly, until eventually failure is attained at point R.

In both cases presented above, the structural analyst is faced with the problem of obtaining a mechanical material model (which should provide correct results in the dynamic range) based on the experimental results from static tests only.

For the sake of simplicity, and to retain only the most important observed phenomena, the authors have adopted constitutive laws which are uniaxial, rate independent and elastic–perfectly plastic for both net cables and friction brakes. This choice could be disputed, of course, as being a too crude approximation. To confute this objection, it seems pointless adopting more complicated mechanical models, in the authors' opinion, if there is no clear experimental evidence that they are better suited to reproduce the response of the structural members under dynamic loads. On the other hand, the validity of this constitutive hypothesis can only be ascertained a posteriori, by comparison with real size crash tests. It should be pointed out, however, that according to experimental tests performed by Grillo et al. [6] the adoption of uniaxial elastic–perfectly plastic constitutive laws seems appropriate for steel members under impulsive loading.

Thus, the assumed constitutive law for net and perimeter cables is shown in Fig. 5: the adopted stress-strain curve is depicted there. The material behaviour is modelled as elastic–perfectly plastic, but the collapse load and the corresponding permanent strain are those deduced from static tensile tests (as in Fig. 3). The elastic behaviour is linear, but the value of the corresponding Young's modulus, $E = 150$ GPa is lower than that of standard steel bars. This is to take into account, in a global way, the initial non-linear stiffening effect.
exhibited by the cables (branch OA in Fig. 3). The plastic plateau is reached with a yield stress \( \sigma_0 = 1500 \text{ MPa} \) and its extension is limited, in terms of plastic strain, by a failure value \( \varepsilon_{f,b} = 0.05 \), i.e. 5\%, and corresponds to the same value obtained in experimental tests under static tensile loading. In the present case the failure value in terms of total strain turns out to be \( \varepsilon_{f,\text{tot}} = 0.06 \) or 6\%.

In Fig. 6, the assumed load-displacement curve representing the mechanical behaviour of a friction brake is shown. It can be seen that the linear elastic section, defined again by a reduced Young’s modulus \( E = 150 \text{ GPa} \) is followed by a trilinear elastic-plastic range, formed by a positive slope, where the behaviour is still elastic, connecting two plateaux. The former models the energy-dissipating mechanism based on dynamic friction, activated by a sliding force \( F_s = 45 \text{ kN} \)—corresponding to a sliding stress \( \sigma_s = 425 \text{ MPa} \)—and leaving the device a free run of 1.00 m. The latter takes into account the residual dissipating resource based on true plasticity. It is activated by a yield force \( F_y = 160 \text{ kN} \) (corresponding to a yield stress \( \sigma_0 = 1500 \text{ MPa} \)) and is limited before reaching failure, to a 5\% plastic strain. (It should be emphasized that plastic strain is intended to be a net measure, obtained by disregarding friction sliding.) The elastic section that follows the dynamic friction sliding exhibits the same slope as the initial elastic one; it takes into account the residual elastic stiffness of the brake at the end of its free run.

Another issue to be addressed before performing any analysis is estimating the shape of the falling block, since it could be argued that, for the same weight and velocity of boulder, the overall response of the intercepting device might depend on it. Regarding this, the lack of well-established criteria led the authors to choose blocks having the shape of a sphere, completely defined, therefore, by the value of its diameter, \( D \).

The choice of a spherical shape has also been dictated by the need to characterize the impact in the simplest way, without the need to specify the orientation of the colliding boulder relative to the intercepting net. Another reason for choosing a sphere is the absence of any sharp edge: this allows the assessment of the overall response of the intercepting device without considering cut-induced local failures.

Moreover, it has been assumed that the boulders are perfectly rigid, that they never rebound before colliding against the intercepting device, and they neither split nor fragment. Their density \( \rho_b = 2600 \text{ kg/m}^3 \) corresponds to that of most common non-porous rocks.

On the other hand, attention is limited, here and in the following discussion, to structures entirely made of steel, such that a value of density \( \rho_s = 7800 \text{ kg/m}^3 \) can be assumed for them; similarly, when acceleration due to gravity needs to be accounted for, a standard value \( g = 9.81 \text{ m/s}^2 \) has been used.

Finally, whenever contact occurs between the boulder and the steel net or structure, a dynamic friction coefficient \( f_d = 0.8 \), has been assumed, which defines the dissipative contact model.

### 4. Single panel simulation: analysis and discussion

In order to gather preliminary information on the behaviour of interceptive devices during rockfalls, the collision of a boulder against a single net panel was considered. It is assumed that the panel lies initially flat and that the rock-block hits it perpendicularly.

A standard square net panel, having a side length equal to 5.00 m, has been used for all analyses. It is made of intersecting cables forming a square grid of 20 x 20 equal cells, each of them having a mesh size of 0.25 x 0.25 m². Each intersection is fastened by means of studs.

The diameter of the cables forming the net is 8 mm and their effective cross-sectional area is assumed to be \( A_{\text{eff}} = 27.5 \text{ mm}^2 \); the perimeter of the panel consists of a
reinforcing cable with a diameter of 16 mm and an effective cross-sectional area \( A_{\text{eff}} = 106.5 \text{ mm}^2 \).

The panel was not fixed along its edges, as this would provide a restraint condition that is never fulfilled in typical in situ installations (see [7, pp. 101–107]); it was, instead, suspended at its vertices by means of four friction brakes aligned with its main diagonals.

In the finite element mesh, each portion of cable lying between two consecutive intersections was modelled as a three-dimensional two-noded truss element; the constitutive law adopted was that which is shown in Fig. 5, and the appropriate effective cross-section area was selected for net and perimeter cables. Three-dimensional two-noded truss elements were also used to model the four energy-dissipating devices, each of them having a length of 1 m. The load-displacement constitutive law which was adopted for the friction brakes (energy-dissipating devices) is illustrated in Fig. 6.

Each intersection was simply considered as a spherical hinge: that would provide zero stiffness to the reference, flat, configuration of the panel. This can result in problems should a static analysis be performed; in the dynamic range, however, no problems were experienced.

The colliding boulder was modelled as an assembly of flat triangular rigid elements approximating the smooth shape of a sphere. By appropriate scaling of the nodal co-ordinates of one block, all the other blocks (for all the range of diameters under investigation) could easily be generated.

Finally, only the last part of the boulder's path (that immediately preceding the collision) was considered and the initial condition consisted only of the linear velocity of the boulder centroid.

It could be said that, in the case of a tennis ball or a bullet, disregarding angular velocity is likely to lead to errors. However, the induced gyroscopic effects are negligible when angular velocities have an order of magnitude of a few rad/s, which are reasonable for a typical falling-rock event. Some preliminary simulations, not shown here for lack of space, confirmed that the net panel response was practically insensitive to small initial values of the angular velocity.

A complete view of the finite element model adopted for simulating the collision of a boulder against a net panel is shown in Fig. 7.

In the first series of simulations, the effects of a perfectly vertical collision, occurring in the centre of the panel were investigated for boulders with a diameter \( D \) ranging from 0.30 to 1.00 m. In this case (see Fig. 8, case 1), the acceleration due to gravity \( g \) is co-axial with the velocity \( v \) of the impacting block.

In the second series of analyses, the effects corresponding to a horizontal collision occurring again in the centre of the net panel were investigated for the same range of block diameters. This time (see Fig. 8, case 2) the acceleration due to gravity \( g \) acts at right angles to the velocity \( v \) of the impacting block.

The results of these simulations are summarized in Fig. 8 (where they are also compared with those of simulations done by disregarding completely the effects of acceleration due to gravity). In both cases, for each diameter several analyses have been performed, in order to assess the limit velocity \( v_{\text{lim}} \) and the limit kinetic energy \( T_{\text{lin}} \) of the colliding boulder as a function of the diameter.
In other words, such values denote the minimum velocity and kinetic energy that a given colliding boulder should have in order to break at least one of the elements of the barrier. Simulations were performed at 1 m/s intervals and, as a consequence, limit velocities are rounded up to the nearest 1 m/s. So, if under some collision conditions a value \( v_{\text{lim}} = 40 \) m/s is obtained, the true limit velocity lies within the range \( 39 \) m/s < \( v_{\text{lim}} < 40 \) m/s; limit kinetic energy values are approximated accordingly.

It should be noted that, with this procedure, the stated limit velocity turns out to be an upper bound of the exact value, and this value is therefore bracketed within a range of velocities which is exactly 1 m/s wide. The amplitude of this bracketing range has been selected by the authors since, according to their judgement, it appeared feasible within the context of their stated purpose of presenting meaningful results with a limited computational effort. Higher accuracy can, however, be achieved by extending ad libitum the number of simulations, in order to narrow the bracketing range.

The choice of performing simulations at 1 m/s intervals, irrespective of the velocity value is extremely easy to implement, but presents a drawback, which the
authors are aware of, because the resulting approximation happens to be non-uniform, and the relative errors increase as the block velocity decreases.

Indeed, let \( v_0 \) be the exact limit velocity and \( v_{\text{lim}} \) the estimated limit velocity, which satisfies the relation \( v_{\text{lim}} - v_o < 1 \) m/s, and is therefore an upper bound for \( v_0 \). Then the relative error in terms of limit velocity is at most (when it is precisely \( v_0 = v_{\text{lim}} - 1 \)):

\[
\frac{v_{\text{lim}} - v_0}{v_0} \leq \frac{(v_0 + 1)}{v_0} - 1 = \frac{1}{v_0}
\]

provided that both \( v_0 \) and \( v_{\text{lim}} \) are expressed in m/s. Similarly for kinetic energy, if \( T_0 \) is the exact limit value, and \( T_{\text{lim}} \) the estimated limit value, the relative error cannot exceed the value

\[
\frac{T_{\text{lim}} - T_0}{T_0} = \frac{\frac{1}{2} \rho (\pi D^3/6) v_{\text{lim}}^2 - \frac{1}{2} \rho (\pi D^3/6) v_0^2}{T_0} = \frac{v_{\text{lim}}^2 - v_0^2}{v_0^2} \leq \frac{(v_0 + 1)^2 - v_0^2}{v_0^2} = \frac{2v_0 + 1}{v_0^2},
\]

where \( \rho \) is the density and \( D \) the block diameter. Eq. (10) may be recast in the following form:

\[
\frac{T_{\text{lim}} - T_0}{T_0} \leq \frac{2}{v_0} + \frac{1}{v_0^2},
\]

where the latter term in the right-hand side may be negligible in comparison with the former.

By comparing Eqs. (9) and (11) it turns out that the relative error of limit kinetic energy is approximately twice as much as that of limit velocity.

Since limit velocity happens to decrease as the block diameter increases, it is also true that the relative errors increase, as blocks become larger. With reference to Fig. 8, for instance, the maximum relative error in estimating the limit velocity ranges from 0.9% (see case 2 with \( D = 0.30 \) m) up to 6.7% (as in case 1, with \( D = 1.00 \) m). As it is expected, the error in computing the limit kinetic energy of the block is larger, but in accordance with Eq. (11) it is just the double of the error in estimating the limit velocity. With the data of Fig. 8, the maximum relative error in terms of limit kinetic energy cannot exceed, in the worst case, 13.7% (as in case 1, \( D = 1.00 \) m). Errors of such magnitude can still be acceptable from an engineering point of view.

Keeping in mind this issue, some useful considerations can nevertheless be outlined. Kinetic energy is already generally used as a typical performance index in technical applications of rockfall interceptive devices. Here for comparison purposes velocity values are used, since the primary variable in a numerical simulation is the block collision velocity, i.e. the block initial velocity, and not the colliding block’s kinetic energy.

In Fig. 8, points denote the upper bound of the relevant limit velocity—or kinetic energy—and error bars denote the corresponding lower bound. It should be emphasized that the limit velocity is, as expected, a non-linear function of the boulder diameter (with a slight difference between vertical and horizontal collisions). Instead, as it is apparent, the limit kinetic energy is not constant, but is a function itself of the block diameter.

This is true in all cases, even if the deviation from a constant value is more pronounced in the case of a vertical collision. This first series of simulations shows, therefore, as will be confirmed later, that the limit kinetic energy is not a rigorous performance index for an intercepting device, but needs to be supplemented by additional information about the block size.

Next, with the same panel dimensions and restraint conditions the effect of the collision location on the behaviour of the restraining net panel was investigated. Only perfectly vertical collisions were considered, as in case 1 above, with acceleration due to gravity, \( g \), acting in the same direction as the impacting block velocity \( v \). By taking advantage of the four axes of symmetry, collision points were restricted to a triangular region having an area equal to one-eighth of the whole panel (see Fig. 9). In particular, in addition to the central point, it was assumed that the colliding block could hit the panel at nine other points, denoted by letters A–H in Fig. 9, where they are shown with black dots. For each collision point four boulders, having diameter \( D \), respectively, equal to 0.25, 0.50, 0.75 and 1.00 m, hit the net panel. After assessing the limit velocity \( v_{\text{lim}} \) in all the resulting cases, by virtue of the aforementioned symmetry criteria, the simulation results were extended to a grid of

Fig. 9. Location of collision points used to investigate the effect of impact point on the net panel behaviour; symmetry axes are shown in dashed lines.
49 (7 x 7) internal points. They are denoted by empty
dots and their precise locations are shown in Fig. 9.

By using interpolation algorithms (Kriging) it has
been possible, for each block diameter, to draw
isosaches, contour maps delimiting zones that share the
same velocity of failure, i.e. regions where a boulder
collision generates the same limit velocity \( v_{\text{lim}} \). No
collision points have been located on the perimeter
cable, to prevent blocks from rolling out of the panel;
the relevant maps cover only the region delimited by the
aforementioned grid.

The resulting contour maps are shown in Fig. 10 (for
\( D = 0.25 \text{ m} \)), Fig. 11 (for \( D = 0.50 \text{ m} \)), Fig. 12 (for
\( D = 0.75 \text{ m} \)) and Fig. 13 (for \( D = 1.00 \text{ m} \)). It is apparent
from these that the point of collision might significantly
influence the response of the intercepting device. For
mid-sized boulders \( D = 0.75 \text{ m} \) for instance, the limit
velocity might change by a factor of 1.55—from 17 m/s
(point C) to 26 m/s (point O)—according to the point
where they collide against the net panel. If the same
comparison is made for boulders of other sizes, the ratio
between the maximum and minimum velocities ranges
from 1.16 \( (D = 0.25 \text{ m}) \) to 1.61 \( (D = 0.50 \text{ m}) \) in the case
of smaller sizes, while it reduces to 1.33 for the largest
boulders considered \( (D = 1.00 \text{ m}) \). These ratios, how-
ever, should be considered carefully since maximum and
minimum velocity values are attained in different
positions.

The influence of collision positions for different
boulder sizes is compared in terms of kinetic energy in
Figs. 14–17, where results are expressed by means of a
contour map of iso-limit kinetic energy, normalized to
the maximum value. This maximum value
\( T_{\text{max}} = 239 \text{ kJ} \) corresponds to that of a boulder having
a diameter \( D = 0.50 \text{ m} \) hitting the centre of the panel.

These results show that both the point of collision and
the block size influence significantly the resistance of the
panel. For the smallest block size considered, the
amount of kinetic energy that can be safely dissipated
by the panel ranges from 37\% to 51\% of the reference
value \( T_{\text{max}} \). In the case of a block having a diameter
\( D = 0.50 \text{ m} \) the maximum kinetic energy can be safely
dissipated if collision occurs in the centre of the panel,
but if the collision point is located close to one vertex,
only 39\% of that value can be dissipated. Similar
conclusions hold true for the other two cases considered;
in the former \( (D = 0.75 \text{ m}) \) the amount of limit kinetic
energy varies between 35\% and 80\% of \( T_{\text{max}} \), depending
on the point of impact; in the latter \( (D = 1.00 \text{ m}) \) the
range lies between 41\% and 82\%.

These Figures should make apparent that the use of
limit kinetic energy alone is not adequate to quantify in
a global way the performance of a single net panel.

5. Whole barrier simulation: analysis and discussion

After investigating the dynamic behaviour of a single
net panel during rock-fall events in several different
conditions, the corresponding analysis of the response of
a whole barrier has been performed. For comparison
purposes, attention was focused on a commercially

![Isotaches contour plots of limit speed \( v_{\text{lim}} \), expressed in m/s for a boulder with diameter \( D = 0.25 \text{ m} \) colliding perpendicularly with the net panel.](image-url)
available barrier type, already used by Peila et al. [1] in their full-scale tests, and denoted by code TSB6.

This rockfall-restraining barrier is synthetically illustrated in Fig. 18: it consists of three steel-made, rectangular intercepting net panels, each of them 10 m long and 3 m wide. They are kept in vertical position by steel posts and by a system of steel cables, namely longitudinal (upper and lower) ropes, upstream cables and lateral additional ropes. Upstream cables and longitudinal and lateral additional ropes are
Fig. 13. Isotaches (contour plots of limit speed $v_{lim}$, expressed in m/s) for a boulder with diameter $D = 1.00$ m colliding perpendicularly with the net panel.

Fig. 14. Contour plots of limit kinetic energy $T_{lim}$ relative to $T_{max} = 239$ kJ for a boulder with diameter $D = 0.25$ m colliding perpendicularly with the net panel.

firmly anchored to the ground with tendons, and equipped with energy-dissipating devices. Posts are hinged to bolted steel plate foundations: the base constraint acts as a cylindrical hinge allowing the post to rotate only in a vertical plane in the downstream direction.

More specifically, the panels are made by two orders of mutually intersecting cables (with a diameter of 8 mm
Fig. 15. Contour plots of limit kinetic energy $T_{\text{lim}}$ relative to $T_{\text{max}} = 239 \text{ kJ}$ for a boulder with diameter $D = 0.50 \text{ m}$ colliding perpendicularly with the net panel.

Fig. 16. Contour plots of limit kinetic energy $T_{\text{lim}}$ relative to $T_{\text{max}} = 239 \text{ kJ}$ for a boulder with diameter $D = 0.75 \text{ m}$ colliding perpendicularly with the net panel.

and an effective cross-sectional area of $A_{\text{eff}} = 27.5 \text{ mm}^2$ forming a square grid of equal cells, each of them having a mesh size of $0.20 \text{ m} \times 0.20 \text{ m}$. Mesh sides are not aligned with horizontal and vertical lines, but are inclined at an angle of $\approx 45^\circ$ with a horizontal line; each intersection is fastened by means of
Fig. 17. Contour plots of limit kinetic energy $T_{\text{lim}}$ relative to $T_{\text{max}} = 239 \text{kJ}$ for a boulder with diameter $D = 1.00\text{m}$ colliding perpendicularly with the net panel.

Fig. 18. Technical sketch of the rockfall-restraining barrier type used in numerical simulations.

studs. Longitudinal and additional lateral ropes and upstream cables have a diameter equal to 16 mm and an effective cross-sectional area $A_{\text{eff}} = 106.5 \text{mm}^2$; the same geometric properties are also shared by the energy-dissipating devices. Posts are 3.00 m high and are built with standard HEA160 beams, in Fe360 steel grade.

From the finite element point of view, all portions of the structure made of cables have been modelled with three-dimensional two-noded truss elements, having the appropriate effective cross-sectional area and obeying the constitutive law sketched in Fig. 5 or in Fig. 6 (energy-dissipating devices only).

Intersections between two or more cables have been represented by spherical hinges.

Long cables, like upstream cables, lateral additional ropes and the portions of longitudinal ropes extending from their anchorage points to the posts have been subdivided in several three-dimensional two-noded truss elements, each of them being 1 m long. Energy-dissipating devices have also been modelled with 1 m long truss elements.
Each post has been modelled with 10 three-dimensional two-noded Timoshenko beam elements; the assumed elastic–perfectly plastic constitutive law is sketched in Fig. 19. Values of Young’s modulus and of yield stress have been chosen that are appropriate for grade Fe360 steel: \( E = 210 \text{ GPa}, \sigma_0 = 235 \text{ MPa} \) moreover total strain was limited by a failure value \( \varepsilon_f = 0.20 \), i.e. 20%.

With reference to the colliding boulders, the same modelling hypotheses previously presented have been adopted again.

Initially, the net panel lies flat in a vertical plane. The trajectory of the colliding rock block belongs to a vertical plane perpendicular to the panel, and forms an angle \( \alpha = 50^\circ \) with the vertical direction. This can be seen in Fig. 20, where a cross-section of the barrier is shown.

As in the case of a single net panel the angular velocity of the colliding boulder has been disregarded, and only the linear velocity of its centroid is specified as an initial condition.

Moreover, also the presence of acceleration due to gravity has been disregarded, since the duration of the phenomenon is very short (a few tenths of a second) and collision-induced accelerations are substantially higher than \( g \) (at least by one order of magnitude). Some preliminary simulations (not presented here for lack of space), showing that the effects of gravity on the overall response range from very little to none, have confirmed this hypothesis.

On the other hand, it should be noted that other simplifying assumptions might introduce greater approximation errors. Among these assumptions, whose adoption is mostly justified by the need to keep computations to a minimum, one should remember that some details of the rockfall-restraining barrier have been modelled only roughly.

For instance, the sliding connection between the upper longitudinal rope and the post top has been modelled as if it were tied by a small truss allowing only small relative motions. Similarly, no attempts have been made to take into account the interaction between the falling boulder, the interceptive net panel and the ground which, in real conditions, limits—by intercepting it—the free run of the block (once caught in the net) and provides, by virtue of a friction mechanism, a dissipating resource which has been disregarded.

Finally, foundations have been considered as being perfectly rigid; this means that dissipation due to both structural damping and plastic strain has not been taken into account.

It seems, however, that these assumptions, by disregarding some dissipating mechanisms, may produce test conditions more severe than the real ones and, therefore, the corresponding results should lie on the safe side.

The complete finite element model described above has been used initially to check the ability of the numerical simulation to reproduce the results of a full-scale test performed, as already mentioned, by Peila et al. (see [1], test TSB6).

The experimental and numerical results are reported in Table 1; for comparison purposes the values of boulder mass, \( M \) (corresponding to a diameter \( D = 1.35 \text{ m} \)), limit velocity, \( v_{\text{lim}} \), limit kinetic energy, \( T_{\text{lim}} \), maximum panel deflection, \( f_{\text{max}} \), and stopping time, \( t_{\text{stop}} \), are given. The last frame of the simulation analysis is also shown in Fig. 21. The collision point is assumed to be the centre of the central panel.

<table>
<thead>
<tr>
<th>Test</th>
<th>( M ) (kg)</th>
<th>( v_{\text{lim}} ) (m/s)</th>
<th>( T_{\text{lim}} ) (kJ)</th>
<th>( f_{\text{max}} ) (m)</th>
<th>( t_{\text{stop}} ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSB6—Expt</td>
<td>3300</td>
<td>20</td>
<td>660</td>
<td>4.6</td>
<td>0.75</td>
</tr>
<tr>
<td>TSB6—Simul</td>
<td>3300</td>
<td>18</td>
<td>535</td>
<td>3.5</td>
<td>0.50</td>
</tr>
</tbody>
</table>

![Fig. 19](image1.png)

Fig. 19. Assumed stress–strain curve modelling the elastic–perfectly plastic behaviour of steel posts. A tensile failure strain equal to 20% has been adopted. The tension branch is shown only, since the compression branch is symmetric.

![Fig. 20](image2.png)

Fig. 20. Cross-section of the rockfall-restraining barrier showing a colliding boulder; hitting it at an angle \( \alpha \) with reference to the vertical direction.
As it can be seen, the experimental results are somehow underestimated (10% in terms of limit velocity) by the present simulation. This can be partially explained by the presence of several dissipating devices (studs, sliding friction between posts and ropes, damping produced by foundations and tendons, etc.) which have not been accurately accounted for in the finite element model—largely because of the difficulty of reliably taking them into account. Also the interaction of a net-trapped falling boulder and the ground (here disregarded) would increase the barrier performance.

Nevertheless, the results of the numerical simulation are in fairly good agreement with the experimental data.

The next step was to check the behaviour of the rockfall-restraining barrier when boulders having a different diameter $D$ collide with it at some variable velocity, always hitting, however, the centre of the central net panel. The results are grouped in Fig. 22, where for boulder diameters ranging from $D = 0.30$ to $1.30$ m it has been possible to define a limit velocity, $v_{lim}$ (and a corresponding limit kinetic energy, $T_{lim}$) and a critical velocity, $v_f$ (and a relevant critical kinetic energy, $T_f$). The former defines the velocity corresponding to a failure of at least one of the barrier’s components, even though its block intercepting ability is not impaired (i.e., the boulder is still trapped). The latter denotes instead the minimum velocity value of the block which eventually results in its breaking through, meaning that not only some components failed, but also that the intercepting capacity has vanished.

Again, simulations have been performed at 1 m/s intervals; this means that both velocity values are upper bounds, with an error not $>1$ m/s from the exact value; the corresponding kinetic energy values are computed accordingly. Exactly like in Fig. 8, points denote the upper bound of the relevant variable, while error bars denote the corresponding lower bound.

It is instructive to note that only for blocks having a relatively large diameter are there these two limits different, in the sense that they delimit a range of progressive failure. Instead, when facing small-sized boulders, a bullet effect takes place, producing a concentrated panel failure severe enough to impair any restraining action.

It should be emphasized that, in terms of kinetic energy and leaving unchanged all other conditions, the type of catch fence under investigation is better suited to intercepting relatively large blocks than smaller ones: in particular, it can be seen that the critical kinetic energy, $T_f$, changes by one order of magnitude simply by switching the boulder size.

Indeed, as shown in Fig. 22, a barrier that experimentally is designed to withstand the impact of boulders having a kinetic energy of 600 kJ (see [1], model TSB6) and which, in the simulation presented, can safely dissipate almost 600 kJ when stopping a boulder with a diameter of 1.30 m might not succeed in stopping a...
boulder having a diameter of 0.30 m and a kinetic energy < 60 kJ, i.e. ten times lower than in the previous case.

These results confirm that the kinetic energy (i.e., a scalar parameter resulting from a combination of mass and velocity, but carrying no direct information about boulder geometry) is not suited to completely characterize the impact resistance of a restraining barrier and that current practice relying on this assumption might result in undesirable failures, should a boulder of a different size, smaller than the tested one (but with the same kinetic energy) hit it. As a consequence of these simulations, it appears that improved resistance qualifying indices, including explicit block-geometry parameters, should be introduced in design and checking procedures, when dealing with rockfall-restraining barriers. This should be achieved, for instance, by specifying at least the diameter of the rock block along with the position where collision takes place. However, it would be more useful to provide some charts, like those presented in Figs. 9–13 or in Figs. 14–17 to better characterize the barrier's response.

It should be noted, however, that the behaviour of the whole barrier is significantly different from that of a single panel, if one looks, for instance, to the performances in terms of limit velocity and limit kinetic energy, by comparing Figs. 8 and 22. For the whole barrier, for example, the decay of limit velocity as the diameter increases is lower, and the kinetic energy vs. diameter diagram is reversed, since limit kinetic energy increases as \( D \) increases.

These discrepancies can be explained by several factors, which, probably, mutually interfere. Among these, one has to consider, at least, that:

1. the collision is not perpendicular in this case, and therefore friction contribution is more significant;
2. the geometry of the net panel (now rectangular, with 10:3 side ratio) and the grids (now inclined at \( \pm 45^\circ \)) involve a different load transfer mechanism during the impact;
3. the whole barrier exhibits a higher degree of static redundancy, which is beneficial to resistance, esp-

Finally, the effect of the location of the collision point on the barrier's overall response has been investigated for three kinds of rock blocks which are representative of small \( (D = 0.30\,\text{m}) \), medium \( (D = 0.75\,\text{m}) \) and large size \( (D = 1.30\,\text{m}) \) falling boulders.

The location of the colliding points are shown in Fig. 23. Collision occurs always with an angle of incidence equal to 50° (with reference to the vertical).

Points are labelled with letters from A to I.

It should be noted that only collisions where the central panel is hit have been taken into consideration, and, by virtue of the vertical axis of symmetry, only those occurring on the right-hand side need to be investigated. While points H and I are placed on the post, it should be noticed that no collision points are located at a distance less than 0.75 m above post foundation, since in such conditions the boulder would hit the ground before wholly engaging the barrier's resistance and deforming resources.

The relevant results, in terms of critical velocity, \( v_r \), and critical kinetic energy, \( T_r \), vs. block-diameter, \( D \), are reported in Table 2.

It should be noted that the results are rather scattered, as shown by the statistical measures listed in Table 2. This indicates that the barrier's resistance to boulder collision, far from being uniform, strongly depends on the impact locations. In practice for smaller blocks, the ratio between critical velocity in the most favourable (point A) and the most unfavourable (point E) conditions might be as high as 2.5; for medium sized boulders the same ratio becomes about 1.5, but for large blocks it rises to about 2.0 again. This consideration would suggest that the resistance of a catch fence cannot be assessed in absolute terms, but explicit mention of the point of collision has to be made.

To gain a better understanding of the barrier's behaviour, based on the results of Table 2 and by making use of the same interpolation techniques (Kriging) already mentioned when studying a single

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Fig. 23. Sketch of the barrier's central panel showing the existing symmetry axis and the location of collision points used to assess the effect of impact point on the global response.
Table 2
Influence of collision point on the global response of the rockfall-restraining barrier for ten different positions of impact point and boulder of three different sizes

<table>
<thead>
<tr>
<th>Position</th>
<th>$v_f$ (m/s)</th>
<th>$T_f$ (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position O</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>Position A</td>
<td>105</td>
<td>203</td>
</tr>
<tr>
<td>Position B</td>
<td>50</td>
<td>46</td>
</tr>
<tr>
<td>Position C</td>
<td>46</td>
<td>39</td>
</tr>
<tr>
<td>Position D</td>
<td>73</td>
<td>98</td>
</tr>
<tr>
<td>Position E</td>
<td>42</td>
<td>32</td>
</tr>
<tr>
<td>Position F</td>
<td>44</td>
<td>36</td>
</tr>
<tr>
<td>Position G</td>
<td>46</td>
<td>39</td>
</tr>
<tr>
<td>Position H</td>
<td>88</td>
<td>142</td>
</tr>
<tr>
<td>Position I</td>
<td>62</td>
<td>71</td>
</tr>
</tbody>
</table>

Average: 61.00 75.88 31.10 282.08 16.30 418.88
Standard deviation: 21.29 56.41 4.09 74.95 4.00 211.58
Variation coeff. %: 34.90 74.33 13.17 26.57 24.55 50.51

Fig. 24. Isotaches (contour plots of critical velocity of failure $v_f$, in m/s) for a boulder with diameter $D = 0.30$ m colliding with the restraining barrier; the central panel is shown only.

net panel, contour plots in the form of isotaches can be deduced, mapping points sharing the same critical velocity, i.e. regions where boulder collision produces the same critical velocity of failure, $v_f$.

The maps for small, medium and large-size boulders are plotted in Figs. 24–26, respectively. Only the central panel is shown, since collision points are restricted to that zone.

It is possible to see that while for small-size boulders (Fig. 24) the part of the barrier exhibiting the best performance is located largely in the upper strip, with some preference, in particular, for the central part and the regions near the posts. As size increases (Fig. 25 and 26) the best resistance properties are attained in the panel mid-span, near to the upper longitudinal rope, and in two narrow vertical strips close to the posts. As a matter of fact, contrary to the common belief that collision against one of the posts is a disastrous event (as it is indeed, in the sense of maintenance/repair), it seems that, at least for the intercepting device under consideration, the energy-dissipating capacity is no worse for a direct impact against a post (points H and I) than for a collision against any other tested position (points A–G and O). An assessment of the barrier’s resistance based in Table 2 would lead to this conclusion.

6. Conclusions

The results presented here aim at assessing the beneficial role of numerical simulations in the process of designing and testing, for evaluation purposes, rockfall-restraining net barriers.
Until now, it seemed that the only way to check in a reproducible, scientifically sound fashion the response of a catch fence to rockfall collision was by making use of full-scale testing. However, experimental tests might only provide an a posteriori validation, requiring therefore a very expensive trial-and-error procedure, if used as a design tool.

The intrinsic imprecision of testing apparatus, and the extremely difficult task of exactly reproducing the same experimental conditions (in terms of mass, velocity, trajectory of the colliding boulder and of the impact point), would then require, in the framework of safe practice, to get statistically validated measures from the results of several tests performed under the “same” conditions. Clearly, such an approach would prohibitively increase design costs, since any minimal structural change would require a new testing program.

On the contrary, numerical simulations (like those proposed here) are easily reproducible, allow for any kind of parametric study and are therefore better suited for a typical design process. They rely, however, on some preliminary knowledge of the material parameters, require the adoption of simplifying assumptions to reduce the problem to a manageable size (in terms of the available computing equipment and the code ability to model complex real phenomena), need considerable operator training in non-linear mechanics, finite element modelling and, above all, require good engineering judgement. Moreover, full-scale testing, cannot be completely left aside, since some experimental validation of numerical simulations (under carefully specified conditions) will be always necessary to validate the adopted models.

Nevertheless, dynamic finite element analyses can shed new light on the response of rockfall-restraining barriers, not yet adequately examined by other approaches.

For instance, to the best of the authors’ knowledge, no experimental tests have been purposely performed by changing the boulder diameter or the impact point. As a
consequence, commercially available catch fences are still
defined solely in terms of the amount of kinetic
energy of the colliding boulder that they are "designed"
to trap, regardless of its size, collision point, etc. But
this, as it has been shown earlier might produce results
which are not within acceptably safe margins.
An integration of full-scale tests and of numerical
simulations could then provide both a better knowledge
of falling-rock phenomena (and the way of intercepting
them) and more reliable design criteria, based on
rational approaches.
The combined use of these techniques could even
supersede current design practices, which rely heavily on
simplifying assumptions and might, therefore, be mostly
inadequate.
For instance, the use of static equivalent loads
(perhaps in conjunction with some symmetry related
stress redistribution hypothesis) is surely questionable in
such a genuinely dynamic field. On the other hand,
energy criteria have a more sound scientific basis, but
lack nonetheless much of their power, if dissipation
effects are only roughly estimated.
The use of preliminary numerical simulations would
also be beneficial for designing experimental tests which
might better allow the assessment of the overall
performances of a rockfall-restraining barrier in
terms of resistance, with reference to general collision
conditions.

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