Philippe Block · Jan Knippers
Niloy J. Mitra · Wenping Wang *Editors*

Advances in Architectural Geometry 2014

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Preface

Architectural geometry lies at the core of the architectural design process, playing important roles from the initial form finding to the final construction phase. Its multi-disciplinary nature provides a world stage for dialogues between architecture practitioners, engineers, geometers, and computer scientists, as testified by the multitude of innovative solutions and new challenges arising from this fruitful exchange.

We are pleased to bring the fourth edition of the *Advances in Architectural Geometry 2014* (AAG'14) to London, arguably the epicentre of architectural geometry with an immense density of advanced and prolific architecture, engineering practices, design firms, and universities that push development in this exciting field.

The *Advances in Architectural Geometry 2014* is the fourth version of the conference series, which was founded under the guidance of Helmut Pottmann and colleagues in 2008. The wealth of knowledge and experience to be shared in the program at AAG'14 reflects the success of the initial purpose and wide interests across the communities of architecture design, structural engineering, computational geometry and applied geometry.

We invited widely recognized and highly distinguished experts in the field as keynote speakers. Cristiano Ceccato is responsible for the geometrical and technological development of a wide series of internationally recognized iconographic buildings of Zaha Hadid Architects and contributed to the development of rule based design processes and parametric form finding in digital design processes; Daniel Bossia, Director at AKT II and Head of the specialist team at P.art®, has both structural engineering and architecture degrees, and is an expert in computational and structural design with extensive knowledge in programming, form finding and non-linear analysis; Behrokh Khoshnevis, Professor at University of Southern California, is widely regarded as a pioneer in contour crafting that represents culmination of knowledge across robotics, motion planning, and civil engineering leading to smart robots that can possibly automate the construction of single buildings or colonies of buildings in the very near future; and finally, Mark Pauly, Professor of Computer Science at the Ecole Polytechnique Federal de Lausanne, brings us back to core studies in geometry and computational approaches to form finding.

The papers co-chairs with the help of a scientific committee have supervised and curated the scientific program of AAG'14. From a pool of 65 submissions, 24 papers have been accepted and included in the present proceedings published by Springer. In addition, 12 workshop proposals and 20+ posters have been accepted. We would like to thank all the authors, reviewers, keynote speakers, and workshop lecturers, and the attendants who have made tremendous efforts to contribute to the exciting program of AAG'14. We would especially like to thank the University College London (UCL) and the sponsors who have made this AAG financially viable. We also thank Dr. Loretta Choi for her excellent administrative support during the paper submission process, and Stephen Merchant, Dawn Bailey, and Moos Heuting from the UCL for their untiring support during the months of preparation leading to the actual conference.

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Contents

Simulation of Aggregate Structures in Architecture: Distinct-Element Modeling of Synthetic Non-convex Granulates

Karola Dierichs and Achim Menges

Abstract Aggregate Architectures are full-scale structures made from large numbers of non-convex, geometrically interlocking designed granules. They form a novel class of material systems which are in many ways directly opposed to conventional architectural assembly systems. Whereas in an assembly structure both local parts and global formation can be clearly defined, aggregates can only be observed in their behavior as a granular mass. Thus one of the core challenges in working with granulates is the development of appropriate tools of observation. Both experiments and simulations are applied and need to be used in combination with each other. In this context the paper will present the most recent development of Distinct-Element Modeling (DEM) Simulations for Aggregate Structures. Previous results have been presented in terms of the geometric principle used to compute the individual grain and its contacts. The new results shown here lay their focus on developing accurate models simulating the construction process as well as specified load cases. Initially the overall field of Aggregate Architecture will be introduced. Consequently a brief description of Distinct-Element Modeling in general and for non-convex granulates in specific will be given. The exact modeling approach for a large excavated dome structure will be introduced both in its concepts and detailed parametric settings. The results of this simulation will be discussed and areas of further developments indicated.

1 Introduction: Aggregate Architecture

Aggregate Architectures are architectural material systems consisting of large numbers of elements in loose contact, which are at the same time performing typically architectural tasks, such as defining spatial organizations, showing structural stability or modulating light transmission and thermal insulation (Dierichs and Menges 2012) (Fig. 1).

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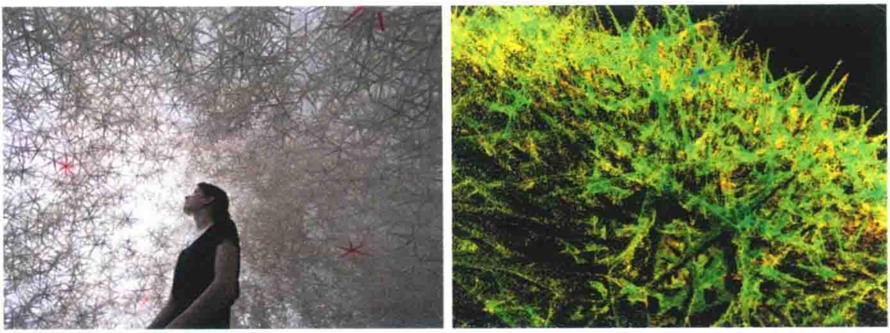

Fig. 1 Aggregate vault 2013 and 3D laser-scan of the structure (K. Dierichs, ICD, A. Scheider, IIGS)

These type of systems are termed aggregates or granulates in the field of soft matter physics (Neddermann 2005, p. 1, Jaeger et al. 1996). They are mainly known from natural systems like sand or snow (Bagnold 2005; Nicot 2004). In an architectural context they are only rarely deployed in their loose form but most commonly known as an addition in a binding concrete matrix (Hensel and Menges 2008). Yet an aggregate's capacity to fully re-cycle, form multiple stable states and be rapidly configured, makes loose granulates a very relevant field of investigation in an architectural context. Especially if the individual grain is artificially made, it can be geometrically defined and thus functionally graded in its architectural performance, mostly and in the first place with regards to structural behavior but also integrating for example light transmission or heat transfer.

Previous applications of loose granulates in an architectural context range from Building Physics (Hausladen et al. 2006), Earth Architecture (Houben and Guillaud 1994) and Geo-Engineering (Hensel and Menges 2006d; Hensel et al. 2010; Trummer 2008) to Form-finding (Gaß and Otto 1990; Hensel and Menges 2006a, b, c, d). Especially in the latter field, the notion of an unbound granulate as a structural-architectural system in its own right has been introduced. Frei Otto at the Institute for Lightweight Structures at the University of Stuttgart conducted initial tests with sand (Gaß and Otto 1990). These experiments were later taken on and further developed at the Architectural Association in Diploma Unit 4 and the Emergent Technologies and Design Program (Hensel and Menges 2006a, b, c, d). Especially the introduction of Designed Granulates presented a significant widening of the potential architectural scope of these aggregate systems (Hensel and Menges 2006b, c; Tsubaki 2011). Parallel developments can in recent years be observed in the field of Granular Physics (Athanassiadis et al. 2014; Miskin and Jaeger 2013).

One of the core challenges in designing with granular systems is the development of appropriate tools for observation and quantitative measurements. Whereas in a conventional architectural assembly system the exact geometry of both local components and global form can be exactly defined by the architect, this paradigm needs to change when one works with aggregates. Granulates require a mode of designing, where the evolving formation is merely observed and consequently interacted with (Hensel and Menges 2008; Dierichs et al. 2012). Both material experiments and mathematical simulations need to be applied for that purpose and ideally combined into a joint model using methods such as laser-scanning and hull-surfaces as a basis for comparison (Dierichs and Menges 2010; Scheider 2014).

In this context, the focus of this paper is to present recent developments in the numerical simulation of non-convex synthetic granulates. The new model shown here allows for analyzing formation and behavior under load-cases of a granular vault structure formed through an excavation process using a clump-based Distinct-Element Modeling (DEM) Simulation.

Initially the DEM method will be introduced both in the wider context of particle simulations and specifically with regards to the physical-mathematical principles it is implementing. Consequently the excavation model, its geometric basics and parametric settings will be described and the results of the simulations will be discussed. Conclusively an outlook on further developments will be given both with regards to the simulations themselves and their incorporation into the wider field of Aggregate Architectures.

2 Distinct-Element Modeling (DEM) of Non-convex Granulates

Various mathematical-numerical approaches to modeling the behaviour of granular substances have been developed (Pöschel and Schwager 2005). The two main categories are Molecular Dynamics (MD) with its sub-category the Distinct-Element Method (DEM) and Event-Driven Molecular Dynamics (ED) (Pöschel and Schwager 2005, pp. 13–30 and pp. 135–136; Luding 1994). Other approaches are Rigid-Body Dynamics (RBD), which is especially wide-spread in gaming applications, or the Distinct- Simulation Monte Carlo (DSMC) (Pöschel and Schwager 2005, pp. 191–192). Depending on the application, these approaches need to be compared to each other with regards to their suitability to solve the problem in question. ED for example uses event-based time-stepping and mainly hard collisions, whereas DEM is based on a clock-based time-stepping and allows for both hard and soft collisions (Pöschel and Schwager 2005, pp. 18–22 and pp. 135–136). DEM is specifically suited for the observation of dynamic micro-mechanical behavior, DSMC for that of the probable behavior of a granulate as a whole at rest (Lanier and Radjaï 2009; Duran 2000, pp. 202–206).

For this specific application, where large amounts of synthetic non-convex granulates need to be observed, a DEM modeling approach has been chosen, since at one point in time there is a multitude of contacts and the observation of micro-mechanical behavior is relevant (Fig. 2).

The main challenge is the fact that the particles are geometrically non-convex polyhedral, whereas the DEM simulation is initially based on the computation of spheres, which allow for a comparatively easy collision detection model based on

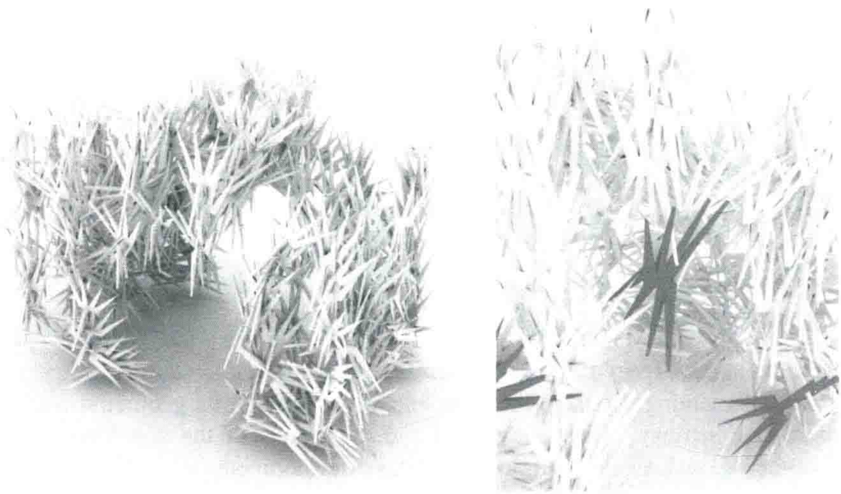

Fig. 2 Simulation of non-convex granules which are composed of convex polyhedral elements (K. Dierichs, ICD, F. Fleissner, ITM)

the spheres' centers and radii. A non-convex body by virtue of its geometry does not allow for this relatively simple model of boundary detection. Incorporating the accurate modeling of non-convex geometries and their collisions in a DEM model is thus one of the core aims of this project.

2.1 DEM

The DEM model has first been introduced by Cundall and Strack and uses the force and torques as well as the Euler's angles of the individual elements to compute the Newtonian equations of motion (Cundall 1971; Cundall and Strack 1979; Pöschel and Schwager 2005, p. 13). The class of algorithms uses the following basic sequence of approximating the differential equations according to Pöschel and Schwager The model is initialized with the particle coordinates (1), consequently the coordinates of the particles at time $t + \Delta t$ are predicted (2), then forces are computed by defining the interacting pairs and their contact forces (3), coordinates are corrected based on the previous results (4), data are extracted (5) and finally the program is terminated (6) (Pöschel and Schwager 2005, p. 28).

2.2 Clump Modeling of Non-convex Granulates

As introduced earlier, the simulation of non-convex polyhedral particles is a challenge within DEM models due to the complexity of collision detection. Two basic

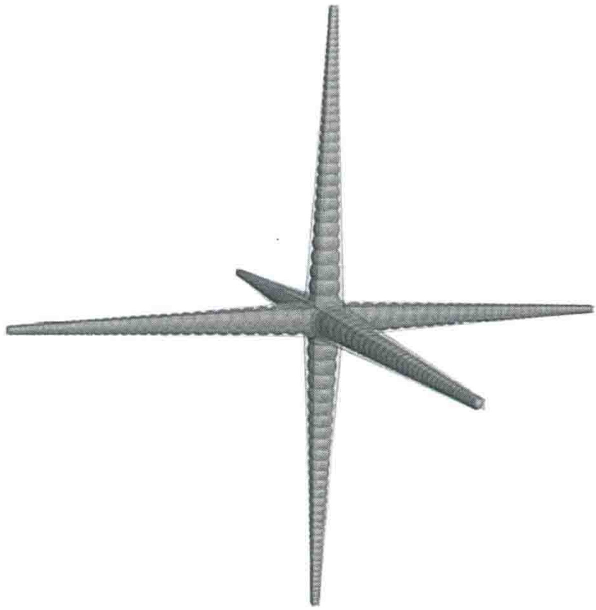

Fig. 3 Clump model of a six-armed, non-convex granulate showing the pebble distribution with 32 pebbles per arm (M. Purvance, ITASCA)

geometric modeling approaches for this problem exist and have been benchmarked (Dierichs and Menges 2013). The first one uses a so-called 'clump'-model, which means that the non-convex shape is composed of individual spheres, also called 'pebbles', which are rigidly bound to each other (Fig. 3).

The second one uses convex polyhedral or 'blocks' to compose the non-convex granule. Benchmarking has shown that for particle numbers below 1,000 the block-model is faster, yet above that critical number the speed of computation increases in the clump-model and it is actually faster than the block-based one (Dierichs and Menges 2013).

Since any of the aggregate systems which are used in this context has at least 1,000 particles, the clump-based simulation method has been chosen. The basic particle is a six-armed cumulated cube measuring 10 cm in diameter. For the purpose of the simulations presented here it has been modeled using 20 pebbles per arm, yet pebble-amount needs to be reduced if particle numbers further increase. The pebbles are references to a surface model of the polyhedral hull, such that the actual surface is used to compute the moments of inertia.

3 Methods: The Hopper- and Excavation-Model

The physical construction experiment has been conducted at a one-to-one scale: Fifty-thousand synthetically produced particles are poured into a tank with a bottom-lid measuring 2.25 m by 2.25 m by 1.35 m which is placed on a sub-construction measuring 0.75 m in height. The bottom is consequently removed, parts flow out and un-loaded material is excavated to leave a dome made of only 10 % of the entire material. The redundant parts are entirely re-usable in this process.

In order to develop a simulation of this process a hopper- and excavation-model has been set-up at a smaller scale using 1,284 particles with the bounding box measuring 600 by 600 by 850 mm. It uses a clump generate command to distribute the particles in the box. This implies that particles are generated individually and consequently their settling is computed which allows for exact computation of contacts and forces.

Material calibration values have been gathered by experiment and on that basis set to a friction coefficient of 0.58 and normal viscous damping of 0.25, the need for deformation modeling has been excluded using high-speed photography showing that energy is dissipated within the granulate (Fig. 4).

The clump template allows for setting different pebble numbers to model the arms, thus for higher numbers less pebbles can be chosen to accelerate the model at the expense of accuracy. After simulation of the excavation process, large and small planar loads are applied to the simulated dome.

The adjustable parameters of the model are thus the material friction, damping, particle surface geometry, pebble number per clump, clump number per model, the cycling, the excavation radius, as well as the size of the planar load.

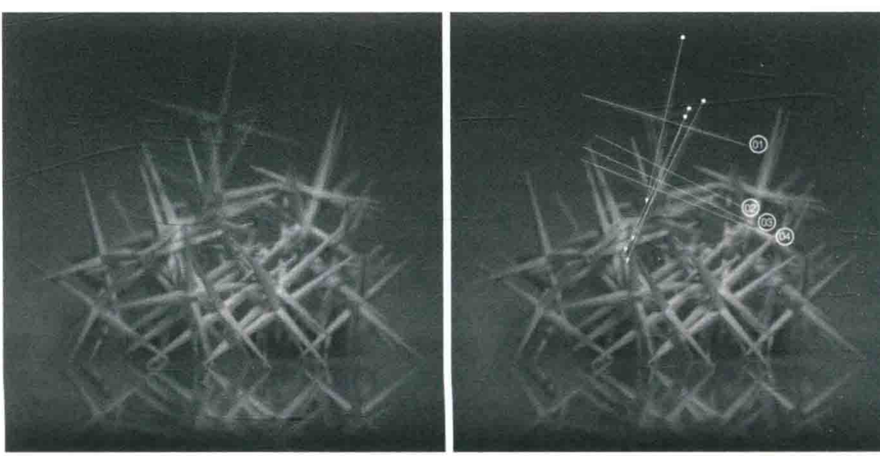

Fig. 4 High-speed analysis at 2,000 fps of a six-armed granule falling onto a pile (K. Dierichs, ICD, S. Poppinga and M. Thiele, PBMG Freiburg)

4 Results

4.1 Simulation of Hopper and Excavation

The entire sequence is split in four parts: simulation of the granular mass in the bounding box, removal of the bounding box and bottom lid, excavation of material from below and loading of the aggregate (Fig. 5).

The model is set to 510,000 fixed time-step cycles and n cycles for close packing in total. The clump generation and settling is computed using an equilibrium parameter to achieve dense packing in n numbers of cycles. The hopper and excavation are both computed for 5,000 cycles each and the planar loading is cycled for 500,000 times. With an average clump number of 1,284, pebbles are set to only 20 per arm in order to accelerate computing time. The overall model run takes an average of 120 min clock time to compute.

An analysis of the clump surface velocity shows that the granular mass comes to rest at the bottom layers first in stage 1. After removal of the lid, the structure

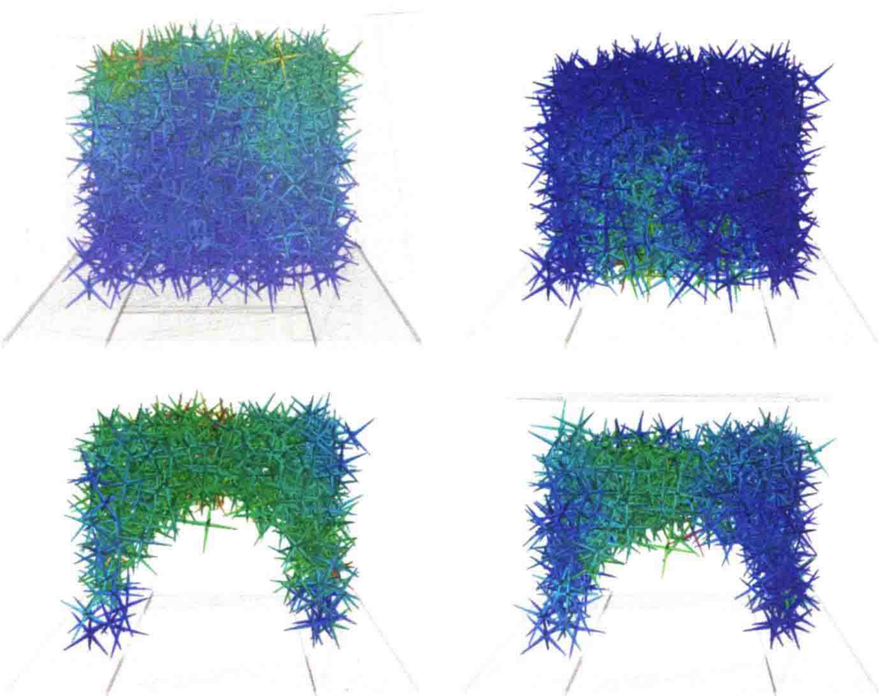

Fig. 5 Hopper- and excavation-sequence in a surface velocity plot shown in a filtered section of the entire granulate formation with the scalar ranging from *blue* indicating low speeds to *red* indicating high ones. *Top left*: simulation of the clump distribution, *top right*: removal of lid and bounding box, *bottom left*: excavation of 200 mm, *bottom right*: loading with a large planar load

is excited at the bottom of the hopper, which proliferates into the top middle layers.

After excavation the motion moves almost symmetrically throughout the entire vault-structure yet the dome does not collapse. Planar loading compresses the configuration with surface speeds remaining higher over the excavated core whereas the corner regions of the aggregate are remaining at relative rest (Fig. 5).

4.2 Load Cases and Excavation Radii

Both excavation radii and dimensions of planar loads can be varied. A set of simulations has been run that uses an excavation radius of 100 and 200 mm in combination with planar loads of 50 by 50 mm and 500 by 500 mm each weighing 30,000 g (Fig. 6). The load is simulated using a servo-control mechanism.

Excavation radius and consequent thickness of the remaining aggregate vault affect the load bearing behavior under both a large and a small planar load, with

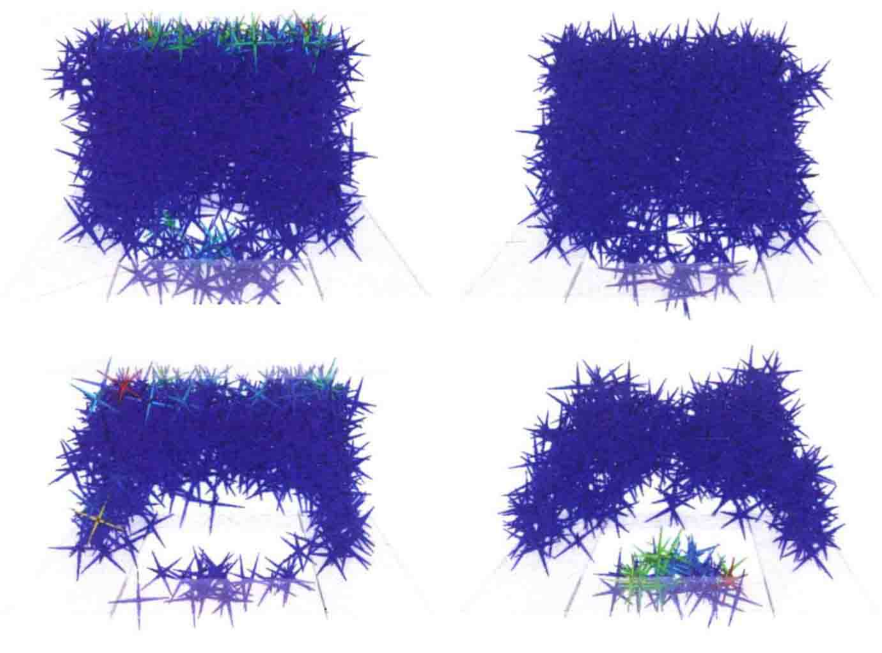

Fig. 6 Load cases and excavation radii in a surface velocity plot shown in a filtered section of the entire simulated granulate formation with the scalar ranging from blue indicating low speeds to *red* indicating high ones. *Top left*: large planar load with 100 mm excavation radius, *Bottom left*: large planar load with 200 mm excavation radius, *Top right*: small planar load with 100 mm excavation radius, *Bottom right*: small planar load with 200 mm excavation radius

thinner structures deforming stronger under the same pressure, which is an expected result.

Load dimensions lead to different effects as well. A large planar load tends to compress yet not deconstruct or deform the current formation, whereas a small planar load strongly deforms or destroys the aggregate vault. Whether or not the common notion of destruction is appropriate within the design theoretical discourse of aggregate structures as reconfigurable systems is of course to be discussed.

4.3 Statistical Simulation of Contact Forces

Contact force can give one indication of how loads are transferred in a designed granulate on a micro-mechanical level. A statistical set of 20 simulations has been run in order to understand the behavior of the six-armed granule under compression in the excavation sequence described in Sect. 4.1 (Fig. 7).

Contact forces have been measured in the centre of the supportive columns using a vector-definition to select the clump measured. Most contact force diagrams show a peak load in the early stages of cycling and consequently plateau with minor oscillations. Only a small fraction of the probes deviate from that pattern (Figs. 8 and 9).

This type of statistical testing of micro-mechanical behavior is especially relevant with regards to analyzing how a variation in particle geometry affects the structural performance of a granulate made from designed particles.

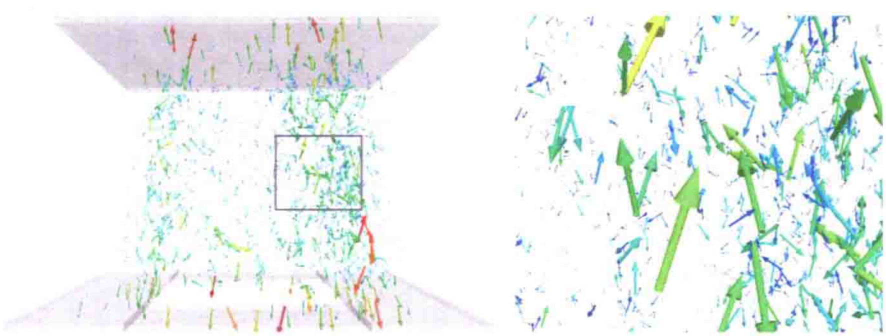

Fig. 7 Global view and detail view of contact forces in a granular probe with a large planar load after 50,000 cycles