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IMPACTS ON CONCRETE STRUCTURES: FROM THE LOCAL ANALYSIS TO THE STRUCTURAL BEHAVIOR

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1 INTRODUCTION

This paper proposes the use of the Discrete Element Method[1] (DEM), which is an alternative to continuum-type methods to study concrete structures submitted to impacts. This method does not rely upon any assumption about where and how a crack or several cracks occur and propagate, as the medium is naturally discontinuous and is very well adapted to dynamic problems. Nevertheless, when one uses a DEM model, one has to address the issue of the modeling scale : the DEM is of course particularly adapted to the modeling of granular material[1,2] in which case one element represents one grain. Numerous authors have also used the DEM to simulate cohesive geomaterials like concrete, at the scale of the heterogeneity[3]. This approach allows a better understanding of concrete fracture, but of course makes real structures modeling impossible, as the computation cost becomes "gigantic". Another approach consists in using a higher scale model, which considers that the whole assembly of elements must reproduce the macroscopic behavior of concrete. Thus some authors[4,5] have simulated impacts on concrete structures, but usually, the model parameters are identified directly on the impact tests, and the different components of the model are not validated through more simple tests.

This paper aims at showing how an impact on a real 3D reinforced concrete structure has been simulated with a DE model, and at showing the quantitative comparison with experimental results. Before this last step was possible, the model had to go through a validation process. Firstly, the model has been validated through quasi-static and dynamical uniaxial tests, which allowed the definition of a parameter identification process[6]. Thus, the modeling scale imposed by the available computing power is controlled, and the simulations are real predictive computations. Last before the simulation of real structures, the introduction of the reinforcement has been validated through the simulation of beam bending tests. This paper will briefly describe the model and will present the structure impact results.

2 DEM MODEL

The present numerical model has been implemented within the SDEC code[7]. It uses discrete spherical elements of individual radius and mass, which allows an obvious and quick computation of the contacts. The orientation distribution of these latter has to be as homogeneous as possible to model a linear, elastic, isotropic and homogeneous material, and the assembly of elements has to be as compact as possible because the non-linear behavior of concrete is more similar to a nearly non-porous medium than to a granular material. Once the assembly has been set, pairs of initially interacting discrete elements are identified. These interactions have been chosen to represent as well and as simply as possible, the elastic and cohesive nature of concrete. To do this, elastic forces with a local rupture criterion are applied between two interacting elements.

Using the constitutive equations for each interaction, the numerical model solves the equations of motion. The explicit time integration of the laws of motion will provide the new displacement and velocity for each discrete element. As time proceeds during the evolution of the system, change in the packing of discrete elements may occur and new interactions be created. One of the features of this numerical model will then be to determine the interacting neighbors of a given element. This will be achieved by defining an interaction range and identifying all elements within it which are interacting.

The interaction force F between elements may be decomposed into a normal and a shear vector F^n and F^s, which may be classically linked to the relative normal and tangential displacements through normal and tangential stiffnesses, K^n and K^s respectively. Interaction stiffnesses are not identical over the sample, but follow a certain distribution, which is another important particularity of the SDEC model. The macroscopic elastic properties, here Poisson's ratio ν, and Young's modulus E, are thus considered to be the input parameters of the model. “Macro-micro” relations are then needed to deduce the local stiffnesses from the macroscopic elastic properties and from the size of the interacting elements. Compression tests have been run with one given sample to fit these relations[6].

Before rupture: To reproduce the behavior of geomaterials like rocks and concrete, a modified Mohr-Coulomb rupture criterion is used. Finally the model is consistent with the behavior of concrete. Failure comes with the coalescence of micro-cracks in tension.

After rupture: After initial interactions have broken, new ones are identified, which are not cohesive any more: they are merely “contact” interactions, and cannot undergo any tension force. Then a classical Coulomb criterion is used. It is to be noted that the model is enriched with a local softening so the obtained macroscopic fracture energy can be controlled.

Local parameters identification process: The goal is the modeling of a structure, whose material and its macroscopic properties are known. The structure geometry is discretized with an assembly of discrete elements: which value is to be given to each local parameter so the set “assembly” and “parameters” is representative of the real material, taking into account the element size distribution, and the random aspect of the assembly generation ?

For this purpose, a procedure[7] has been established and is based on the simulation of quasi-static uniaxial compression/traction tests. For a large structure, it is then possible to extract a standard-sized specimen, and to run the procedure on it. Thus, the expected properties are obtained. The model has been completed with a local strain rate dependency that was identified by means of simulations of Split Hopkinson Pressure Bar (SPHB) tests in tension[8] and compression[9]. This dependency is based on the CEB formulation[10], the model is modified so that the local tensile strength depends on the strain rate.

Introduction of the reinforcement: The reinforcement is introduced in the model as lines of elements placed next to each other. The diameter of the elements is that of the real reinforcement and the local behavior is considered as elastic, perfectly plastic. Thus, the local parameters may be easily identified through the simulation of a tension test on the line of elements alone.

3 SIMULATION OF IMPACTS ON A REINFORCED CONCRETE STRUCTURE

The structure of concern is a rockshed protecting public roads. These structures are conventionally composed of RC sub-structural elements and a roof slab covered by a thick backfilling layer: the structure is not designed to resist the impact of blocks but only to support the backfilling layer. This solution has the main disadvantage of producing over dimensioned reinforced concrete elements. For the purpose of finding an optimal solution, a new system was proposed by the consulting company TONELLO IC, which consists in a roof slab pin supported (no continuity) on the sub-structural elements. The roof slab is subjected to the direct impact of falling rocks and slab reactions are transmitted to the sub-structures throughout ductile steel supports that act as dissipating energy fuses and protect the sub-structural elements. Experiments were carried out on a one third reduced scale model in order to evaluate the response and the performances of this new system. The experiments consisted in dropping a concrete block from a crane above the experimental slab[11]. Three impacts were carried out: the first and the second from *15* and *30 m* high in the inner part of the slab and the third from 30m on the edge of the slab (above the support line).

The reinforcement is identical to the experimental one. Local parameters are identified with the quasi-static procedure already defined: fundamental uniaxial tests are simulated on a numerical sample extracted from the slab (Figure 1) so the expected concrete properties are obtained. Finally, 221000 elements were used for this computation (the simulation of 0.01s real time demands roughly 10h on a P IV 2.8GHz).

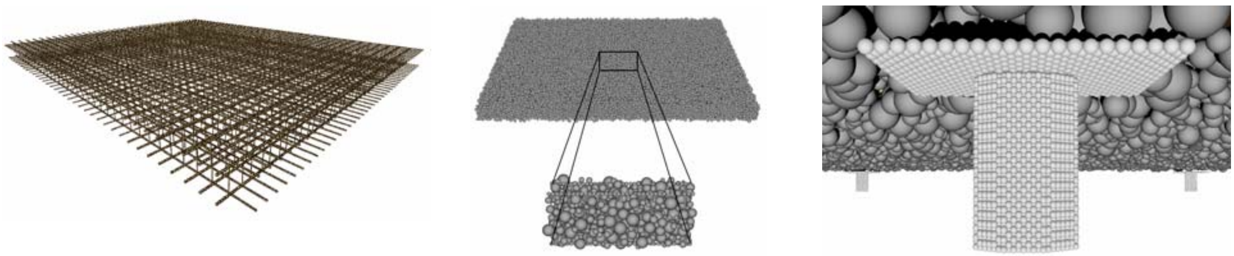

Figure 1: DEM model for reinforcement (left), the concrete slab (center) and the fuses (right)

The block is initially placed just above the slab surface, with the initial velocity corresponding to its free fall (Figure 2). Displacements were measured on the under-surface of the slab. Table 2 summarizes the results obtained with the simulation of the three tests, and compares the maximum displacement obtained, and the yielding of both reinforcement and fuses. These results are very satisfying, and in particular, the relative errors concerning the maximum displacements range from to *5* to *8 %*.

4 CONCLUSION

In this work, three rock-fall tests were simulated with this model, from different heights and at different positions, on a RC slab at a real scale. Results were compared with experimental results: Qualitatively, kinematics, damage, and fuses deformation are very coherent with respect to experimental results. Moreover, quantitatively, maximum deflections are very close to the experimental results. This fact in particular is very satisfying, and confirms that this approach may be used as a predictive tool for the design of structures.

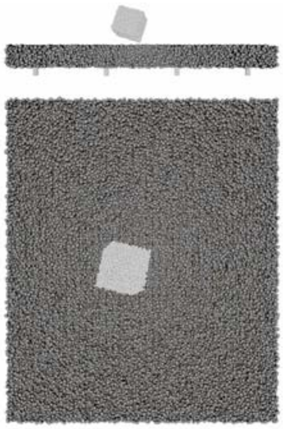

Figure 2: The numerical setup

Test	Experiment	Simulation
Centered *30 m* high	Max. displ.: *22,5 mm* No fuse buckling Yielding of vertical frames	Max. displ.: *21.4 mm* No fuse buckling Yielding of reinforcement
Centered *15 m* high	Max. displ.: *14,5 mm* No fuse buckling No horizontal reinforcement yielding	Max. displ.: *13,9 mm* No fuse buckling No reinforcement yielding
30 m high on the edge	Max. displ.: *21,5 mm* Buckling of three fuses No horizontal reinforcement yielding, no information on vertical frames	Max. displ.: *19,9 mm* Buckling of four fuses Reinforcement yielding

Table 1: Comparison of numerical and experimental results

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