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# ROCKFALL PROTECTION 2014: ANALYSIS OF THE BEHAVIOR OF SOFT ROCKFALL BARRIERS

Leyla Ghoussoub<sup>1</sup>, Cyril Douthe<sup>2</sup>, Karam Sab<sup>3</sup>

Soft rockfall barriers are complex structures that generally consist of a metallic net supported by steel posts and cables with brake elements. Several experimental and numerical studies have been carried out to evaluate their behaviour and a technical agreement in EU was recently established to certify these barriers based on experimental tests. Actually, manufacturers develop rockfall kits with their own technical specificities. The objective of the present paper is to determine the intrinsic properties of most common nets technologies and to investigate their influence on the overall mechanical behaviour of the structure. To this end, a comprehensive comparison between the local behaviours of the different nets is first presented using equivalent homogeneous membranes. Results derived for square nets under static concentrated loading illustrate the influence of the manufacturing technology on the deflection and stresses distribution. Then, a numerical and analytical model for the so-called 'curtain effect' is developed and validated. In the conclusion, it is focused on the capacity of the proposed methodology to study and evaluate the response of the whole barrier.

**Keywords:** Rockfall barriers, Homogenization, Geometrical non-linearities, Sliding cable.

## INTRODUCTION

Soft rockfall barriers are complex structures that generally consist of a metallic net supported by steel posts and cables with brake elements. A lot of experimental and numerical studies have been carried out to evaluate their capacity and they have led to the recent issue of a technical agreement in EU [3] to certify these barriers based on experimental tests.

Over the last years, most rockfall barriers were designed using an experimental approach based on full-scale tests with varying test sites geometries and procedures [8]. However the cost of these experiments oriented the research toward numerical simulations which allow more easily for parametric studies. Generally the models concentrate on a specific kit architecture or net technology in collaboration with a manufacturer who produced abundant experimental data at the mesh/net scale to calibrate the models [5-9]. Two main trends can be distinguished in the numerical models: the Finite Element Method [2] and the Discrete Element Method [5], [6] and [8]. In [2], Cazzani studies the behaviour of a structure with a square cable net and determined the limit velocity of the boulder and the limit kinetic energy of the net with different boulder's sizes. Nicot [6] worked on anti-sub-marine net with six contact points and developed a constitutive model in finite strains to describe the interaction between pairs of particles located at the center of each ring. The sliding of the net along the edge cable, often called 'curtain effect' was not taken into account until the work of Volkwein [5,10]. In his model, beside sliding cable, he also integrated interactions between three and four particles to account for non-fixed contact points between rings and for the interaction between the deformations in the two directions of the net plane. Recently, Trad *et al* [8] work-

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ing on a new rockfall fence with an omega net proved the validity of discrete element method by comparisons with extensive experimental results.

Hence most of the previous researches focused on a specific type of nets. The economical reasons of these model specificities are obvious but did not lead to a kind of general understanding of the mechanical behaviour of a rockfall barrier which could be used by a building owner or a project manager. The objective of this paper is thus to present various tools which could be used to conduct a wide investigation of the dynamical behaviour of these structures. The intrinsic mechanical properties of the most common types of nets will be first determined using homogenization techniques. Their behaviour (the way they deform and redistribute stresses) will be then compared on a simple example under static concentrated loading. Then, a sliding cable model which thus allow taking into account the 'curtain effect', will be shown. Finally a short conclusion will present the potential of the proposed methodology for the investigation the response of the overall barrier and its optimisation.

### THE HOMOGENIZATION OF THE NETS

A homogenization method for periodic discrete medium is used to determine the intrinsic mechanical properties of the most common nets, which mean to determine the mechanical behaviour of an equivalent homogeneous membrane. The method used here was first developed by Florence *et al* [4]. Each net is seen as a discrete periodic media, as an assembly of different types of interacting particles with three translational degrees of freedom each. Defining a unit cell and applying to it a set periodic loadings (either a macroscopic strain or macroscopic stress field), a stiffness matrix characterising the intrinsic behaviour of the net is derived.

Four nets have been investigated: regular cable nets, ASM4, ASM6 and Omega net. For regular cable nets, two orientations have been tested ( $0^\circ$  and  $45^\circ$ ) and for ASM4 and ASM6, two schemes have been included: the first one based on Nicot's approach with interaction by pairs and the second one based on Volkwein's approach including interactions of three and four particles. In all models, two phases were considered in the in-plane behaviour: the first one corresponding to the straightening of the cables and the bending stiffness, the second one to the elongation of the cables and the tension stiffness. A typical example of unit cell is shown in Figure 1.a). It represents an ASM4 ring net formed of 4 nodes at the contact points with two kinds of interactions: an interaction of two particles (in diagonal) with a stiffness  $K_1$  associated with the bending stiffness and an interaction between 4 particles (in square) with a stiffness  $K_2$  associated with the extension of a ring. The results of the homogenization are shown in Figure 1.b) where a typical tension test is represented with the two characteristic slopes and the corresponding stiffness matrix.

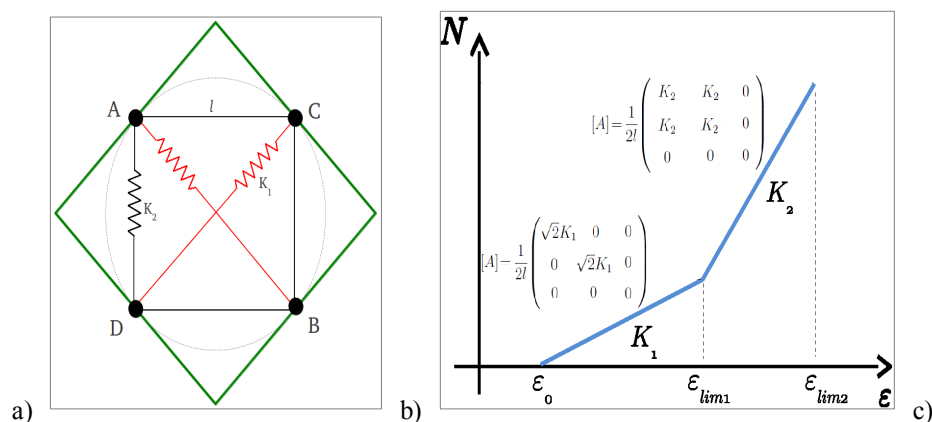


Fig. 1 a) ASM4 unit cell, b) the bilinear elastic behaviour of ASM4,

The intrinsic behaviours of the various nets or nets models proved to be very different. First of all, the macroscopic behaviour obtained from Nicot and Volkwein approach for ASM4 or

ASM6 are similar in the first stage but very different in the second phase. In Nicot's approach the behaviour in the second phase is identical to the first phase, only stiffer. In Volkwein's approach, in the second phase, the multiple particles interactions create a kind of plane-strain incompressible material (ie with a Poisson ratio close to 1). To our opinion, this last approach reflects better to the true behaviour of ASM as it incorporates the 'ring actions' or the interaction between solicitation in various directions of the plane.

The characteristics of the behaviour of the homogeneous membrane obtained for the various nets are shown in table 1. Square nets and ASM4 in the first phase can be seen as bi-directional material with no shear. ASM6 in the first phase is isotropic. ASM4 and ASM6 in the second phase are incompressible. Omega nets are orthotropic with a ratio close to 4 between the two principal stiffnesses. To illustrate the effect of these behaviours on the overall deformations of the nets, an example was studied by implementing these behaviour in finite element software which supports shell elements in large displacements and large strain. It consist in a square net (10m by 10m) with a constant thickness (1mm) and fixed boundary conditions in translation. The Young modulus of each equivalent membrane was chosen so that the membrane stiffness in the x direction is identical for all nets and its absolute value mimic the stiffness of common orthogonal cable net (see the corresponding values in table 1). The results of the maximal deflexion in the middle of the net are shown in Figure 2. Non-linear effects are clearly visible, as well as the difference of the response of the different types of nets. It must be noticed that in this first modelling, the material non-linearity have not been included, so that the two phases of the ASM4 and ASM6 behaviours are not taken into account. The implementation of material non-linearity is currently under progress.

Tab. 1 Results of homogenized membranes

Net	Behaviour	Test	Young Modulus (Pa)	Poisson's ratio
ASM6 (1 <sup>st</sup> stage)	Isotropic	A	$E=285 \cdot 10^6$	0.33
ASM4 (1 <sup>st</sup> stage)	No shear	B <sub>0</sub>	$E=320 \cdot 10^6$	0
Square Net	No shear (direction: 45°)	B <sub>45</sub>	$E=320 \cdot 10^6$	0
ASM6 and ASM4 (2 <sup>nd</sup> stage)	Incompressible	C	$E=60 \cdot 10^6$	0.99
Omega net	Transverse isotropic	D	$E_{11}=74 \cdot 10^6, E_{22}=295 \cdot 10^6$	$\nu_{12}=0.13, \nu_{21}=0.57$

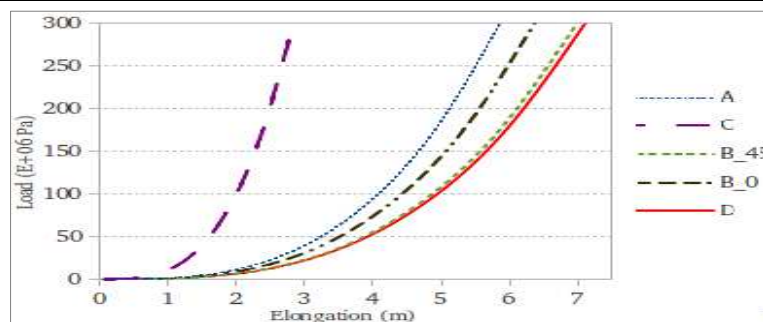


Figure 2: Comparison of the maximum deflection under concentrated load.

Concerning the distribution of stresses, the numerical results showed also significant disparities. High stresses are concentrated in the middle of the edges for all nets and diminish when going to extremities and the angles. Nevertheless, for a given load, the incompressible membrane presents the higher stresses and the omega net the lower. These differences at local scale will have significant effects on the way the various nets transmit forces to the structures and to lead to different optimization strategies.

## A SLIDING CABLE MODEL

The curtain effect shown in figure denotes the phenomenon of sliding of the net along a ridge cable to allow for large deformation of the net in the impacted area without loosing too much

height. Recent research [8-9] have shown that this phenomenon is essential to the modelling of the barrier. A model of sliding cable with  $n$  nodes has thus been developed. It is inspired by the work of Zhou *et al* [11] who had work on a sliding cable with 3. nodes. This model is based on the assumption that the strain is uniform in the cable and constant along all its sub-elements ( $n-1$  sub-elements for a  $n$  nodes cable). From this assumption, internal forces and stiffness matrix are derived using standard incremental virtual work theory.

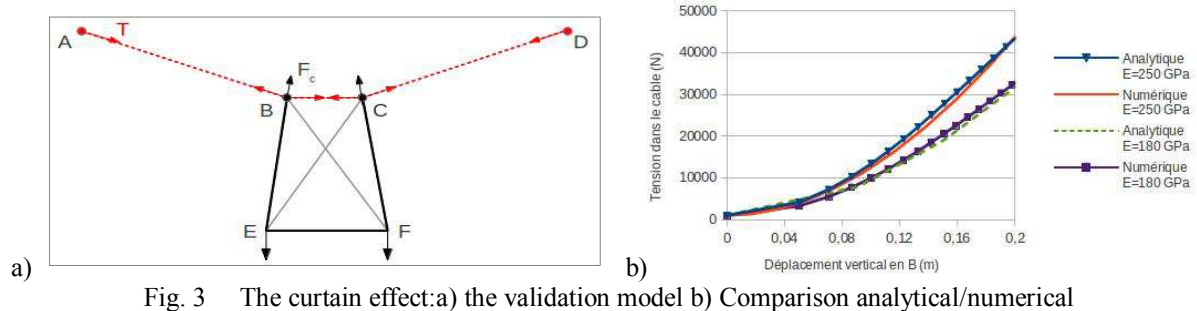


Fig. 3 The curtain effect: a) the validation model b) Comparison analytical/numerical

To validate the model, it is tested on a simple structure shown in figure (3a) for which an analytical solution involving large displacements exist. The structure is formed by a 4 nodes sliding cable, fixed at its extremities. A trolley composed of two rigid bars (BE, CF) and two flexible bars (BF, CE) is attached to the two central nodes. A vertical displacement is imposed on points E and F which induces the sliding of the nodes B and C toward the center. The comparison of the analytical solution and the numerical solution is shown on figure 3b (tension in the sliding cable). It can be seen that the agreement is very good.

## CONCLUSION

In this paper, novel approach have been proposed for the two main elements of a rockfall barrier: the net and the sliding cable. The development of homogenised membrane characteristics for the standard technologies of net has shown that their mechanical properties are very different, that their anisotropy is very different. Consequently the way they deform and the way they distribute stresses are very different. A sliding cable has also been tested following standard finite element formalism. It has shown very good agreement with analytical results and satisfying stability properties. It is currently under implementation on a whole barrier coupling sliding cable and homogenised membrane. The goal of the coming research being the better understanding of the mechanical behaviour of the structure and then the optimisation of this behaviour.

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