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COMPARISON OF TWO DEM STRATEGIES FOR MODELLING CORTICAL MESHES

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Abstract. This work deals with the particle-based modelling of cortical wire meshes. Such meshes are being used in many engineering applications but their modelling is particularly complex because of the common large displacement serviceability conditions, the chance of localized failures, and the intrinsic geometrical and mechanical anisotropies. The discrete element method has proved to be an excellent numerical tool for the investigation of such structures. Here, two modelling strategies are compared using a wire-node description and a wire-cylinder description: in the first the wire mesh is described by a collection of spheres at nodes linked by long-range interaction forces, in the second the wires are represented by means of interconnected cylinders. The force-displacement constitutive model of the interactions is calibrated based on specific tensile tests. The comparison is performed on results of tensile tests and punch tests on a reference mesh panel.

1 INTRODUCTION

Metallic cortical wire meshes are currently being used in many engineering applications, especially for the mitigation of the rockfall hazard along slopes and for protection of people and infrastructures. They wrap rock cliffs or steep soil slopes supporting the horizontal and tangential stresses which arise from the weathering of the shallow layers. The evaluation of the contact and the stress distribution between these structures and the backfill material as well as the knowledge of the strain behaviour of these meshes is relevant for their correct design.

These structures are constituted by ordered intersections of steel wires and cables generally having a ductile mechanical behaviour. The complex geometries and pattern of the wires, their different material properties, and the existence of non-trivial boundary conditions make these structures difficult to be modelled as simple continuum membranes. Moreover, their high deformability and the chance of local ruptures in the mesh make the numerical modelling of such structures very challenging. One of the approaches for efficiently simulating these structures is the discrete element method (DEM) which is particularly well suited to treat high deformable problems including discontinuities and complex failure modes [1]. The DEM approach also allows to efficiently handle the mechanical behaviour at the contact between these meshes and other elements.

This work shows a comparison of two different discrete element modelling strategies for the simulation of a double-twisted hexagonal wire mesh. The first one represents the wire mesh as a collection of remote interactions. The second strategy, describes each wire of the mesh in a more realistic way as a collection of interconnected cylindrical elements. The two modelling strategies are applied to a tensile test and a punch test and the results are compared.

2 THE WIRE-NODE APPROACH

In the first model, each node of the mesh is represented by a fictitious spherical particle that concentrates the mass of the related wires, while the wires are substituted by long-range tensile interaction forces having zero mass and no shape (Figure 1a). This representation permits to efficiently decrease the computational effort in terms of contact detection and rigid body dynamic [2,3]. The approach has been successfully applied to the modelling of large scale drapery systems [4].

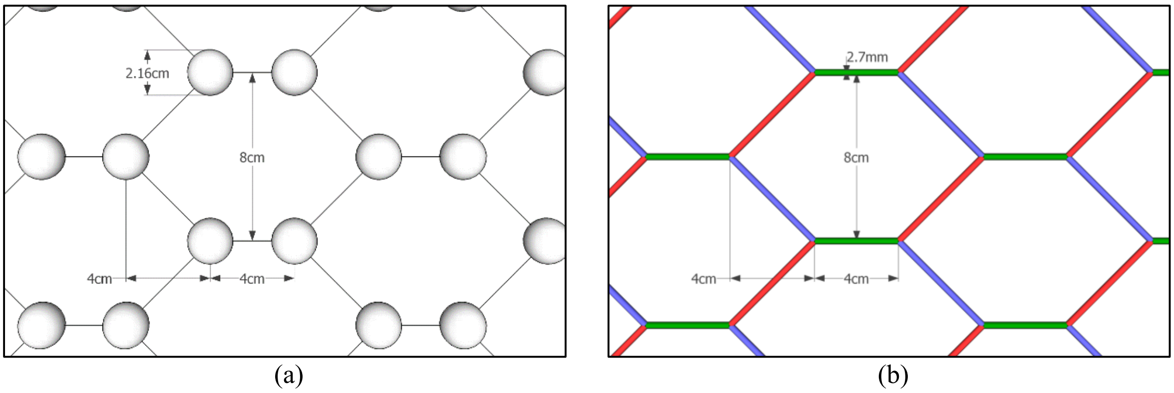


Figure 1: Sketch of the (a) wire-node approach and (b) wire-cylinder approach.

The density of these nodal particles is calibrated to match the total mass of the mesh panel while, for arbitrary convention, their radius is fixed equal to 4 times the single wire diameter. In this way the inertial properties of the mesh are correctly conserved also for analyzing dynamic problems like impacts. These nodal particles generally cannot touch one each other (this probability is very low in well-posed boundary problems like the one presented here), while contacts between the particles and other external elements are permitted to study the interaction of the mesh with other bodies and surfaces.

The long-range contact forces between nodal particles have been implemented in the model on the basis of laboratory results of single wire and double-twist tensile tests [2]. These stress-strain curves were implemented in the long-range constitutive interaction model by using a piecewise linear approximation. Only tensile forces are allowed as the wires would generally buckle under compression.

In Figure 2, the tensile constitutive models for single wire and double-twisted wire are depicted.

It can be seen that the single wire interaction law has a higher initial stiffness compared to the one of the double-twisted wire as well as a higher maximum tensile elongation.

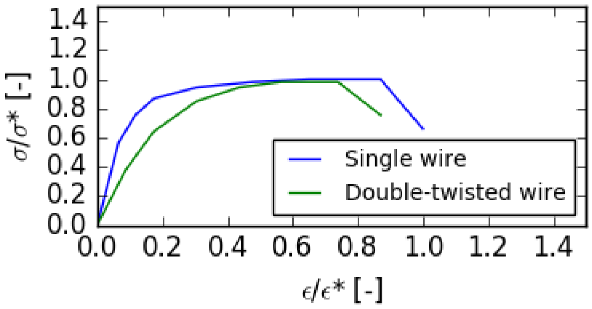
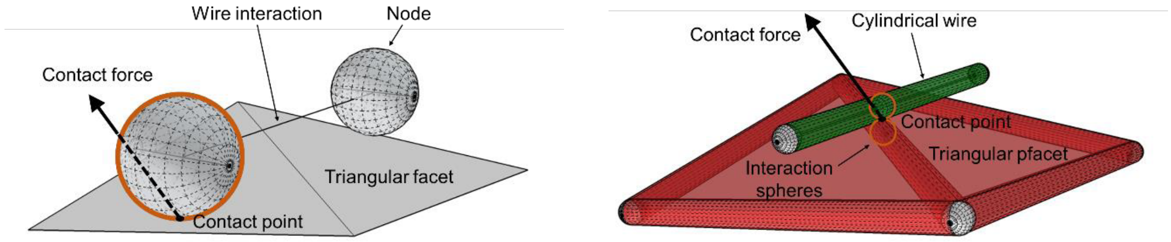


Figure 2: Normalized stress-strain tensile curves for the wires of the double-twisted wire mesh.

Two methods have been used to assign the constitutive model at each wire type [2]: a deterministic model and a stochastic one. The deterministic model uses the same two interaction laws previously described for the two wire types. In the second approach, instead, the two piecewise curves are corrected with a stochastically distorted wire model which is used to model the variability of mechanical and geometrical properties in the wire mesh. The two parameters controlling this second model are λ_u, which defines an initial horizontal shift for the force-displacement curve, and λ_F, which modifies the stiffness of the wire in the shifted part. These parameters mostly act on the mechanical behavior of the first phase of the tests, during the initial tensile deformations, when the hexagons are geometrically distorted. Indeed, during this phase, single and double-twisted wires are stretched from completely unloaded conditions showing an initial softer tensile response which leads to a horizontally shift of the force-displacement curves.

2 THE WIRE-CYLINDER APPROACH

In the second approach, interconnected rigid cylinders [5] with a diameter of the single wire are used to represent single and double-twisted wires (Figure 1b). The connections between these cylindrical elements are represented by perfect hinges. As in the previous model, the mechanical response of the wire-cylinder is calibrated only on the basis of tensile laboratory tests performed on samples of single wires and double-twisted wires. Differently from the previous model, these solid bodies have a physical shape, similar to the real one, and they may experience contact with other bodies along the cylindrical wire lateral surface. The contact between a single wire-cylinder and other elements (spheres, cylinders, pfacets) is treated with a hierarchical strategy that finally reduces to only two types of contact: sphere-sphere or sphere-plane. In our case, only normal forces between these bodies are considered while frictional tangential forces have been set equal to zero (i.e. mimicking a frictionless mesh). In Figure 3, the contact between a hypothetic wire and two facets (or pfacets) of an idealized body is depicted comparing the two approaches. With regards to the mesh, it is clear that the contact with angular bodies as well as the interception of small particles may be better described with the wire-cylinder approach but the price to be paid for the improved realistic representation is the higher computational effort. This particular aspect will be further discussed in Section 5.



(a) (b)

Figure 3: Sketch of the contact between two facets and one wire using the (a) wire-node approach and (b) wire-cylinder approach.

Wire-cylinder elements could potentially handle bending and twisting moments at nodes like elastic perfectly plastic beams [6] but this option was not considered to allow a clear comparison with the first model.

3 TENSILE TEST

The two approaches are tested with reference to a tensile test on a rectangular mesh panel of size 36x92cm. Details about the setup and the procedure of this experiment can be found in [2]. In Figure 4, the mesh panel used is depicted, while boundary conditions applied at the nodes are marked with red triangles and blue dots.

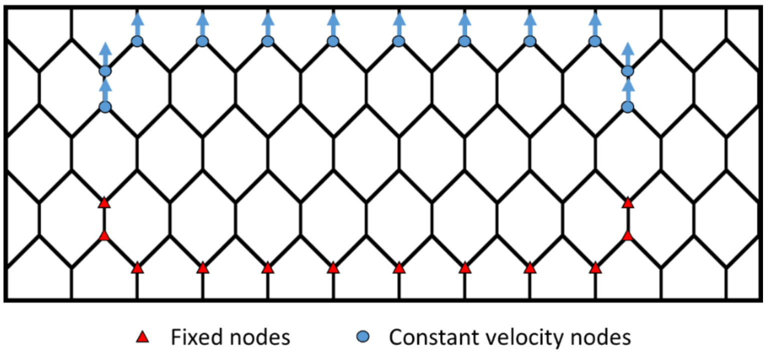


Figure 4: Sketch of the mesh sheet used in the tensile test with the imposed nodal boundary conditions.

The results of the deterministic and stochastic model using the two approaches are depicted in Figure 5 and compared with the experimental result. It is clear that the deterministic model of the wire is not able to reproduce the response of the mesh panel, while the stochastic one, after calibration, is in agreement with the laboratory result. The deterministic model, in this case, gives a stiffer response that is not realistic. This is mainly due to the regular geometry of the numerical mesh and to the perfect rigidity of the boundary conditions (constraints) in the numerical model as well. Instead, the introduction of some geometrical irregularities leads to a less rigid behavior of the mesh panel in the initial part of the test which is not reproducible with the deterministic model.

Regarding the comparison of the two approaches, they appear very similar with a little discrepancy for the stochastic model which is compatible with the intrinsic randomness of the initial geometrical and mechanical conditions.

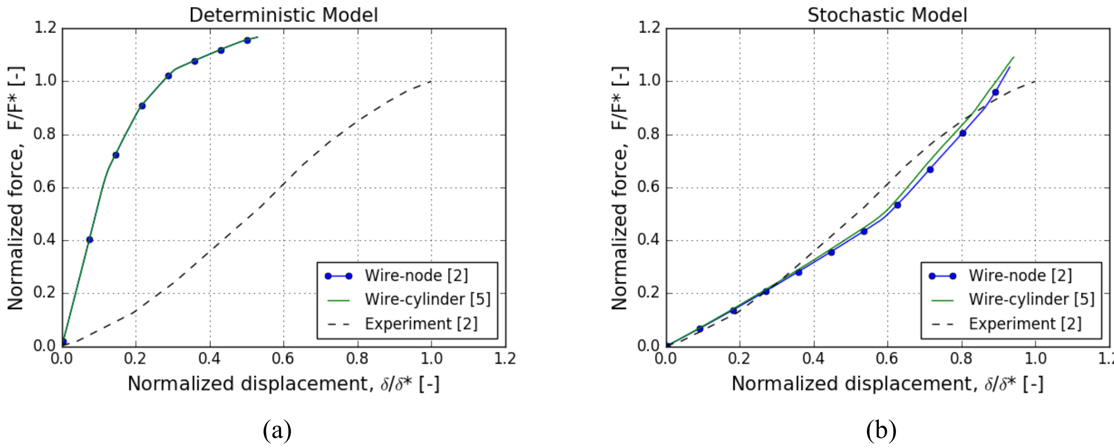


Figure 5: Comparison of wire-node approach and wire-cylinder approach with reference to a tensile test using (a) a deterministic model (b) a stochastically distorted model after calibration.

4 PUNCH TEST

In order to assess the differences of the two approaches with regards to the contact of the wire mesh with other bodies we also considered the results of punch tests where the wires come in contact with the external punching element [3].

The two models have been tested with reference to a 3 x 3 m mesh panel. The punching element is represented by a frictionless spherical cup with a curvature radius equal to $R = 1.2$ m, diameter equal to 1 m and smoothed edges having a curvature radius of $r = 0.05$ m.

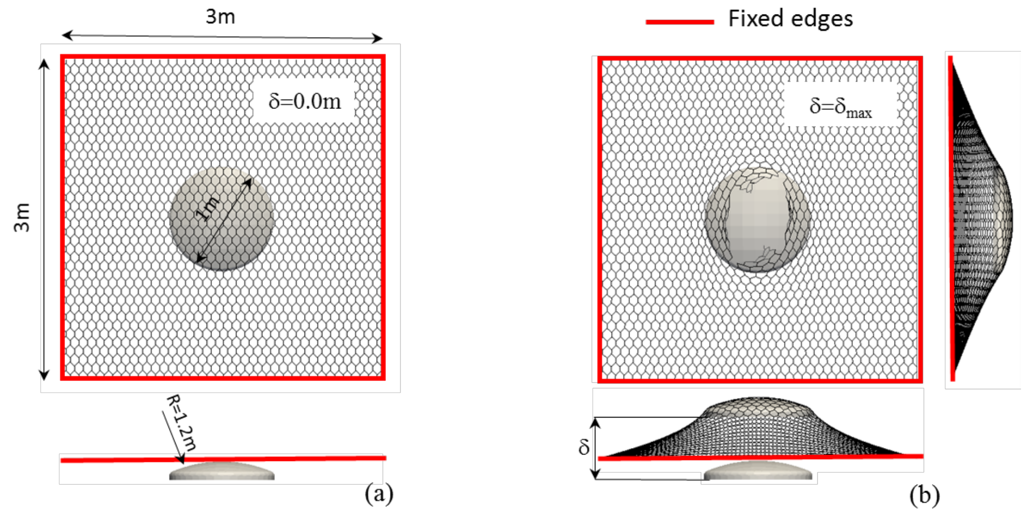
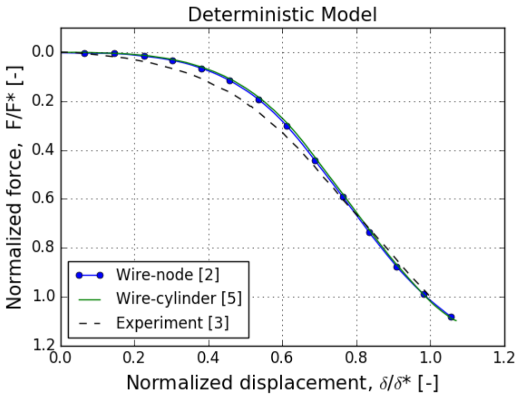
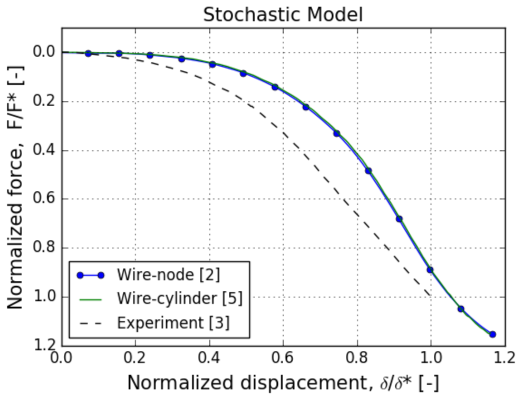


Figure 6: Snapshots of punch test geometry (a) at the beginning of the test and (b) at failure.



(a)



(b)

Figure 7: Comparison of wire-node approach and wire-cylinder approach with reference to the punch test using (a) a deterministic model and (b) a stochastically distorted model after calibration.

Differently from the tensile test, the deterministic and the stochastic models provide approximately the same results: this is also confirmed by the low values of the stochastic parameter λ_u after calibration ($\lambda_u = 0.02$). Moreover, as in the previous test the two approaches resulted approximately equal with small differences which are probably due to the intrinsic randomness linked with the stochastic model and also to the emergence of slightly shifted contact positions and directions.

5 TIMING PERFORMANCE

With regards to the computational performance of the two approaches we compared the computational time of a representative time window of the punch test in the same conditions: same velocity of the punching element, fixed time step $dt = 1.3\text{x}10^{-6}$ s and equal number of time steps.

Figure 8 reports the results of these tests underlining the computational cost of each phase of the DEM algorithm. From the figure we note that the importance, in terms of relative computational time, of the different phases of the DEM algorithm is roughly the same for the two considered approaches. Only a slightly higher influence of the contact detection phase is notable in the wire-cylinder approach than in the other case. Besides that, the total time requests for the computation with the wire-cylinder approach is approximatively equal to 4.5 times the one for the wire-node approach (respectively 1223 s and 266 s).

It is interesting now to focus on the ratio of total time to the total number of bodies. The upper histogram in Figure 8 shows that the computational cost, with reference to the number of bodies, for the wire-cylinder approach (#bodies = 9197) is approximatively equal to 2 times the one required using the wire-node approach (#bodies = 3584). Therefore, the computational time required using the wire-cylinder approach is controlled by the greater number of bodies, as well as by the higher computational complexity of the contact detection (‘SortCollider’) and forces calculation phases (‘InteractionLoop’).

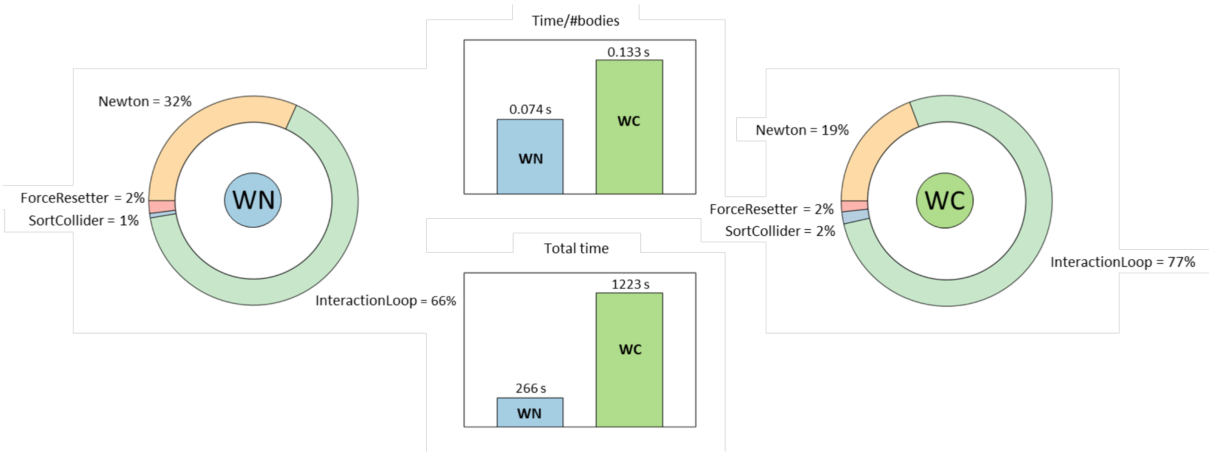


Figure 8: Comparison of (a) wire-node approach (WN) and (b) wire-cylinder approach (WC) with reference to a punch test in terms of computational time. The different phases of the DEM algorithm are split.

6 CONCLUSIONS

In this work the discrete element method has been proved to be an excellent tool to describe the mechanical behavior of wire meshes in quasi-static loading conditions. The good agreement of numerical and experimental results also confirms the potentials of this method for the characterization of the behavior of the mesh in contact with large bodies.

Both the wire-cylinder approach and the wire-node approach applied to the wire mesh representations are proved to be broadly equivalent in terms of the overall mechanical response for what concern tensile and punch tests, with small discrepancies due to the different contact position and direction using the two methods and also to the intrinsic randomness connected with the stochastic model.

The differences in terms of number of bodies to be stored as well as the treatment of contact detection and contact dynamics lead to a higher computational cost of the wire-cylinder approach. The latter appears more suitable to handle the details of realistic contacts with small elements or angular particles especially in mesh-soil embedded conditions, whereas to study problems where the wire mesh interacts with large bodies or without external bodies (as in the tensile test) the wire-node approach allows to obtain a good approximation of the real response with much lower computational costs.

Further investigations are required to study the effect of other parameters like contact friction, and twisting and bending stiffness of the wires with the wire-cylinder approach.

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