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DISCRETE ELEMENT MODEL OF CEMENT-BASED MATERIALS BY ADDITIVE MANUFACTURING

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Abstract *The aim of the paper is the simulation of cement-based materials by the discrete element method (DEM) and its application to 3D printing, also known as additive manufacturing. DEM is a way of simulating discrete matter and it captures the dual nature of granular media which behaves both like a solid and a fluid.*

DEM is a very useful tool for the study of the mechanical properties of granular materials, such as compressive strength or wear. Numerical modelling of granular materials can be used to study the microscopic behaviour of rocks and similar materials (such as concretes, ceramic materials and different composite materials). These materials can be simulated as particles with an interaction of bonding between them.

Previous work of the research group has employed discrete element methodology to study the wear behaviour of concrete. The numerical analysis will allow us to study innovative multilayer components of cement-based materials. The flexural behaviour of multilayer components will be simulated. These components are the object of the multidisciplinary research project in which additive manufacturing of structural components using cement-based materials is studied.

1. INTRODUCTION

The construction industry has evolved over time, introducing improvements, developments and innovations in its production processes to meet the needs of the times. Advanced manufacturing technologies based on 3D printing (processes) are increasingly present in all industry sectors because of freedom of design, cost reduction, minimization of material usage, reduction of time-to-market and production flexibility.

In this manuscript a research project that integrates 3D printing with the construction industry is presented. The three main points to consider are the additive manufacturing equipment (of large dimensions), the advanced materials for this technology and the production process, optimized in terms of material usage and production times. The additive manufacturing equipment includes various elements, such as the print heads for cement-based materials, the system designed to deposit reinforcement elements, the mixing and pump system and the control system. These elements are shown in Figure 1.

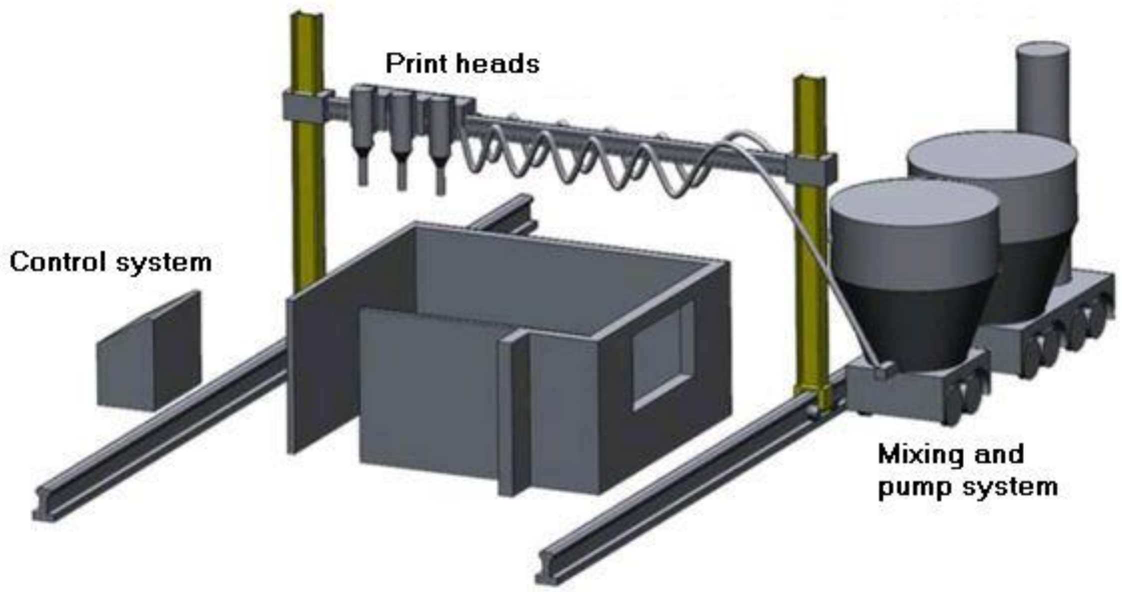

Figure 1. Additive manufacturing equipment

The material used for 3D printing technology is cement-based. Among its properties, this material must be self-supporting so that, in its fresh state, it can resist the weight of the layers that will be deposited successively. A key point of this material is its rheology and fresh state behavior in relation to its application to 3D printing technology. In addition, this material must have a suitable finish as well as high mechanical strength.

The discrete element method (DEM) is able to simulate the movement and the interaction of a large number of particles found in granular materials [1]. The calculations alternate between the application of Newton's second law with respect to the motion of particles and the force-displacement law at the contacts. Numerical modelling of granular materials can be applied to study the microscopic behavior of rocks and similar materials, such as concrete, ceramic

materials and different composite materials. These materials can be approximated by amounts of little particles bonded by different interaction models.
The aim of this paper is to simulate the behavior of hardened concrete components built by additive manufacturing under flexural load. Several authors have simulated the behavior of (hardened) concrete using DEM. Tran et al [2] presented a model based on the discrete element method able to reproduce the behavior of concrete under a high-confining pressure.

2. FINITE ELEMENT MODELLING

The finite element method (FEM) has been used to simulate the flexural behavior of multilayer components similar to those built by additive manufacturing. These numerical models have been completed using the properties obtained in the characterization of the cement-based material (compressive strength, Young's modulus and flexural strength).
The geometrical model is based on flexural strength tests according to standard UNE-EN 12390-5:2009 Testing hardened concrete – Part 5: Flexural strength of test specimens. In figure 2 a 100x100x400 mm specimen of fiber reinforced concrete is shown.

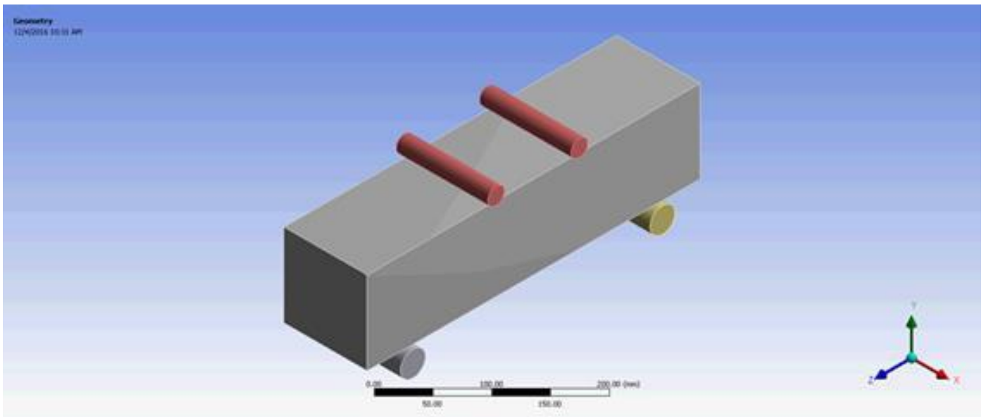

Figure 2. Geometrical model

The specimen is divided into 2 parts in order to apply the symmetry of geometry and load application. This way the calculation time is minimized. The plane of symmetry is located in the plane xy. The model is shown in figure 3. The contacts between the specimen and the cylindrical bodies and between the specimen and the load cylinders are bonded. The displacement applied in 3 steps to the load cylinders will produce reactions at the supports which are equivalent to the applied force in the tests.

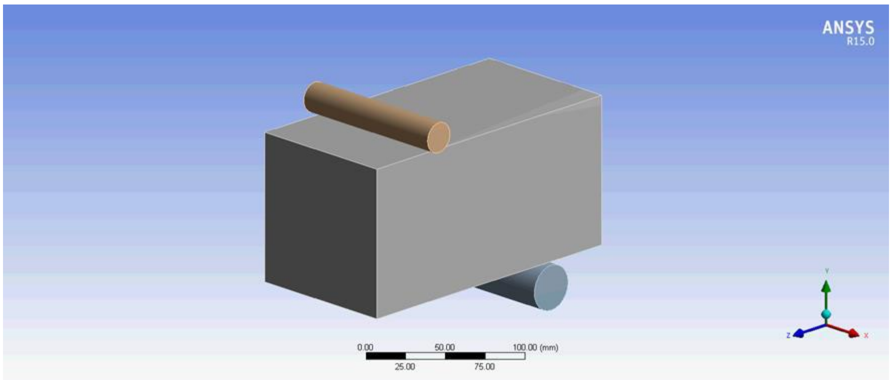

Figure 3. Geometrical model applying symmetry

To model multilayer components, the specimen is now divided into 2 parts so that 2 concrete elements are joined horizontally, as shown in figure 4. In this case the contact between faces is frictional, with a friction coefficient of 0.85. Structural nonlinearity is introduced in the model.

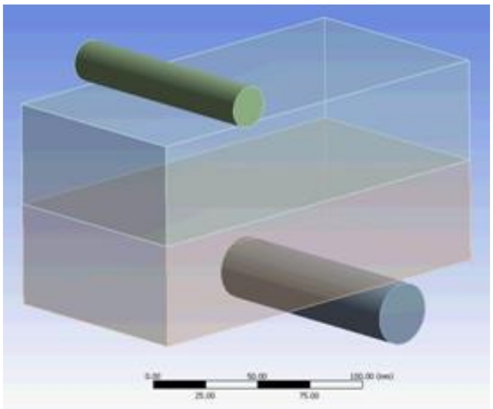

Figure 4. Multilayer model

The results show that the neutral axis is not in the middle of the specimen, but it is moved to the middle of both upper and lower elements. The maximum stress in the lower part of the symmetry face is approximately 1.79 MPa. The vertical displacement of the lower edge of the face of symmetry is 1.69 mm for a force of 9340 N. All these values are similar to those obtained in the laboratory tests.

3. DISCRETE ELEMENT MODELLING

The discrete element method (DEM) is designed to solve problems that include significant discontinuities both in the material behavior and geometrical. This method models the media as an assembly of individual elements that, in addition to their own deformation response, interact (by a contact model) to simulate the same response as the media.
The selected contact model to simulate the mechanical behavior of cement-based materials is the bonded-particle model (referred to hereafter as BPM), which is based on work by

Potyondy and Cundall [3]. The BPM simulates the behavior of a collection of aggregates joined by cement. The five parameters that define a parallel bond are: normal and shear stiffness per unit area (k_n and k_s), normal and shear strengths (σ_c and σ_c), and bonded disk radius ($\bar{R}$).

This numerical model based on the discrete element method (DEM) is proposed to simulate the behavior of hardened concrete built by additive manufacturing under flexural load. Additive manufacturing consists in depositing layers of material, in this case of cement-based, to obtain the desired form. The simulation must reproduce the test process to compare the model with the laboratory tests. The geometry of the simulation is comprised of a 100 mmx100 mmx400 mm specimen and 4 cylindrical bodies of 25 mm in diameter, 2 of them can move (upper supports). The simulation process in the DEM software is divided into the following steps:

1. At time 0 s, a 100 mmx100 mmx400 mm assembly of particles is generated following a cubic structure to simulate the 3D printing technology, shown in figure 5.

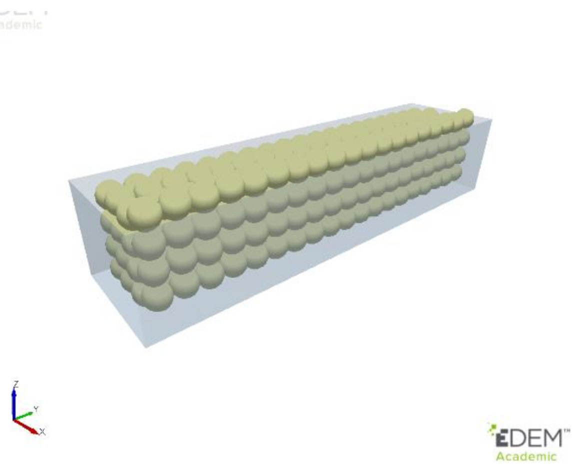

Figure 5. Step 1 of the simulation

2. At time 0.85 s, parallel bonds (in blue) are installed between all particles (all directions), shown in figure 6.

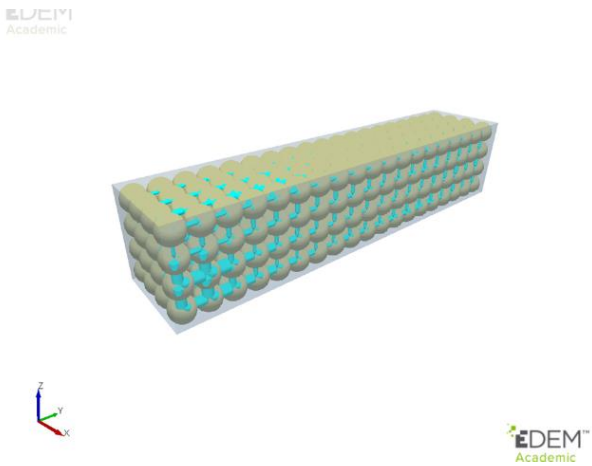

Figure 6. Step 2 of the simulation

3. At time 1 s, the lower cylindrical supports are created and the specimen is placed on them by gravity, shown in figure 7.

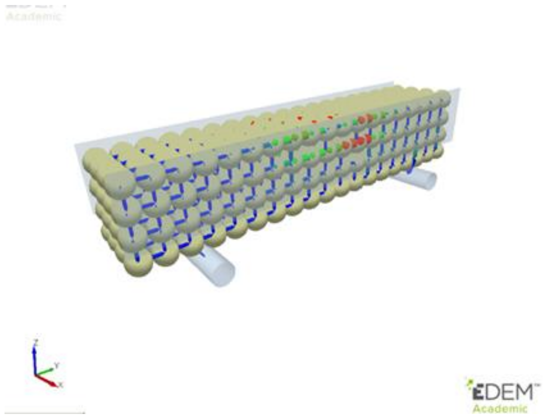

Figure 7. Step 3 of the simulation

4. At time 1.25 s, the upper cylindrical supports are created and a linear movement is applied to them in order to come into contact with the specimen, shown in figure 8.

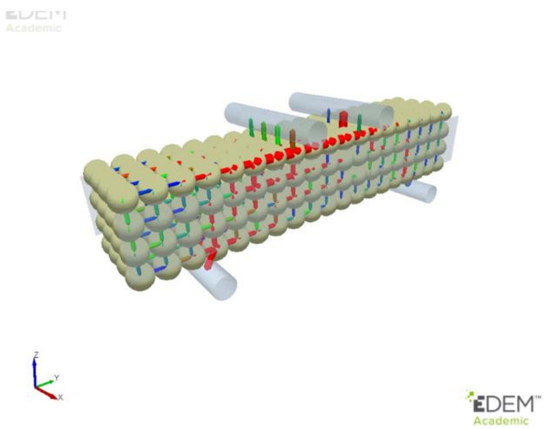

Figure 8. Step 4 of the simulation

4. CONCLUSIONS

The present article proves that the finite element method (FEM) and the discrete element method (DEM) can be applied to efficiently simulate the behaviour of concrete fabricated by additive manufacturing:

- The numerical results of the finite element model are similar to those obtained in the laboratory tests and the numerical model simulates the behaviour of multilayer components.
- The discrete element model simulates the qualitative behaviour of multilayer components with high accuracy in comparison to laboratory tests This methodology offers reliable numerical models to predict the behaviour of concrete under flexural load.

REFERENCES

[1] P. A. Cundall, O.D.L. Strack, A discrete numerical model for granular assemblies. Geotechnique, vol. 29, pp. 47-65, 1979

[2] V.T. Tran, F. V. Donzé and P. Marin. A discrete element model of concrete under high triaxial loading. Cement & Concrete Composites 33 (2010) 936-948

[3] Potyondy D. O. and Cundall P. A. A bonded-particle model for rock, International Journal of Rock Mechanics and Mining Sciences, 41, 1329-1364 (2004)