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DISCRETE MODELLING OF A ROCKFALL PROTECTIVE SYSTEM

K. Thoeni*, C. Lambert†, A. Giacomini* and S.W. Sloan*

*Centre for Geotechnical and Materials Modelling
The University of Newcastle
Callaghan, NSW 2308, Australia
http://www.newcastle.edu.au

†Department of Civil and Natural Resources Engineering
University of Canterbury
Christchurch 8140, New Zealand
http://www.civil.canterbury.ac.nz

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Abstract. Metallic wire meshes are used worldwide for rockfall protective systems, such as rockfall net barriers and drapery meshes. Within different types of meshes, the double-twisted hexagonal mesh is commonly used. This paper focuses on the implementation and validation of a computational tool for the simulation of the behaviour of such meshes as a single part and as a component of a rockfall protective system. The discrete element method (DEM) is used to model the rockfall mesh and the impacting blocks. The open-source framework YADE has been extended in this context. Tensile tests of a plane net sheet subjected to a constant strain rate are used to calibrate the numerical model. Finally, the simulation of an impacting block on a horizontally spanned net is investigated where numerical results are compared to experimental results.

1 INTRODUCTION

Rockfalls pose a significant safety hazard for people and infrastructure which needs to be rigorously managed, not only when dealing with mountainous regions, but also in quarries and mines. It is almost impossible to prevent these phenomena. However, the installation of rockfall protective systems, such as rockfall net barriers and drapery meshes, is a common and effective way to reduce the hazard. The design of such structures is mostly based on empirical assumptions and, therefore, there is still a need to develop efficient numerical models in order to efficiently control the rockfall hazard. A principal component of these protection systems is the metallic wire mesh. The mesh can be installed in a more complex system as a rockfall barrier or directly installed on the slope, as in the case of drapery mesh systems. Different types of meshes are currently available from rockfall barrier producers, with the double-twisted hexagonal mesh being the most commonly used (see Figure 1). This wire mesh is made by continuously twisting two wires to form hexagonal-shaped openings as shown in Figure 2(a).

Figure 1: Application of double-twisted hexagonal rockfall mesh in a mine in New South Wales, Australia.

Several approaches for modelling steel wire meshes in numerical simulations have been proposed in the literature, with the most common being the finite element method (FEM). The FEM has been used to simulate the impact of falling rocks against rockfall protection systems where the wire meshes have been modelled by using truss elements (see e.g. [4]), beam elements (see e.g. [3]), shell finite elements (see e.g. [10]) and special purpose finite elements (see e.g. [11]). The FEM is well established for dynamic modelling of non-linear geometries with complex mechanical and contact behaviour for continuum problems but, when dealing with discontinuous problems, computing time becomes a big issue especially if the failure of the wire mesh needs to be considered. Therefore, the discrete element method (DEM) is a good alternative since the method is particularly suitable for dynamic impact problems involving failure. In this work the open-source framework YADE [8, 12] has been extended to model the double twisted hexagonal wire mesh. For this purpose, a new material and the related contact laws for the double-twisted wire mesh have been implemented.

2 DISCRETE MODELLING OF THE WIRE MESH

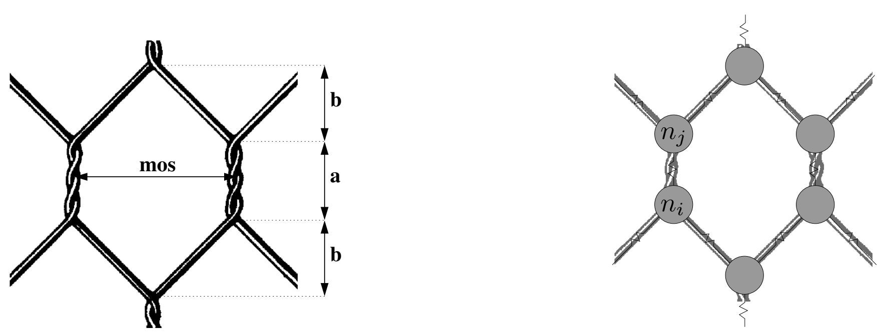
Following an initial idea by [9], and later extended by [1, 2], the mesh is discretised by a set of spherical particles which are located at the physical nodes of the mesh. The positions of the particles and remote interactions (i.e. interactions between the particles exist without direct contact) are defined by the initial geometry of the mesh. Two different remote interactions have been introduced to represent single and double-twisted wires. The constitutive relations proposed by [1] are used at the contact level to take the elastoplastic behaviour of the metallic wire mesh into account.

2.1 Remote interaction model and particle interaction

A nodal description of the wire mesh with remote interaction is used. As shown in Figure 2(b) particles are generated at the physical nodes of the mesh only. The wire itself is not discretised because interactions between particles exist without contact. In YADE the interactions are created by defining a interaction radius. Firstly, the particles are generated depending on the initial geometry of the mesh. Figure 2(a) shows a hexagon of the double twisted mesh with the requested dimensions to generate the mesh in YADE. Secondly, a simulation step is executed by defining a specific interaction radius. This simulation step initialises the interactions and creates the physical net. The generation of the mesh particles is done in a specific way in which double-twisted interactions are automatically identified. The algorithm always starts at the left lower corner of the mesh and generates a pair of particles which corresponds to a double-twist. Therefore, the number of the particles is used to identify if the interaction is a double-twisted or a single wire. For double-twisted interactions the following relation holds

$$|n_i - n_j| = 1 \tag{1}$$

where n_i and n_j are the number of particle i and j respectively. However, not all interactions might be created by the initialisation step since only interactions between the same wire material are identified automatically. The interactions for the selvedge wire, which is used to edge the wire, has to be defined manually. The same applies if additional wires (or wire ropes) are used to strengthen the wire mesh.



(a) Basic hexagonal shape of the double-twisted wire mesh [5] with dimensions used in YADE.

(b) Particles and remote interaction model.

Figure 2: Shape and remote interaction model of the double-twisted hexagonal mesh.

2.2 Constitutive law

The constitutive relations proposed by [1] have been adapted in this work. However, the implementation in YADE does not follow the incremental formulation presented in [1]. The contact law is directly defined by a piece-wise linear force-displacement curve (e.g. Figure 4) which is derived from the stress-strain curve of a single wire. Figure 3 shows the stress-strain curve used for the simulation. The relation corresponds to the stress-strain curve used by [1].

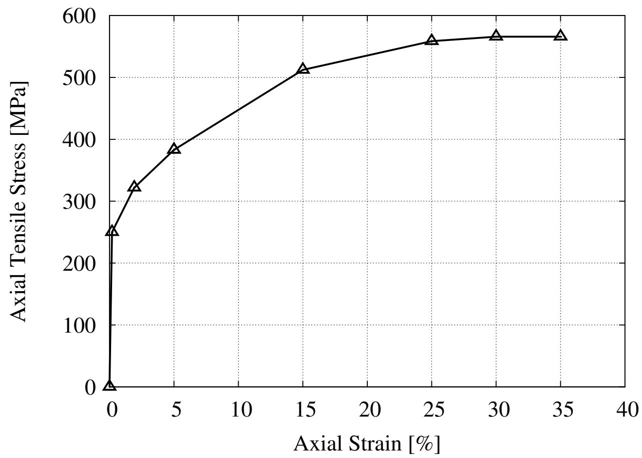


Figure 3: Piece-wise linear stress-strain curve used for the modelling of the steel wire.

It should be mentioned that the current implementation for the constitutive behaviour was kept very general in YADE. In fact, there is no limitation on how many points are used to define the piece-wise linear stress-strain curve. Any piece-wise function can be used to represent the tensile behaviour of a wire and, therefore, additional wire or even wire ropes can easily be considered in the model.

The force-displacement relation for a double-twisted wire is derived from that of the single wire by introducing two local parameters λ_k and λ_ε as shown by [1]. The parameter λ_k defines the initial stiffness of the double-twist, whereas λ_ε takes the length reduction at failure into account. These parameters are then used to calibrate the numerical model. The implemented model considers tensile forces only. It is assumed that tensile forces are much higher than compressive forces because of the buckling effect. Therefore, the stiffness in the compression regime is set to zero. Furthermore, only normal forces and no shear forces are considered in the model. Unloading is considered by setting the corresponding stiffness equal to the initial elastic stiffness. The interaction breaks when its strain limit is reached. Figure 4 shows the basic behaviour of a single wire on a loading path with unloading and reloading.

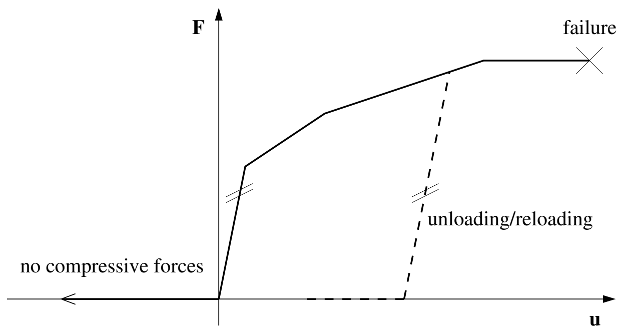


Figure 4: Schematic force-displacement diagram which shows the general behaviour of the interaction for a single wire.

3 CALIBRATION OF DISCRETE WIRE MODEL

The procedure presented in [2] is used to calibrate the two parameters used in the model. A tensile test of a plane net sheet of 0.5 m $\times$ 1 m subjected to a constant strain rate is analysed. The net is fixed at the bottom while a constant strain rate is applied at the top as shown in Figure 5(a). The diameter of the wire used for the mesh is 2.7 mm. The selvedge wire which is used to edge the mesh at its sides has a diameter of 3.4 mm. The behaviour of both wires follows the stress-strain curve presented in the previous section. A mesh of the type 80 mm $\times$ 100 mm is considered. The dimensions used for the generation of the mesh are $mos = 80$ mm and $a = b = 40$ mm.

No gravity is considered in this simulation since its influence on the tensile strength can be neglected. A displacement of $1.144 \cdot 10^{-3}$ mm is applied in each time step. The time step proposed by [2] is used. It is defined as

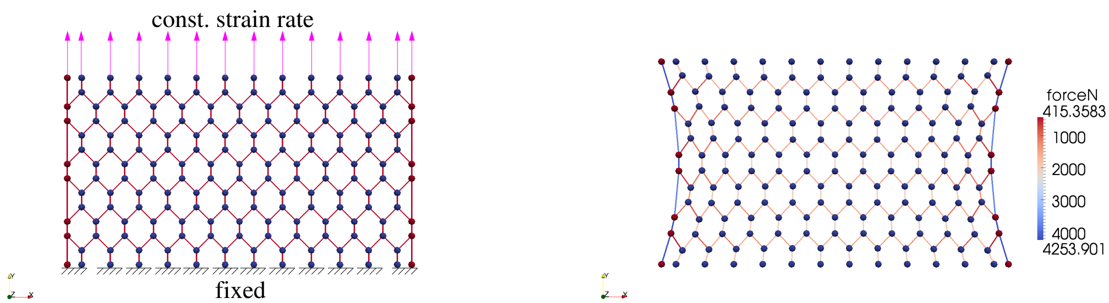
$$\Delta t = \frac{1}{5}\sqrt{\frac{m}{2k_s}}, \tag{2}$$

where m corresponds to the mass of a particle and k_s is the elastic stiffness of the single wire. The mass of the type of mesh considered in the analysis is $1.42\,{}^{\mathrm{kg}}/_{\mathrm{m}^2}$.

The influence of the two parameters λ_k and λ_ε is studied and shown in Figure 6 where the numerical results of this work are compared to the experimental results presented in [2]. As can be seen from Figure 6(b), a good approximation of the experimental curves is obtained with $\lambda_k = 0.73$ and $\lambda_\varepsilon = 0.47$.

4 SIMULATION OF IMPACT

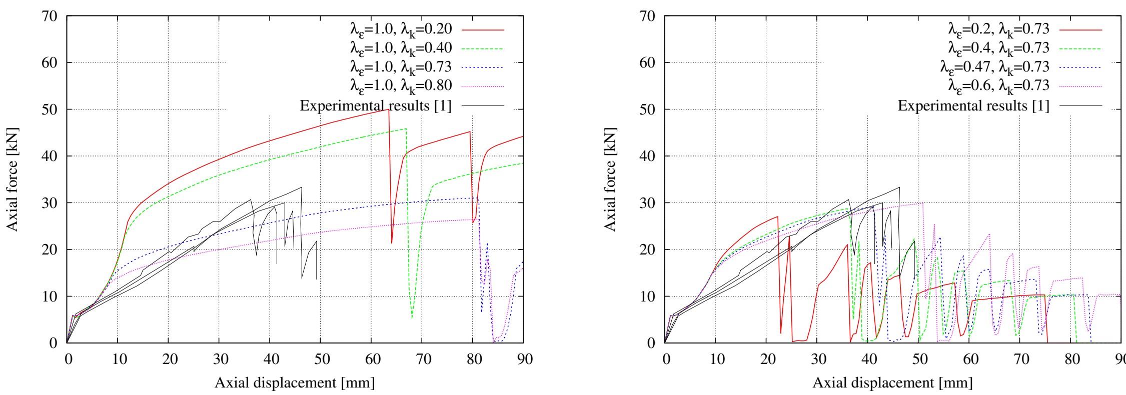
The dynamic impact of a concrete block on a horizontal hexagonal mesh is analysed and compared to experimental results in order to investigate the contact behaviour of the wire mesh with a block. Experimental tests have been carried out at the laboratory of The Centre for Geotechnical and Materials Modelling at The University of Newcastle according to the experimental set up developed in [3]. In this study, a series of tests have been carried out by fixing a double-twisted hexagonal mesh at two sides of the testing



(a) Boundary conditions and discretisation for the tensile test.

(b) Deformed mesh and normal forces before failure ($\lambda_k = 0.73$, $\lambda_\varepsilon = 0.47$).

Figure 5: Tensile test of a plane net sheet subjected to a constant strain rate.



(a) Calibration of λ_k with $\lambda_\varepsilon = 1.0$.

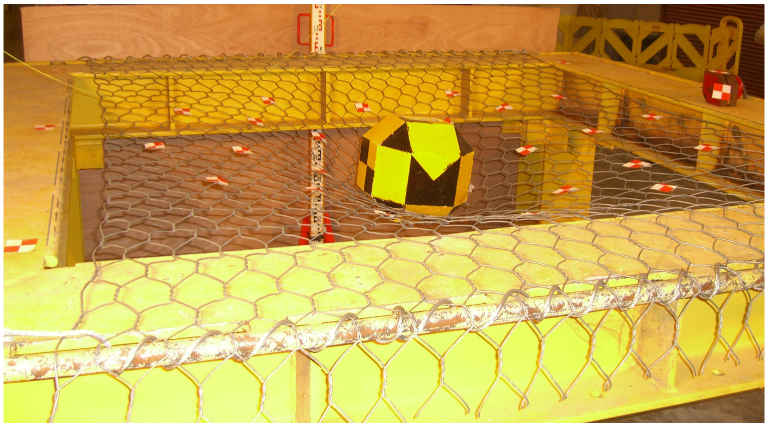
(b) Calibration of λ_ε with $\lambda_k = 0.73$.

Figure 6: Calibration of the parameters λ_ε and λ_k.

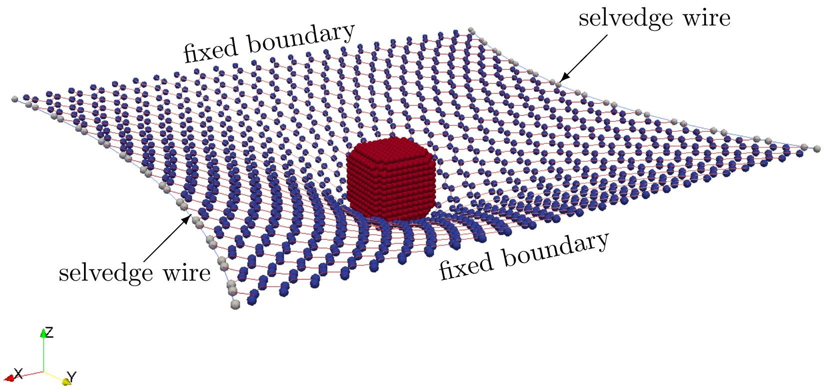
frame structure and then dropping concrete blocks on to the mesh from different heights. Figure 7(a) shows the experimental set up and the boundary conditions. The impacting concrete block, shaped according to the European Organisation for Technical Approval guidelines [7], has a mass of 44.5 kg and dimensions of 30 cm. The block was dropped from a dropping height of 0.5 m.

In the simulation, the block is represented by a clump generated by 1576 particles which have the same size as the particles used to represent the mesh (see Figure 7(b)). The mesh used for this example is the same as that used in the previous section where a sheet of $2\,\mathrm{m} \times 2\,\mathrm{m}$ is considered. The contact forces between the block and the wire mesh are computed using the classical linear elastic-plastic law from [6], which is implemented in YADE [12]. A local friction angle of $\varphi = 30\,^\circ$ has been assumed.

In the numerical simulation, gravity is applied to the wire mesh and after it has reached equilibrium the block is released. The maximum deformation of the mesh after the impact has been compared to the experimental measurements. The calculated deformation is 31 cm, whereas the deformation measured in the experimental tests varies between 32 cm and 38 cm. A very good agreement is thus observed. However, the behaviour of velocity and acceleration still needs to be analysed in order to fully validate the model.



(a) Experimental set up with concrete block and deformed mesh.



(b) Discrete model and deformed mesh with block clump.

Figure 7: Experimental test and numerical model for a block impacting on a horizontal spanned double-twisted wire mesh.

5 CONCLUSIONS

This paper presents a discrete wire mesh model currently implemented in the open-source framework YADE, which has the capability to model hexagonal double-twisted wire meshes. The application to rockfall protective systems has been investigated. However, only a very simple example is presented and further research is under way.

The current work is part of an ongoing research project with the objective to assess the rockfall hazard in open pit coal mines. The discrete model will be used to study rockfall trajectories and velocities at highwalls which are protected by double-twisted hexagonal meshes.

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