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Mesh sensitivity in discrete element simulation of flexible protection structures

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Abstract

The Discrete Element Method (DEM) has been employed in recent years to simulate flexible protection structures undergoing dynamic loading due to its inherent aptitude for dealing with inertial effects and large deformations [1]. The individual structural elements are discretized with an arbitrary number of discrete elements, connected by spring-like remote interactions. In this work, we implement this approach using the parallel bond contact model [2] and compare the numerical results at different discretization intervals with the analytical solutions of classical beam theory. Successively, we use the same model to simulate the punching test of a steel wire mesh and quantify the influence of a different number of elements on the macroscopic response.
Key words: *Mesh sensitivity; Discrete Element Method; Remote Interactions, Flexible protection system*

1. Introduction

Flexible structures are the most widespread and economical passive protection measure against natural hazards such as rockfalls, avalanches and debris flows. These systems are essentially composed by a steel mesh attached to fence posts, with strand ropes transmitting the impact force to the anchorage. In recent years, numerical models have been developed to aid their development and optimization, by reducing the required number of expensive field tests [3] and enabling the investigation of complex loading conditions, that can be difficult to reproduce experimentally [4]. For efficiency, the mesh panel is typically simulated using a multi-scale approach, in which the local scale response (i.e. elasto-plasticity) is implemented into structural elements such as truss beams, which constitute the mesh [5]. The Discrete Element Method (DEM) [6] has the advantage of efficiently solve the required set of problems, such as large deformations, inertial effects and contact interactions [7], [8] . Additionally, DEM allows the simulation of both the natural hazard and the barrier inside the same framework (i.e. debris flows [9]). The desired small-scale behaviour is introduced in the remote contact interaction between two DEM particles [1]. Typically, the contact behaviour follows the truss [10] or beam [11] formulation, whereas wires are constituted by a series of connected particles [12]. Although multiple approaches exist to improve the *external* contact detection (i.e. between wires and particles, see [13]), the necessary spatial discretization (i.e. the number of beams in a wire) to obtain the correct wire *internal* behaviour is typically not investigated.

The behaviour of steel wires is equivalent to that of a thin beam. Therefore, we investigate the mesh discretization effects by comparing the analytical solution for Bernoulli beams [14] with numerical DEM results. Successively, the same mesh resolution analysis procedure is carried out for the quasi-static response of a strand-rope mesh to punch tests. Since strand ropes are significantly less stiff than steel beams, for simplicity the DEM bond bending stiffness is set to a fraction of that required to simulate cylindrical beams of equivalent section area, following the sensitivity analysis presented in [15]. Finally, the response of a double-twisted mesh, represented with the remote contact bond approach [10] is compared at different discretization intervals.

2. Numerical setup

For the analytical model, a two meters long, 10 cm thick cylindrical beam is employed. The Young modulus is set to 200 GPa and the Poisson ratio is 0.3. For tensile and compressive tests, one end of the beam is clamped (encastré), while the other end is loaded with a constant compressive/tensile force of 10 kN. The same boundaries and load magnitudes are employed in the tip-load bending test. For the three-point bending test, both ends are subject to a constant bending moment of 10kNm, in opposite directions. Since the test is quasi-static, a local damping coefficient of 0.8 is applied to the DEM elements to lower the residual inertial effects and decrease the simulation time. A sensitivity analysis (not reported here for brevity) has been carried out and the damping parameter does not appear to affect the results. All tests are carried out with force-control and cycled until equilibrium (the ratio of unbalanced to balanced forces is lower than 1e-4). The beam discretization is carried out with 2, 3, 5, 7, 11 and 15 DEM spherical elements, also referred to as particles.

The square mesh punch test is carried out on a 3x3 meters mesh panel, with a square pattern of 30 cm side, constituted of 1 cm thick strand rope. The ratio between bending stiffness and that of an equivalent section beam is set to 0.01. The same material parameters of the analytical beam test are employed. Each mesh square side is discretized with the same number of particles as the beam tests. No material plasticity is introduced in the square mesh following [15], [16]. On the other hand, for the double-twisted mesh, a 3x3 meters mesh panel is employed, with a wire thickness of 2.7 mm, hexagon size of 100x80 mm (see Figure 2b) and the elasto-plastic hardening model of [10] is adopted. Three tests are carried out, one in which the wire is discretized with three particles and possesses the bending stiffness of a beam of equivalent section (Study 1), one in which it is discretized with two particles and presents zero bending stiffness (Study 2), following [10] and the last one in which the wire is discretized with two particles and the bond possess the beam-equivalent bending stiffness (Study 3).

For the punch tests, more details can be found in [15]. All simulations were carried out using the software PFC3D 6.0 [17].

3. Results

The numerical results for the different loading tests of a steel beam are listed in Table 1. The error is calculated from the displacement of the loaded particle, following Bernoulli's theory for thin beams [14]. No difference was found in the results of compressive and tensile uniaxial tests. The most significant result is the large error encountered for the 2 balls tip loading bending test. This is because the beam bending response is implemented through a roto-translation of the bond, which, being a line between two points, can only change in length. The same is valid for cylinder-based models. Therefore, the numerical error of the bond rotation is magnified at the other end of the beam, resulting in a large error. While it is not possible to compute the displacement of the beam center in the 2-balls model for the three-point bending test, we expect that the error would be much lower than the one for the tip-load bending, due to the change in contact branch length. We explain the increase in error with the number of balls for the tip-load bending test with the simulation setup: since the DEM formulation is dynamic, once force is applied to the beam end, it starts oscillating until the local damping reduces the unbalanced energy (i.e. inertial effects) below the prescribed threshold. Increasing the number of particles, the number of oscillating beams increases, and an additional damping effect is introduced by the sum of these out-of-phase signals. This causes the model to reach the energy threshold for a lower number of iterations, obtaining a less accurate solution (see Figure 1). The same phenomenon is also observed in the other tests (Figure 1b), but with less influence on the results (i.e. it is hidden by the greater accuracy inherent to the larger number of particles) as the system is less prone to oscillation due to the different boundary conditions.

Table 1: Relative error of the numerical results in comparison to the analytical solution.

	ERROR (%)					
Number of particles	2	3	5	7	11	15
Uniaxial loading	3.80E-09	1.41E-10	9.90E-11	2.28E-11	1.73E-11	2.20E-11
Tip load bending	24.88	0.765	1.18	1.26	1.31	1.32
Three-point bending	/	1.46	1.46	0.588	0.144	0.0213

Regarding the square-mesh punch test (Figure 2a), the 2 particles discretization simulation shows a significantly stiffer response, consistent with the results obtained for the beam bending tests. N significant difference in the results is observed starting from the three-particles wire onwards, except for the initial portion of the curve, where an increase in the number of particles causes the cone-wire contact detection to happen at lower displacement values. We assume this to be caused by the choice of simulating the wire with spheres and it could be overcome by transitioning into a cylinder-based beam representation [13]. Finally, the results for the double-twist mesh punch-test (Figure 2b) show a similar trend, with the 2-balls hexagon contact (Study 3) exhibiting a stiffer response. For most of the tests the difference between the force-displacement curves for a 3-balls beam and a 2-balls beam with no bending stiffness (Study 1 and 2, respectively) appears to be minimal, as the wires still behave mostly in tension. Toward the end, when the out of plane component becomes significant, the stiffness of the 3-balls beam model increases, following the same trend as study 3.

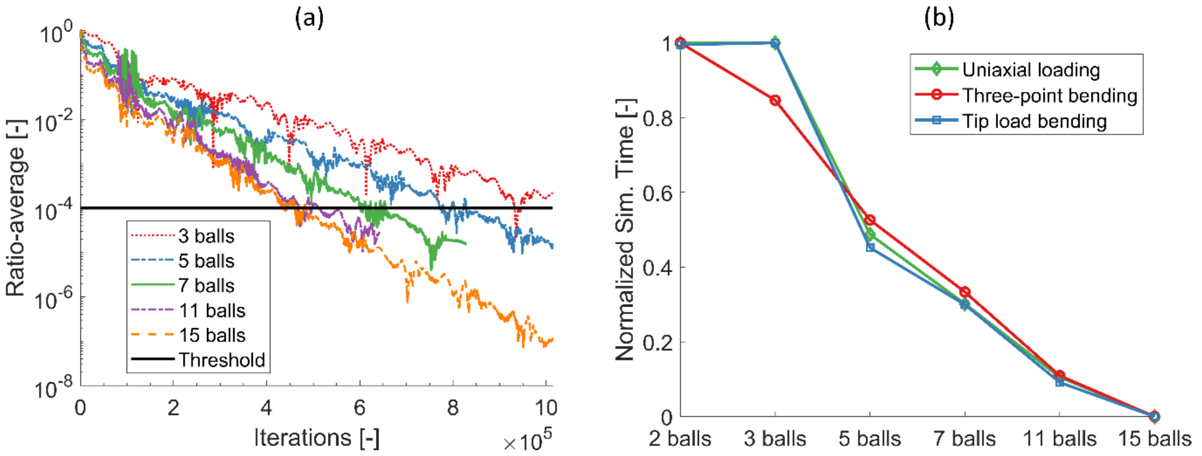

Figure 1: a) Evolution of the ratio of unbalanced forces (i.e. inertial) to balanced forces in the systems for different spatial discretization. b) Decrease in simulation time with the number of elements. Time is normalized by the minimum and maximum simulation times for the test type (roughly 1.5e4 and 3.5e4 seconds).

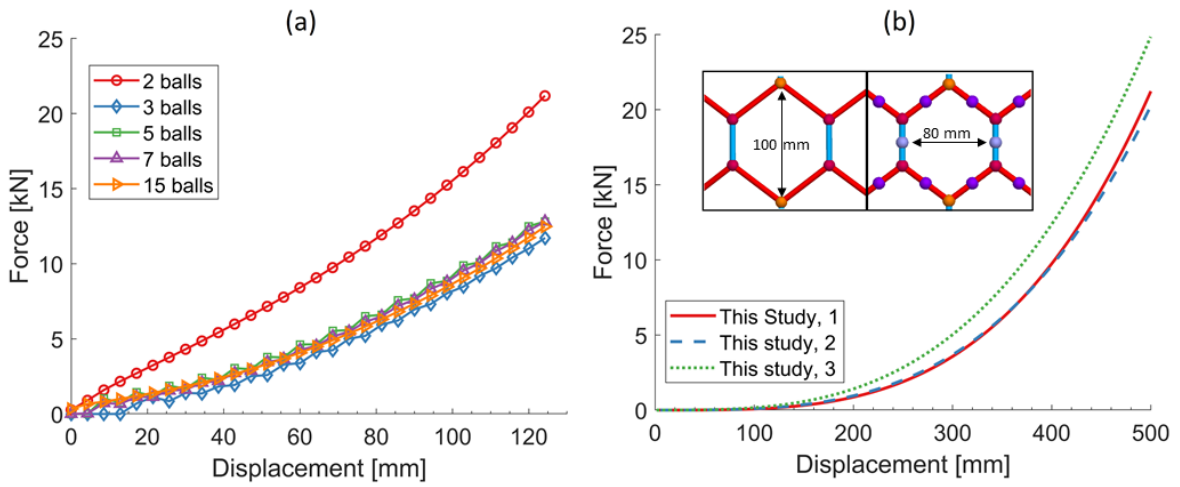

Figure 2: a) Force-displacement curves for the cone punch-test on the square mesh. b) Force-displacement curves for the platter punch-test on the double-twist hexagonal mesh. The 2 and 3 particles wire models are shown in the hexagons sketch.

4. Conclusions

A series of mesh sensitivity analyses for the response of a system of bonded DEM particles and compared were carried out and the numerical results with the corresponding analytical solution, with overall good fitting and positive correlation between the number of particles and the model accuracy. A potential pitfall of this type of DEM analysis is shown, in which the mesh resolution-accuracy relation appears to change trend due to assumptions employed to obtain quasi-static results. The two balls models showed a significant error in the comparison with the analytical results, as the fixed conditions on the first ball make the system prone to rounding errors magnification. The flaw propagates to the macro-scale response, where 2-partilce systems exhibited a significant stiffer behaviour compared to 3-particle systems. The requirement of a third particle for the discretization of bending beams is a criterium which is ignored in literature, where two-particles are typically used for beams of non-zero bending stiffness [18][13]. As shown herein, this causes a non-physical stiffer response under quasi-tensile loading conditions. No significant variation is shown for tensile conditions and in that case a 2-particles model with no bending stiffness should be adopted instead, as done by [10].

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