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Thoeni, Klaus; Lambert, Cedric; Giacomini, Anna; Sloan, Scott W.; 'Discrete modelling of hexagonal wire meshes with a stochastically distorted contact model.' Published in *Computers and Geotechnics* Vol. 49, p. 158-169 (2013)

Available from: <http://dx.doi.org/10.1016/j.compgeo.2012.10.014>

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Thoeni, K., Lambert, C., Giacomini, A., Sloan, S.W.: Discrete modelling of hexagonal wire meshes with a stochastically distorted contact model, *Computers and Geotechnics* 49, 158169, 2013.

This document contains the final accepted version (before copy editing). The published version of this manuscript is available on:

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Discrete modelling of hexagonal wire meshes with a stochastically distorted contact model

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Abstract

This paper presents an improved discrete element model, which incorporates stochastically distorted contact mechanics, for the simulation of double-twisted hexagonal wire meshes that are commonly used in rockfall protection. First, the characteristics of such meshes are investigated by conducting quasi-static and dynamic experimental tests. Second, the discrete model for the simulation of such meshes is presented. A stochastically distorted contact model is introduced to account for distortions of the wires and hexagons, allowing a more realistic representation of the mechanical response of the mesh from the deformation point of view and the force point of view. Quasi-static tensile tests of a plane net sheet, subjected to a constant strain rate, are used to study the effect of the stochastically distorted contact formulation and to calibrate the numerical model. Finally, the dynamic response of an impacting block on a horizontal mesh sheet is used to compare the numerical predictions against experimental results in order to validate the proposed approach.

Keywords: Discrete element method (DEM), Remote interaction, Double-twisted hexagonal mesh, Wire structure, Rockfall protection, Dynamic response

1. Introduction

Metallic wire meshes are a key component of various types of structural protection measures against rockfall such as embankments, catch fences and draperies. Commonly used wire meshes include chain link and double-twisted hexagonal meshes [17]. Fig. 1 shows two applications of a double-twisted hexagonal wire mesh as part of a rockfall protection system. The wire mesh, installed in a complex rockfall barrier structure (Fig. 1(a)) or a simple drapery (Fig. 1(b)), is one of the main components of these systems. Correct design of both the full system and each component is clearly of primary importance for safe management of the rockfall hazard.

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Over the last few decades, the behaviour of structural protection measures against rockfall has been investigated experimentally [e.g., 20, 1, 21, 13] and numerically [e.g., 15, 6, 19]. The latter are becoming increasingly important since the influence of different parameters can be investigated efficiently in order to optimise the design [27]. Experimental tests, however, are still necessary to calibrate the numerical models and to identify the governing characteristics of the components [17, 23].

Figure 1: Applications of double-twisted hexagonal meshes in rockfall protection: (a) rockfall catch fence and (b) simple mesh drapery system.

Various approaches for modelling rockfall protection systems with steel wire meshes have been proposed in the literature [27]. The finite element method (FEM) is the most common and can be used to simulate the impact of falling rocks against protection systems and to investigate their energy absorption capacity. Indeed, the FEM has been widely used to model entire rockfall protection systems [e.g., 6, 26, 11] as well as the constituent components, such as steel wire meshes [e.g., 23]. The latter have been modelled using various types of finite elements including truss elements [6, 11], beam elements [5], shell finite elements [23] and special purpose elements [25]. Beside these three-dimensional models, some simplified two-dimensional models have also been developed [e.g., 14]. The FEM is well established for dynamic modelling of continuum problems with non-linear geometries, complex mechanical behaviour, and various contact conditions. Its computational demands, however, are very high for discontinuous problems, especially if failure of the wire mesh needs to be considered, and alternative numerical methods, such as the discrete element method (DEM), are gaining in popularity [e.g., 18, 3].

The DEM is particularly suitable for dynamic impact problems involving discontinuous materials and failure mechanisms, since the material is represented by a discrete number of rigid particles which can overlap during collision [7]. The interaction between each particle is considered explicitly and is defined via a contact law. Although the particles can have any shape, spherical particles are commonly used since any shape can be approximated by an assembly of spherical particles [9]. The DEM has been used extensively in the design of highly flexible rockfall protection structures [e.g., 15, 18, 19] and to simulate the damage induced by impacting blocks on complex engineered rockfall protection barriers such as rockfall embankments [22] or geo-composite cells [2]. More recently, the DEM has been used to investigate the behaviour of rockfall fences including special dissipation devices and a newly-developed cable net [4]. The DEM has also been adopted for the modelling of double-twisted hexagonal wire meshes, where the mesh is represented by particles located at the physical nodes of the mesh [3, 24]. However, it is still necessary to improve the numerical description of the mechanical response of such meshes, and other rockfall barrier components, and to take into account spatial heterogeneity of stiffness and strength which strongly influences the random failure modes of the structure [4].

This paper presents a novel approach for improved discrete element modelling of double-twisted hexagonal wire meshes. The elementary tensile behaviour of single wires and double-twists are characterised experimentally. These characteristics are then used to define the basic properties of the contact law used in the proposed discrete model. Global mesh characteristics, such as distortion of the wires and hexagons, are considered by introducing a stochastically distorted contact model. To the authors' knowledge, this is the first time that such characteristics have been considered. Quasi-static tensile tests on a plane net sheet, subjected to a constant strain rate, are used to calibrate the numerical model. Finally, the dynamic response of an impacting block on a horizontal mesh is investigated since this plays an important role for simulations with simple drapery meshes [12]. The numerical results are compared to experimental results in order to validate the proposed approach. The model discussed in this paper is implemented in the open-source framework YADE [16, 28].

2. Wire mesh characteristics

As pointed out by Bertrand et al. [3], hexagonal wire meshes are woven systems. They are made by twisting continuous pairs of steel wires three half turns and by interconnecting adjacent wires to form hexagonal-shaped openings as shown in Fig. 2. The hexagonal honeycomb-like structure increases the macroscopic strength of the wire mesh and the double twists ensure that failure of a single wire does not compromise the panel. The lateral sides of the mesh are mechanically selvaged in parallel to the double-twists with a slightly thicker wire which is of the same material. The selvedge wire is woven continuously into the wire mesh as can be seen in Fig. 2(a).

This work considers the Maccaferri double-twisted hexagonal wire mesh of the type 80×100 with a wire diameter of 2.7 mm. The diameter of the selvedge wire is 3.4 mm, and the characteristics and dimensions of the mesh which are relevant to this research are summarised in Tab. 1.

Figure 2: Characteristics of a double-twisted hexagonal mesh: (a) close-up view of a double-twisted hexagonal wire mesh and (b) definition of the size of a hexagon.

Table 1: Summary of the mesh characteristics and dimensions as indicated in Fig. 2(b).

Mesh producer	Maccaferri
Mesh type	80×100
Wire diameter	2.7 mm
Selvedge wire diameter	3.4 mm
Mesh opening size (<i>mos</i>)	80 mm
Length of double-twist (<i>a</i>)	40 mm
Height of single wire (<i>b</i>)	40 mm
Mass per unit area	1.4 kg/m ²

2.1. Tensile test on a single wire and double-twist

The basic mechanical characteristics of a hexagonal wire mesh are defined by the tensile behaviour of its sub-structures: the single wire and the double-twist. These characteristics will be used to define the constitutive relations of the numerical model and are investigated in the following.

A series of tensile tests were performed on single wires of a diameter of 2.7 mm and 3.4 mm and on double-twists of a wire diameter of 2.7 mm. The length of the samples was between 120 and 150 mm and, during the tests, the wire ends were clamped within the testing device. Thus, tension was applied to an effective length ranging from 40 to 50 mm. A constant strain rate of 5 mm/min was applied to the samples, and it was noted that failure during the tests did not occur in the vicinity of the clamps. A summary of the performed tests is provided in Tab. 2.

Table 2: Summary of the performed tests on wire samples.

Wire type	Wire diameter [mm]	Number of samples	Effective length [mm]	Maximum axial force [kN]
Single wire	2.7	2	40.0, 40.0	3.03, 3.01
Single (selvedge) wire	3.4	1	48.3	4.66
Double-twist	2.7	3	45.3, 40.5, 41.2	5.89, 6.11, 5.88

Fig. 3 summarises the force-displacement curves of all the wire tests. Fig. 3(a) shows the curves obtained for the single wires. It can be seen that the maximum axial displacement is similar for all three samples, whereas the maximum axial force of the selvedge wire (3.4 mm) is much higher than that for the single wire (2.7 mm). Fig. 3(b) shows the force-displacement curves obtained for the three double-twist samples. For a wire diameter of 2.7 mm, the maximum axial force measured for a double-twist was almost twice that for a single wire.

Figure 3: Experimental force-displacement curves of the tested (a) single wires and (b) double-twists.

The forces and displacements in Fig. 3 were transformed into stresses and strains, respectively, in order to develop a model for all types of wire which is independent of the length. Thus, the cross-sectional area of the double-twists is assumed to be twice the cross-sectional area of a single wire. The stress-strain curves for the single wires and the double-twists are shown in Fig. 4(a) and Fig. 4(b) respectively. When comparing the maximum axial stress of the single wires to that of the double-twists it can be seen that both have almost the same strength.

Figure 4: Stress-strain curves and EWM for (a) single wire and (b) double-twist.

2.2. Tensile behaviour of a mesh sheet

Experimental tensile tests on Maccaferri mesh sheets, conducted at the University of Bologna [8], were considered for the present research. In these tests, a mesh sheet of about

$0.36 \times 0.95 \text{ m}^2$ was hooked to a metallic plate which was used to apply a constant strain rate of 10 mm/min (Fig. 5). The device allowed the application of uniform stress over a defined area of the mesh sheet of about $0.32 \times 0.58 \text{ m}^2$. Three tests, on mesh samples of the type 80×100 with a wire diameter of 2.7 mm , were carried out.

The testing device is shown in Fig. 5(a). Fig. 5(b) shows a sketch of the testing system with the connection points between the metallic plates and the mesh sheet (red points) and the wires which failed during the tests (black ellipses). Axial displacements and axial forces were recorded during the tests and are presented in Fig. 6.

Figure 5: Experimental test of a mesh sheet after [8]: (a) example of a tested mesh sheet with testing device and (b) connection points between the metallic plates and the mesh sheet (red points) and the wires which failed during the tests (black ellipses).

Figure 6: Plot of the experimental results after [8].

2.3. Block impact on a horizontal mesh sheet

The dynamic response of a horizontal, double-twisted hexagonal mesh sheet, subject to low velocity impact by a block, was investigated experimentally. The experimental set-up consisted of a testing frame (designed and built specifically to perform laboratory free fall tests on metal meshes [5]), a vertical level staff, and a high-speed camera positioned in front of the structural frame. Two mesh sheets were tested.

A concrete block shaped according to EOTA [10] with a mass of 44.5 kg was dropped on the mesh sheet, which was fixed at two sides of the structural frame with a steel wire rope of a diameter of 16 mm (Fig. 7). The block was dropped from a height of 0.5 m, measured from the top of the frame to the bottom of the block. The motion of the block was recorded by a high-speed camera and the sequence of images was analysed using the free 2D video analysis tool Tracker (<http://www.cabrillo.edu/~dbrown/tracker/>). This allowed the vertical position of the block to be tracked and additional estimates of the vertical velocity.

The mesh was installed under slight tension in order to reduce its initial deflection. The latter, prior to dropping the block, was measured to be 1 cm for both tests. Fig. 7(a) shows the configuration before dropping the block, while Fig. 7(b) shows the first impact of the block on the mesh at the point where the maximum deformation occurred.

Figure 7: Impact on a horizontal mesh sheet from a dropping height of 0.5 m: (a) situation before the drop and (b) the first impact (maximum deformation).

The evolutions of the vertical position and vertical velocity of the block are given in Fig. 8(a) and 8(b) respectively. It should be noted that the vertical position of the block is measured from its bottom face. The maximum vertical deformation of the mesh occurred after the first impact on the mesh at approximately 0.45 s, and was recorded as -0.36 m and -0.35 m. Afterwards, the oscillations faded until the arrest of the block. After about 2 s, static equilibrium was reached with a final deflection of -0.31 m and -0.29 m.

3. Discrete modelling of the wire mesh

3.1. Mesh representation

The approach of Nicot et al. [18] and Bertrand et al. [2, 3] has been adopted in this study. The steel wire mesh is represented by a set of spherical particles located at the physical nodes of the mesh, with no physical contact between these particles. Remote interactions are introduced to represent the wires between the nodes, so they are not discretised explicitly. The single wires and double-twists are defined by the initial geometry of the mesh (Fig. 9).

The generation of the mesh follows a three step procedure [24]. The particles are first generated in accordance with the initial geometry of the mesh, as defined in Section 2.

Figure 8: Experimental results for the vertical drop from 0.5 m: evolution of (a) vertical position and (b) vertical velocity of the block.

Figure 9: Location of particles and remote interaction model for the double-twisted hexagonal wire mesh.

This leads to about 326 particles per m^2 . All particles have the same diameter of 10.8 mm, corresponding to four times the diameter of a wire, and their density is adjusted so that the mass of the numerical mesh panel (i.e. total mass of the particles) is equal to the physical mass of the panel (cf. Tab. 1). Thus, the adjusted density in the numerical model is 5300 kg/m^3 which results in a mass of 4.3 g for each particle. Second, remote interactions are defined between particles where single wire and double-twist interactions are automatically identified by checking the distance between the particles. Finally, interactions for the lateral selvedge wires are manually introduced.

3.2. Elementary wire model

In the DEM, the constitutive relations are defined in terms of contact laws which govern the force-displacement relationship between two interacting particles. The discrete model presented by Bertrand et al. [3] and implemented into YADE by Thoeni et al. [24], uses the same relationship (i.e. same stress-strain curve) for single wires and double-twists. In this study, two distinct elementary wire models (EWM) are developed by using the experimental results presented in Section 2.1. The same stress-strain curves are used for single wires and selvedge wires.

The experimental results are numerically approximated by a piecewise linear function as shown in Fig. 4 (EWM single and EWM double-twist). These piecewise linear functions define the tensile component of the EWM implemented into the discrete element program. The stress-strain representation is then transformed back into a force-displacement relationship

by using the defined wire diameter and the distance between two interacting particles (i.e. wire length). Hence, the implemented contact law is directly defined by a piecewise linear force-displacement curve which is derived from the related stress-strain curve. However, the model considers tensile forces only, since it is assumed that these are much higher than compressive forces because of the effect of buckling [2]. Thus, the stiffness in the compression regime is set to zero. Furthermore, only normal forces and no shear forces are considered in the numerical model of the wire mesh. Unloading is considered by setting the corresponding stiffness equal to the initial elastic stiffness. The interaction breaks when its limit is reached. Fig. 10 shows the basic behaviour of the EMW on a loading path with unloading, reloading and rupture.

Figure 10: Schematic representation of the force-displacement curve defined by the EWM.

3.3. Stochastically distorted wire model

As mentioned in Section 3.2, the elementary wire models are defined on the basis of the behaviour of a single wire or double-twist. However, the curves presented previously are for straight specimens. A close observation of a physical mesh panel, shown in Fig. 2(a), reveals that the wires and hexagons usually show some distortion and that the real length of the wire between two nodes may differ from the actual distance between the nodes. Such irregularities influence the macroscopic behaviour of the mesh and should be considered in the formulation of the model. In this work, the irregularities are assumed to be randomly distributed over a mesh panel, and the contact laws are altered stochastically to account for the distortion of the wires and hexagons.

Two parameters are introduced in order to define a stochastically distorted wire model (SDWM). The first parameter, λ_u , defines a horizontal shift to the force-displacement curve as depicted in Fig. 11. The second parameter, λ_F , determines the stiffness of the wire in the shifted area. It should be noted that the unloading stiffness is not influenced by λ_F . Both parameters are limited to values between 0 and 1.

The following assumptions are made in the development of the SDWM:

- The real “undistorted” length of a single wire or double twist, L , is limited by

$$L_0 < L < L_0 + \Delta L \quad (1)$$

where L_0 is the initial distance between the two interacting particles and ΔL is the additional length considered due to the mentioned irregularities. ΔL defines the horizontal

Figure 11: Schematic representation of the influence of the parameter λ_u and λ_F on the contact law.

shift and is calculated randomly by using the following expression

$$\Delta L = \lambda_u \tilde{r} L_0 \quad (2)$$

where $\tilde{r}$ is a random number between 0 and 1.

- The irregularities are distributed according to a triangular distribution (i.e. hardly any wires are not distorted or highly distorted whereas many are moderately distorted). Therefore, the random number generator implemented in the model generates numbers according to a triangular distribution. The parameters for the triangular distribution are set to 0 for the smallest, 0.5 for the most probable, and 1 for the largest value. In other words, the value for ΔL will be between 0 and $\lambda_u L_0$ with the average value being around $0.5\lambda_u L_0$. Therefore, for moderately distorted wires with ΔL corresponding to about 10% of the initial length, the value for λ_u is around 0.2.
- The initial positions of the particles remain unchanged whereas the constitutive behaviour (i.e. force-displacement curve) differs slightly for each interaction because of the introduced random modification.
- The parameter λ_F and the elastic limit force F_1 are used to define the new stiffness in the shifted area. $\lambda_F = 0$ means that the wire will not be activated until a relative displacement of $\lambda_u L_0$ occurs. In this specific case the stiffness in the shifted area does not change whereas for $0 < \lambda_F \leq 1$ the stiffness in the shifted area changes according to the introduced random shift.

Finally, it should be mentioned that each mesh panel is associated with a seed number which initialises the random number generator. Each seed number generates a new random distribution of the contact properties (i.e. random number $\tilde{r}$) in the mesh panel.

4. Calibration and quasi-static response of the mesh

The experimental tests conducted at the University of Bologna [8] are now used to calibrate the two parameters λ_u and λ_F . The numerical representation used for the calibration process is shown in Fig. 12.

The size of the mesh sheet replicates the experimental dimensions. The boundary conditions are enforced by applying constraints to affected particles. Particles corresponding to the

lower hooks (red boxes in Fig. 12) are fixed, while a constant vertical velocity of 10 mm/min is applied to the particles corresponding to the upper hooks (yellow boxes in Fig. 12). All remaining particles are free to move. The time step is set to $\Delta t = 2 \times 10^{-5}$ s, which corresponds to 30% of the critical time step as defined by Bertrand et al. [3]. The simulations are stopped when the first wire ruptures.

Figure 12: Numerical discretisation and boundary conditions for the tensile test of a mesh sheet.

Since the mesh sheets are generated stochastically, they are expected to exhibit a range of behaviour. The parameters λ_u and λ_F are, hence, calibrated statistically by comparing the average numerical response to the average experimental behaviour. A total of six indicators is used to characterise the behaviour of the mesh: displacement at failure $u_{y,\max}$, maximum tensile force $F_{y,\max}$, and displacements at four intermediate load levels. The intermediate load levels are chosen as a fraction (90%, 75%, 50% and 25%) of the average experimental tensile strength $F_y^* = 30.92$ kN (Fig. 15(a)).

Several series of simulations are performed for a range of combinations with λ_u varying between 0.16 and 0.28 and λ_F varying between 0 and 1. Each series consists of one hundred simulations for which one hundred mesh sheets are randomly generated with the same set of parameters λ_u and λ_F . Average values and standard deviations for each indicator are then calculated for each series and compared to the experimental results.

For each series, the distribution of the failure points are compared to the three experimental test results presented in Section 2.2. As can be seen in Fig. 13(a), λ_F has almost no influence on the failure point, and the point clouds for the various values of λ_F are nearly coincident. Nevertheless, the points are less dispersed for values of λ_F close to 1. Fig. 13(b) shows the influence of λ_u for $\lambda_F = 1$. It can clearly be seen that the points are shifted from left to right with increasing λ_u . A best fit with the experimental results occurs for values of λ_u between 0.2 and 0.28.

The sensitivity of $F_{y,\max}$ and $u_{y,\max}$ to λ_u and λ_F is illustrated in Fig. 13(c) and Fig. 13(d), respectively. The black solid line indicates the mean value of the experimental results and the black dashed lines indicate the corresponding standard deviation. It can be seen that the mean force at failure $F_{y,\max}$ increases with increasing λ_F while the mean displacement at failure $u_{y,\max}$ is not influenced by λ_F . Furthermore, the mean force at failure $F_{y,\max}$ decreases with increasing λ_u whereas the mean displacement at failure $u_{y,\max}$ increases with increasing λ_u . The best fit to the experimental results for the mean force at failure is obtained with values of λ_u in the range of 0.16–0.18 and $\lambda_F = 1$. The best results for the mean displacement at failure are obtained with values for λ_u around 0.28.

Finally, the two parameters λ_u and λ_F are calibrated considering the response during the entire test (i.e. at various intermediate load levels) rather than just at the ultimate

Figure 13: Results for the series of analyses with the SDWM: (a) influence of λ_F on failure point, (b) influence of λ_u on failure point and mean values and standard deviations for (c) force at failure and (d) displacement at failure.

capacity of the mesh. The sensitivity of these indicators to λ_u and λ_F is shown in Fig. 14. In general, it can be seen that the displacement at a specific load level decreases for increasing λ_F , whereas it increases for increasing λ_u . For a load level of $0.9F_y^*$, the best agreement with the experimental results is obtained with values of λ_F smaller than 1 and with values for λ_u between 0.2 and 0.24 (Fig. 14(a)). The best agreement for load levels of $0.75F_y^*$ and $0.5F_y^*$ is achieved with values for λ_F around 1 and with values for λ_u between 0.16 and 0.2 (Figs. 14(b)–(c)). For a load level of $0.25F_y^*$ the best value for λ_F is 1 and the best value for λ_u is between 0.18 and 0.22 (Fig. 14(d)). Overall, the best fit with the experimental results is obtained using $\lambda_u = 0.2$ and $\lambda_F = 1$.

Figure 14: Mean values and standard deviations of the vertical deformations for the different series of analyses at different intermediate load levels: (a) $0.9F_y^*$, (b) $0.75F_y^*$, (c) $0.5F_y^*$ and (d) $0.25F_y^*$.

Fig. 15(a) summarises the mean values and standard deviations of the force-displacement response at various load levels by using the best-fit parameters $\lambda_u = 0.2$ and $\lambda_F = 1$. Very good agreement with the experimental results can be observed along the whole loading path. Four examples of force-displacement curves are compared to the experimental curves in Fig. 15(b) and their corresponding failure modes are given in Fig. 16. It can be seen that one of the single wires at the lateral sides is failing. This corresponds to two of the failure modes observed in the experiments (Fig. 5).

Figure 15: Comparison of experimental and numerical results for final set of parameters $\lambda_u = 0.2$ and $\lambda_F = 1$: (a) for different intermediate load levels and (b) for different mesh panels.

Figure 16: Failure mode (black ellipse indicates the failing wire) for four different mesh panels for final set of parameters ($\lambda_u = 0.2$, $\lambda_F = 1$): (a) Numerical 1, (b) Numerical 2, (c) Numerical 3 and (d) Numerical 4.

5. Dynamic response of the mesh under impacting block

The dynamic response of the numerical model is investigated by simulating an impact on a horizontal wire mesh. The experiments presented in Section 2.3 are used to validate the numerical model. The concrete block is represented by a rigid assembly (clump) of uniform spheres with a radius of 2 cm as shown in Fig. 17(a). The mesh sheet has a size of $2\text{ m} \times 2\text{ m}$, and the same boundary conditions as those used during the experiments are imposed on the numerical model. As it can be seen in Fig. 17(b), two sides of the mesh are fixed (indicated by the red boxes around the particles) whereas the two lateral boundaries with the selvedge wire are free to move. To replicate the initial deflection of the mesh in the experiments, tension is applied to the mesh by slightly moving the upper fixed particle in the direction of the y -axis until the required maximum vertical deflection is obtained. The contact forces between the concrete block and the wire mesh are governed by the classical linear elastic-plastic contact law presented by Cundall and Strack [7]. A local friction angle of $\varphi = 25^\circ$ and a stiffness ratio of $k_t/k_n = 0.1$, where k_t and k_n correspond to the tangential and normal stiffness respectively, is used. The time step corresponds to the time step introduced in Section 4.

Figure 17: Discrete model for the dynamic response of the mesh: (a) concrete block as rigid clump and (b) wire mesh sheet with imposed boundary conditions.

The contact behaviour between the wire mesh and the impacting concrete block is investigated by studying the influence of the contact stiffness k_n . It should be noted that the influence of φ and k_t/k_n has also been studied. However, as these have only shown minor influence, the results are not presented for brevity.

The results for k_n values in the range from 1×10^4 N/m to 1×10^7 N/m are plotted in Fig. 18. The maximum deflection obtained for the first impact and the final deflection (i.e. once static equilibrium is reached) are influenced little by the contact stiffness k_n . However, the contact stiffness significantly influences the amplitude and frequency of the post-impact oscillations of the wire mesh. Indeed, the amplitude of the oscillations increases for decreasing values of

k_n whereas the frequency decreases. The influence of k_n on the amplitude and frequency is minimal for values of $k_n > 5 \times 10^4$ N/m, but both the amplitude and frequency are smaller than the observations in the experiments. Only $k_n = 1 \times 10^4$ N/m gives an amplitude and frequency which is bigger than the observed values.

Figure 18: Influence of the contact stiffness k_n [N/m] and comparison to experimental data: evolution of (a) vertical position of the block and (b) vertical velocity of the block.

The proposed numerical model for the double-twisted hexagonal mesh takes only normal forces into account. However, when a block impacts on a mesh, local bending of the wires results in an additional source of energy dissipation. This is a source of energy dissipation which is not directly considered in the model, but non-viscous local damping can be introduced to dissipate some of this kinetic energy. The numerical damping scheme of YADE [28] is adjusted so that a damping force term is added to the particles of the mesh while particles of the block remain unaffected. The magnitude of the damping force is controlled by the dimensionless parameter λ_d . It is assumed that both the amplitude and the frequency for $k_n = 1 \times 10^4$ N/m can be reduced to match the experimental results by introducing non-viscous local damping. Therefore, the influence of the damping parameter λ_d , for $k_n = 1 \times 10^4$ N/m, is studied with values ranging from 0 to 0.5. Fig. 19 highlights the effect of non-viscous damping on the dynamic behaviour of the mesh. It can be seen that numerical damping is essential to dissipate additional energy and to reproduce the correct amplitude and frequency of the post-impact oscillations of the wire mesh. Experimental results are best reproduced with a damping coefficient of $\lambda_d = 0.5$.

Finally, four mesh panels are stochastically generated and their dynamic response under the impact of a block is numerically investigated with $k_n = 1 \times 10^4$ N/m and $\lambda_d = 0.5$. In Fig. 20, the evolutions of the vertical position and the vertical velocity of the block show very good agreement with data from the two experimental tests. Moreover, the correct behaviour for amplitude and frequency of the post-impact oscillations is obtained. Fig. 21 shows the results at the first impact for one of the mesh panels. In Fig. 21(a) it can be seen that the maximum vertical deformation of the mesh is predicted to be around 0.35 m, which matches the observed values. Fig. 21(b) shows the normal forces during the first impact where negative values indicate tensile forces.

Figure 19: Influence of the damping parameter λ_d with $k_n = 1 \times 10^4$ N/m and comparison to experimental results: evolution of (a) vertical position of the block and (b) vertical velocity of the block.

Figure 20: Comparison of experimental and numerical results for $\lambda_d = 0.5$ and $k_n = 1 \times 10^4$ N/m: evolution of (a) vertical position of the block and (b) vertical velocity of the block.

Figure 21: Results for the first impact of the block for one of the presented numerical simulations: (a) vertical position of the particles and (b) wire normal forces (tensile forces negative).

6. Conclusions

This paper presents a novel approach for realistic modelling of double-twisted hexagonal wire meshes, based on the discrete element method. The steel wire mesh was represented by a set of spherical particles located at the physical nodes of the mesh. The behaviour of the wires was described by remote interactions between particles. Elementary tensile behaviours for single wires and double-twists were characterised experimentally, and the stress-strain curves obtained from the experiments were then numerically approximated by piecewise linear functions. Two new elementary wire models (EWM) were derived and implemented into the discrete element program. The EWM models were stochastically altered to account for existing distortions of wires and hexagons in a typical mesh. Two parameters, λ_u and λ_F , were introduced to define a stochastically distorted wire model (SDWM). The parameter λ_u introduces a horizontal shift to the force-displacement curve and the parameter λ_F determines the stiffness of the distorted wire in the shifted area.

Quasi-static tensile tests on a mesh sheet were used to calibrate the SDWM. For this purpose, several series of one hundred simulations were performed varying the two distortion parameters λ_u and λ_F . The numerical model predicts the experimental observations with good accuracy, not only at the ultimate load but also for intermediate load levels. Furthermore, very good predictions of the failure mode in the experiments were obtained.

Finally, the discrete wire mesh model was used to simulate the dynamic impact of a concrete block on a horizontal wire mesh. A study was made of the influence of the normal contact stiffness k_n between the particles forming the mesh and the particles forming the block on the dynamic response of the system. It was shown that the maximum and final deflections of the mesh are not influenced by k_n , while the amplitude and frequency of the post-impact oscillations of the system are sensitive to this parameter. Local non-viscous damping was introduced in the model to dissipate additional energy and to reproduce the correct amplitude and frequency of the post-impact oscillations of the system. Appropriate values for the contact stiffness and the damping parameter were identified to accurately reproduce the experimental results.

Acknowledgements

The financial support of the Australian Coal Association Research Program (C19026) is greatly acknowledged. The financial support of the Australian Research Council (LP0989965) provided to the Newcastle authors is also acknowledged. Acknowledgment is also made to Maccaferri for providing the material for the experimental tests.

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