Experimental and Numerical Modeling of Highly Flexible Rockfall Protection Barriers

Modelo experimental y numérico de desprendimiento de rocas altamente flexible Barreras de protección

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Abstract

Ring-net barriers are used to protect highways and communities against rockfall. Since calculation methods are not available for these structures, empirical design procedures are applied to dimension the component parts. Within the present work, new experimental methods were developed to understand the complex, dynamical behavior of the systems. Full-scale tests were performed using single and three-span net configurations. Net deformations and cable forces were measured over the time. Furthermore, accelerometers were placed in an artificial concrete boulder in order to determine the nature of the breaking force acting on the falling rock. In parallel to the experimental research, the finite element program FARO was developed to model the large deformations of the ring-nets. It can be used to simulate the full-scale rock fall tests. For the first time, a complete mechanical description of these efficient, light-weight, multi-component systems was obtained.

Resumen

Las barreras de redes en anillo protegen autopistas y comunidades contra el desprendimiento de rocas. Desde el momento en que los sistemas de cálculo no son válidos para estas estructuras, son aplicados procedimientos basados en diseños empíricos para dimensionar los elementos componentes. Mediante el presente trabajo, se han desarrollado nuevos métodos experimentales para entender el complejo y dinámico comportamiento de estos sistemas. Fueron realizados tests a escala real utilizando configuraciones de 1 y de 3 redes tensadas. Se midieron las deformaciones de la red y los esfuerzos en los cables en función del tiempo. Además, se colocaron acelerómetros en un canto rodado artificial de hormigón con objetode determinar la naturaleza de la fuerza de rotura en acción en la roca desprendida. Paralelamente a la investigación experimental, fue desarrollado el programa de elementos finitos FARO para modelar el comportamiento de la enorme deformación de la red de anillos. FARO fue utilizado para simular a escala real los tests de desprendimiento de rocas. Por primera vez, fue obtenida una descripción mecánica completa de estos eficientes sistemas, de peso ligero y multicomponentes.

1 INTRODUCTION

1.1 Situation

Rockfalls are a serious danger to the inhabitants and to the infrastructure of mountain regions. In Switzerland annual investments on defense measures are of the order of US $ 6.7 million. This corresponds to four kilometers of rockfall protection systems per year.

Special highly flexible wire-net protection systems treated in the present paper consist of wire-ring nets supported by steel cables with inelastic brake elements and columns. They are installed like fences above transportation lines and residential areas to stop falling rocks with masses of up to ten tons and velocities of up to 60 mph (see Figure 1). This corresponds to a kinetic energy at the time of impact of 3’000 kJ.

Figure 1. A Wire-net rockfall protection system.

The energy absorbing capacity of the wire-net systems has been increased by a factor ten over the last ten years. In comparison with concrete sheds and barriers, the energy absorbing capacity of the flexible systems is 30 % higher and the investment costs are a factor ten smaller.

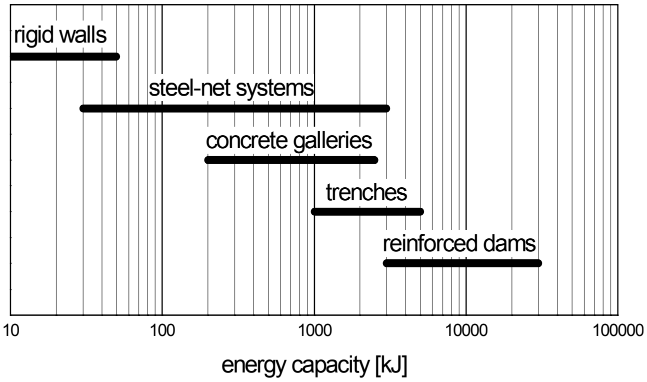


Figure 2. Range of application of different rockfall protection systems. From the design code, *Loadings on Rockfall Protection Sheds* (in German) (1998).

Figure 2 shows a comparison of the energy capacity of different rockfall protection measures. The large range of energy capacity proves how competitive wire-net systems are becoming in comparison to other systems.

1.2 Behavior of rockfall protection systems

The advantages of the wire-net systems are the high flexibility of the ring nets and the inelastic brake elements. The braking distance from the position of the first impact of the boulder to the position corresponding to the maximum deflection can measure between 3 m to 8 m. In contrast to rigid barriers the boulder is stopped smoothly over a relatively long distance which leads to a reduction of all peak-loads in all barrier components (Grassl et al., 2002).

Figure 3. Rockfall protection system after dynamic field test. Note the concentration of the ring net at the position of the maximum cable sag.

The flexibility of the steel nets is guaranteed by loosely connected wire rings with a diameter ∅ 300 mm made of high strength wire ∅ 3 mm turned from 5 up to 19 windings, which are held together by small clamps. The specialty of the rings is their property to stretch and to slide along each other during the braking process (see Figure 3).

1.3 Design of rockfall protection systems

Although kilometers of these barriers have been constructed worldwide, their design is still based on ad-hoc empiric procedures. Without the knowledge of the deformation behavior of the systems, loads acting on the system can only be specified in terms of impact energy rather than in applied forces (Gerber, 2001; Gerber and Böll, 2002).

Comprehensive testing programs have been realized to measure the energy capacity and, depending on the use of measuring devices, to obtain additional information, such as cable forces (Gerber et al., 2001). However, testing procedures cannot provide complete information about stresses and strains in the individual components as well as reactions at the support. Furthermore, full-scale field tests are time and cost intensive.

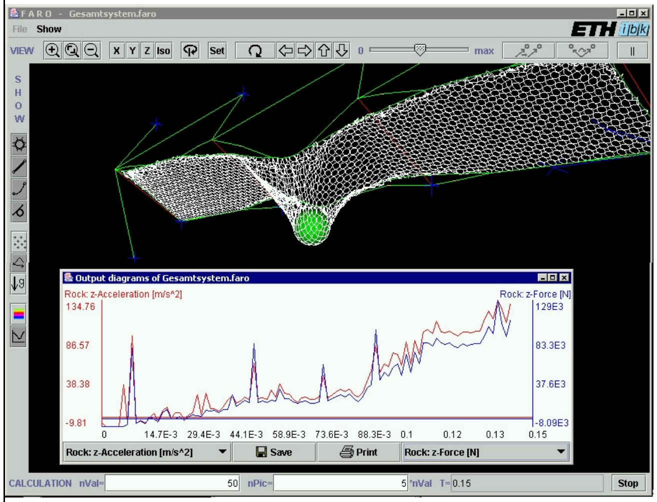
For this reason, advanced simulation models were developed. A research project with the goal to combine specialized field experiments and numerical modeling was started in the year 2000. The newly developed program FARO uses an explicit finite element method and combines special purpose ring and cable elements with non-linear materials, contact and sliding effects, large deformations as well as friction (Anderheggen et al., 2002).

To calibrate and to verify the numerical simulation a multistage testing program with new measuring methods was realized (Grassl et al., 2002). The finite element computer program contributes to reduce prototyping time and development costs. Furthermore, in the future, the program will enable engineers to rationally develop rockfall protection systems.

2 NUMERICAL METHODS

2.1 Development of the simulation software

The program code is divided into two parts, the numerical simulation and the graphical user interface (GUI). This concept allows a consequent separation of calculation and visualization during the development and strengthens the advantages of the single parts. FARO can be used in both modes with the graphical user interface and as a stand-alone application in command-line modus for efficient parameter studies. The interface between the components optimizes the performance of the whole application.



nVal= 50 nPic= 5*nVal T= 0.15

Figure 4. Graphical user interface during the simulation. Note the diagram window showing the deceleration curve of the falling rock.

The user interfaces as well as all three-dimensional visualization procedures are written in Java based on the OpenGL standard. For an improved performance the numerical part of the code is linked to the Java program as a dynamic, speed-optimized C/C++ library.

Contrary to the post-processing of conventional finite element codes visualization takes place in real-time with the calculation. This avoids the collection and saving of large amounts of unneeded data and also allows the interruption of a running simulation for a restart or for simulating a further rockfall event into the same, pre-loaded protection system.

The finite element model has been developed, tested and verified on a simplified two-dimensional model. After the successfully completion of the 2D-model the numerical procedures could be extended to the third dimension with a fully-equipped graphical user interface with real 3D-graphics (Figure 4).

2.2 Impact calculations

The impact of the spherical rock into the protection barrier is handled by means of constraining contact forces determined by the distance of the nodes to the rock surface (Figure 5). Only the nodes which are reachable by the falling rock are checked for contact at every single time-step. The contact force can be determined by applying the condition that the loss of the rocks energy equals the kinetic energy increase of the nodes involved in the contact. This implies elastic contact with no energy loss according to the relation

$$\Delta E_{Rock} = \sum_{Nodes} \Delta E_i \qquad (1)$$

Alternatively, the contact forces can be determined assuming plastic contact associated with energy loss by requiring that the velocity components of the node and of the spherical rock in radial direction are equal:

$$\vec{v}_{Node} \circ \vec{r} = \vec{v}_{Rock} \circ \vec{r} \qquad (2)$$

Both approaches result in a symmetric equation system for the unknown contact forces to be solved at each time-step by the Gauss algorithm. In some cases, its solution provides a "negative" contact force, which would push one node further into the rock. The corresponding unknown and the related equation are then deleted and the equations are solved again. This is repeated until all contact forces become "positive", which seldom requires more than a couple of iterations.

The algorithm mentioned above may result in very high but short-timed contact forces which cause a high deceleration of the rock for one time step. The result is an unwished peak in the related diagram curve. To avoid these peaks a very thin elastic layer was numerically simulated. It covers the whole rock and distributes above contact forces linearly over its thickness. Therefore, the resulting contact forces stay the same but are softened.

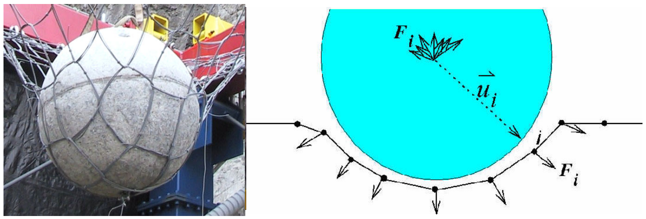


Figure 5. Contact computed with forces constraining the rock and the nodes.

2.3 Cable element

The cable elements have to guarantee long distance slides of the net along the cables or sliding of themselves over the supporting posts. Conventional cables with several incidence nodes made of single tension-only truss elements react like a continuous cable over the time but the sliding effects would require expensive constraining conditions. Therefore, the developed cable elements consist of single tension-only springs with several nodes in between and a constant normal force over the whole length. This allows the movement of middle nodes as well as boundary conditions on these nodes. The overall cable behavior is not disturbed and therefore sliding of the cable over its supports is possible. These effects are qualitatively demonstrated in Figure 6.

The friction caused by the sliding effects is determined from the relative node velocities and the forces moving the nodes perpendicular to the cables track. The resulting loss of energy is modeled by an energy equivalent brake down of the moving node.

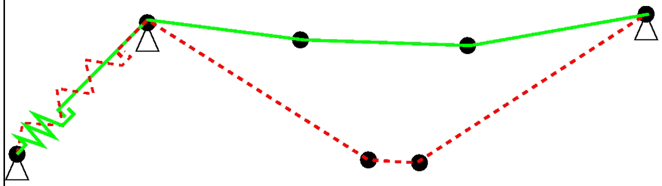


Figure 6. Modelisation of steel cable enabling arbitrary node movements.

2.4 Brake element

The brake elements have a characteristic behavior as shown in Figure 7. Modeling this behavior by finite element simulation would require a great computational effort. Furthermore the brake elements are only used as 1D elements in the systems. Therefore, the characteristic brake behavior is read from an extra file as a piecewise linear function.

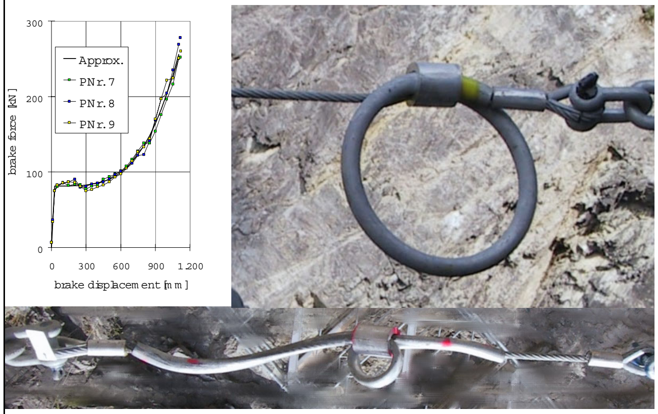


Figure 7. Unloaded and loaded brake element and the characteristic load-deflection-behavior.

2.5 Ring element

The finite ring element describes the mechanical behavior of the wire ring as a member of the wire-net (Grassl, 2002). The resistance due to traction and bending is modeled with eight bar and eight spring elements per ring (see Figure 8).

The bar elements are connected to one ring with eight nodes. The nodes describing an intersection point of two rings can move. Therefore, the ratio of the length of the neighboring bar elements is variable and the rings can slide at their intersection points. The bending behavior is concentrated on the eight nodes, which consist in joints and springs. The mass of the rings is concentrated at the nodes. The bending stiffness of the bar elements is infinite.

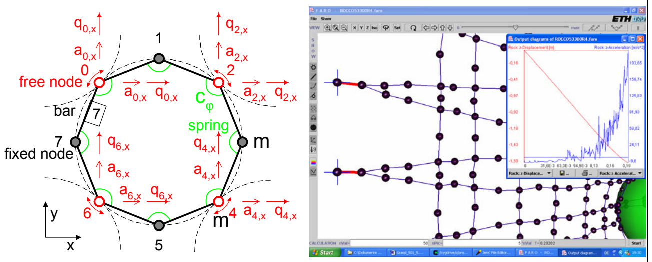


Figure 8. Kinematic parameters of the finite ring element. Deformation states.

3 EXPERIMENTAL METHODS

To verify the numerical model quasi-static laboratory and dynamic field experiments divided into four well defined stages were performed. The focus on the experimental program was to determine the mechanical behavior of the single components as well as the overall behavior of a complete protection system.

3.1 Quasi-static ring experiments

To determine the non-linear behavior and the energy capacity of the wire rings, quasi-static tensile tests were performed in the laboratory. Different configurations of single rings and groups of rings were investigated (see Figure 9).

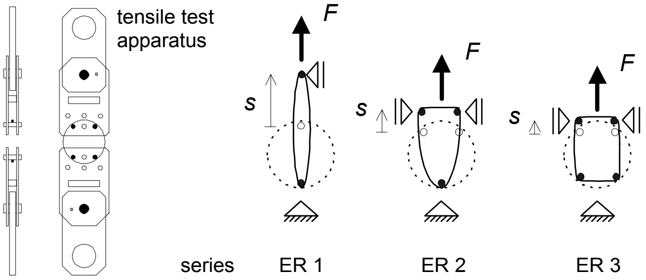


Figure 9. Quasi-static tensile test series with single rings supported with two, three or four bolts (ER 1, ER 2 and ER 3).

3.2 Rockfall experiments

The field tests were performed in the Swiss Federal Rockfall Test Site near Walenstadt/St. Gallen (see Figure 10). The site is used for type-testing, research purposes and product development. The boulders have a maximum mass of 16 tons and are released from a crane. They can be dropped a vertical distance of up to 60 m before the impact with the protection systems. To prevent ground contact during the deceleration phase the complete systems with three fields are installed in a vertical rock face 15 m above the ground. The free fall test guarantees the reproducibility of the velocity, the (vertical) trajectory and the location of the impact.

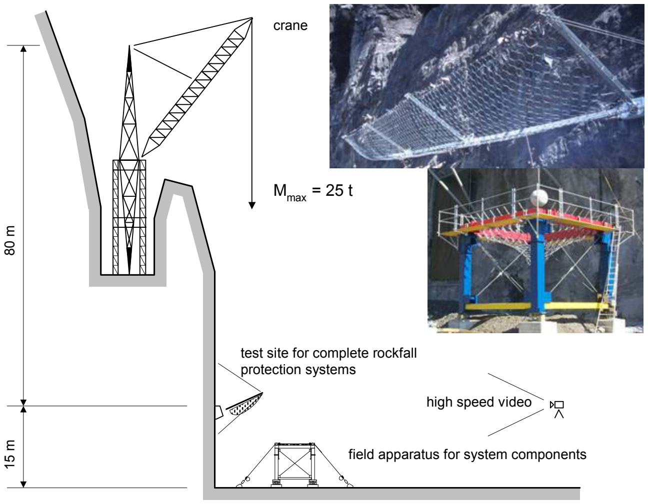


Figure 10. Rockfall test site in Walenstadt (Switzerland) for three span systems and single spanned nets supported in a steel frame or on cables with and without brake elements.

The dynamic behavior of the single components is investigated using a specially constructed field apparatus. High energy full-scale tests are performed on a complete system with three spans.

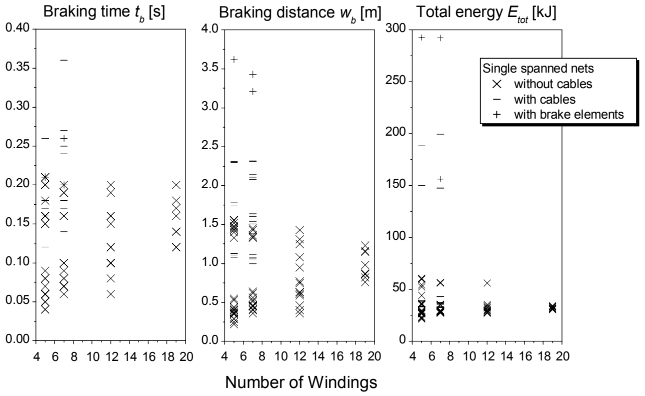


Figure 11. Series with single spanned nets: braking distance, braking time and total energy.

A multi-stage procedure, single spanned nets in a frame, suspended on cables with and without brake elements, was selected in order to understand the behavior of the single elements within the system. The rockfall test results of single spanned nets with wire rings of 5, 7, 12 and 19 windings are shown in Figure 11. The simplified configuration of a single spanned net reduces the number of model parameters and makes integral and accurate measurement possible. After the individual components were tested dynamically, field tests with complete systems were performed. Both the simplified and full-scale tests were back-calculated with the finite element model.

Several measuring techniques are used to record the braking process of the boulder in the net. The horizontal and vertical bearing reactions were measured with load cells fixed at the four supports of the columns. Eight load sensors measured the tensile forces in the ropes.

To obtain the resulting braking force which acts on the net in a direct manner, accelerometers and a computer control unit have been integrated in the boulder. The boulder consists of two semi-shells of fiber reinforced high performance concrete with a total mass of 825 kg. This instrumented rock is dropped from heights of up to 32 m.

In addition to that a high speed video system with two cameras recording 250 frames per second was used to track the entire braking process.

4 COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

4.1 Single ring

In Figure 12 the mean curve of tensile test diagrams of single wire rings with twelve windings supported on two, three and four bolts are compared with the results of the numerical simulation of the tensile test with an experimental set-up as shown in Figure 9.

The coincidence of the curves illustrates that the numerical ring model describes the mechanical bending and sliding behavior for different boundary conditions in a appropriate way.

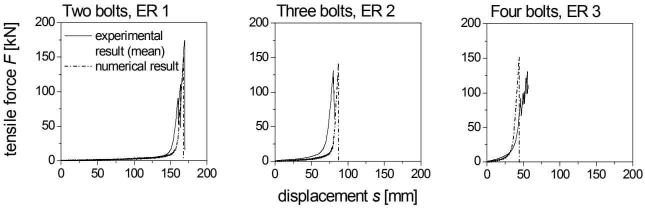
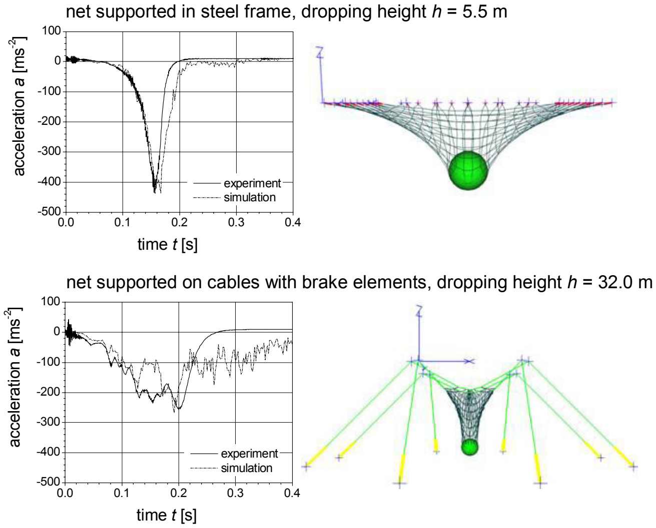


Figure 12. Comparison of experimental and numerical results of tensile test of single wire rings with twelve windings supported on two, three and four bolts.

4.2 Single spanned net

Figure 13 shows the results of the experimental and numerical simulation of square nets with blocked displacements at the boundary (steel frame) and square nets suspended on cables with brake elements. The experimental data were measured by the instrumented boulder. Plotted are the vertical components of the boulders acceleration during the braking process. Time $t = 0.0$ s corresponds to the first contact of the boulder with the net. The minimum of the acceleration-time-relation corresponds to the standstill of the boulder before unloading.

The accordance between the numerical and experimental results is independent of the boundary conditions of the net and is also valid for the dynamic loaded single spanned nets.


net supported in steel frame, dropping height *h* = 5.5 m

net supported on cables with brake elements, dropping height *h* = 32.0 m

Figure 13. Comparison of experimental and numerical result of single spanned 16 m^2 square nets with 5 windings per ring supported in a steel frame and on cables with brake elements, boulder mass $m = 825$ kg.

5 CONCLUSIONS

In order to investigate the behavior of flexible wire-net protection systems, an experimental and numerical research program was undertaken.

The finite element program FARO is capable to simulate the highly non-linear dynamic behavior of the steel-ring-net systems. A computer program is necessary to obtain information concerning displacements, stresses and strains in all components of the systems as well as the boundary reactions at the anchors of the cables and at the support of the columns.

An essential condition for the validation of the numerical model was the detailed multi-stage experimental program. The testing program specifically obtained information about the mechanical behavior of the single components as well as the complete multi-component systems. For the first time new measuring techniques like accelerometers in the boulder were successfully applied to directly measure the boulder deceleration.

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