Feedback- and Data-driven Design for Aggregate Architectures

Analyses of Data Collections for Physical and Numerical Prototypes of Designed Granular Materials

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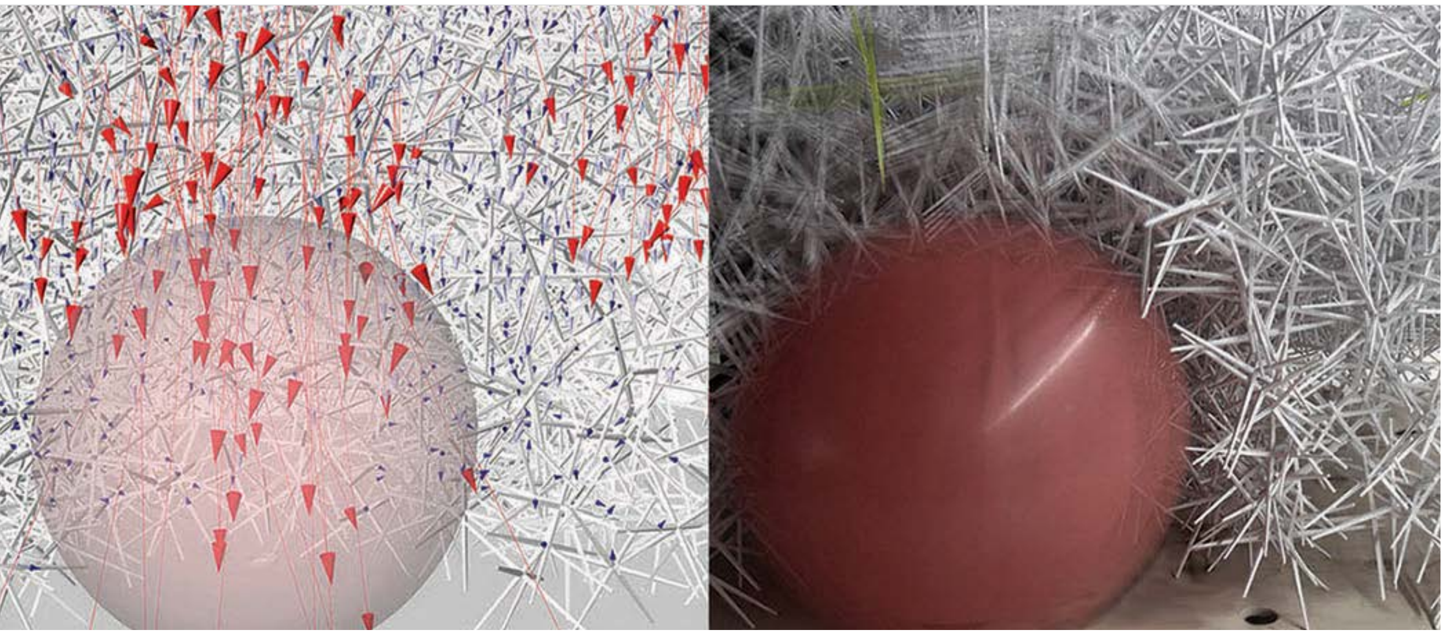

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ABSTRACT

This project contributes to the investigations in the field of aggregate architectures by linking two research areas: the numerical simulation of aggregate formations, and a concept for an online-controlled pneumatic formwork system.

This paper introduces a novel approach for constructing with designed particles based on a feedback process. The overall aim was to investigate the capacity of aggregates as an architectural material system, which create emergent spatial formations. Initially the particles´ micro-mechanical behavior and the fragile stability of the formations were analyzed using numerical simulations. Based on this, an online-controlled inflatable formwork system was developed. The formwork was designed to react to the actual stability state of an aggregate formation; for this, a statistical set of simulation data was gathered, which directly informed the physical system. This overall concept was proven and verified in a one-to-one scaled physical model.

The methods developed within this research provide a first set of baselines for comparison between the behavior of simulated and physical designed granular materials.

1 Comparison between physical and numerical prototype constructed with synthetically produced non-convex particles and using inflatable formwork system.

INTRODUCTION

Aggregate Architecture

In the context of architecture, aggregates are a material system defined as a large amount of natural or designed particles in unbound contact. Based on the ability to change their state from one of a fragile solid to one of a dry liquid, they form a separate branch in the context of material systems (Rivier and Fortin 2011; Hensel and Menges 2006a). As such, aggregates necessitate the development of a feedback-driven design approach, where the fabrication of a formation consists of iterative steps and is based on the actual state of matter. The field of designed particles offers a wide range of research topics, such as the development of observation techniques for better understanding of the material behavior (Dierichs and Menges 2010); studies about possible element shapes (Dierichs and Menges 2016; Miskin 2016; Murphy et al. 2016; Athanassiadis et al. 2014); and robotic-driven design (Angelova et al. 2015; Dierichs et al 2013).

This research project seeks to build upon research based on a previously developed material system consisting of non-convex synthetic particles. The focus is on two aspects of the material performance: first, the fragile stability (Cates et al. 1998) of aggregate formations relying on friction, and second, the self-organizational capacity of granular materials to demonstrate emergence (Wolf and Holvoet 2004).

Fragile Stability

In the context of this research, the concept of stability should not be viewed from the perspective of continuum mechanics where the behavior of materials is modeled and analyzed as a continuous mass rather than as discrete particles. This paper suggests that the principles of aggregates´ behavior are aligned with investigations in the field of soft matter physics (Jaeger et al. 1996) and more precisely with the concept of fragile matter (Cates et al. 1999), which in materials science is described as a granular matter conditionally prevented from moving. The marginal stability of the formations constructed with such matter is related to the force chain network within the material (Cates et al. 1998). In this context, one of the core questions is how fragile stability can be understood and analyzed. One approach recently published in the context of physics and nonlinear complex systems suggests to quantify stability of columns constructed with non-convex aggregates by measuring the mass of particles which drop off when a column collapses (Zhao et al. 2016). The points of stability and of collapse then become constitutive parameters of scientific material analysis; they can, however, also become active design drivers.

Therefore, this paper proposes a rather architectural strategy for using fragile stability of aggregate formations. The research project focused on investigations on the aggregates´ micro-mechanical behavior, and data collected through analyses of both numerical simulations and physical prototypes. The aim was to extract parameters that describe the marginal stability of an aggregate composition. These parameters were used as lever points to form an IF/THEN conditional statement in a complex adaptive system (CAS) (Holland 1995, 2006).

Emergence

The behavior of the aggregates as a material system can be considered fundamentally emergent, since the global shape and the state of matter of the overall aggregate formation depend on the interactions and the movement of the individual particles on a local level (Wolf and Holvoet 2004). The performance of a single aggregate is contingent on two factors: first, the environmental conditions, such as pouring methodologies, boundary conditions, and external impacts, and second, the interactions with other particles. Thus, the collective self-organizational capacity of the material system is the cause for changes in the state of the overall composition from fluid to static and backwards. This dynamic behavior predefines the ability of aggregates to exhibit emergence.

Furthermore, this paper presents the concept of an online-controlled pneumatic formwork system, whose behaviors can also be described as emergent. The logic behind the system´s performance is based on statistical series of digital simulations, where the performance of the aggregates was traced and analyzed, and clear parameters for the stable state of the digital models were established.

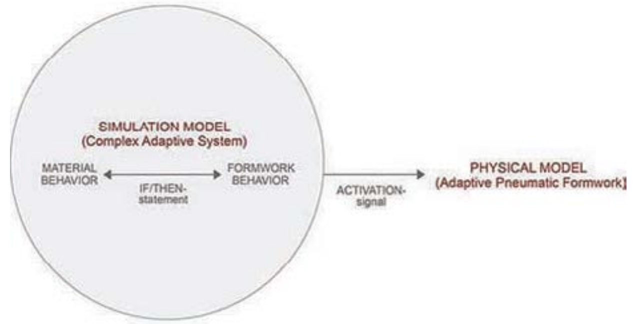
Both systems, formwork and material, worked together in a process described as a continuous feedback-loop. The behavior of one system is the cause for the performance of the other one, and vice-versa.

STATE OF THE ART

The state of the art for this project has two primary trajectories: first, experimental setups with aggregates, which focus on the implementation of formwork, and second, Discrete Element Method (DEM) simulations of discontinuous materials.

Experimental Setup

A common construction technique for small-scale experiments with designed particles is the casting of material in predefined molds. Non-convex designed particles take the shape of the confining space they are initially poured into. Moreover, because of the particle geometry and static friction, aggregate formations exhibit a stable state even after the supporting structure is removed. Thus, the concept of simple and reusable formwork is a



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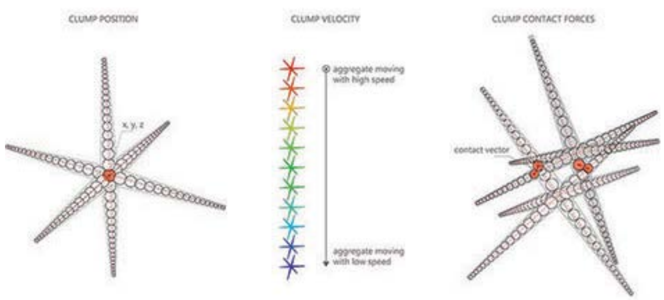

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2 Complex adaptive system and formwork activation diagram.

3 Simulation parameters - clump position, velocity and number of contact forces.

4 Analyses of simulation parameters.

5 Velocity-contact forces diagram.

key aspect of the experimental setup. In the context of architecture, such flexible systems were first proposed by Eiichi Matsuda (Hensel and Menges 2006b). In his research project, a series of experiments was conducted where aggregates were poured into cubic test containers filled with balloons. Once the balloons were deflated, a self-stabilizing process took place. A new fragile stable state of the aggregate formation was achieved, and the final result was the formation of spatial voids inside of the material. The project described within this paper also concentrated on the implementation of inflatables as a relevant experimental setup. However, the focus was shifted toward the development of a complex adaptive system (CAS) where the inflatables´ performance was synchronized with the behavior of the digitalized material system.

DEM Simulations

The DEM simulations are mathematical models for simulating the dynamic micro-mechanical behavior of large numbers of small particles. The theoretical background is based upon the laws of motion by Sir Isaac Newton. Later, several scientists, such as Cundall and Strack, created the foundations of the method when solving problems related to rock mechanics (Cundall 1971; Cundall and Strack 1979). The simulations are based on algorithms for calculating the nearest neighbor, which makes it possible to observe the interactions inside the material and the motion of each individual particle.

DEM simulations are widely used for solving engineering problems in discontinuous materials like powders, grains, rocks etc. Thus, for the purposes of this research, their implementation was included as a relevant mathematical method for numerical modeling of aggregate formations. The simulations were executed with a state of the art DEM-software. In its first part, this research used already developed algorithms for observing the behavior of non-convex particles (Dierichs and Menges 2015). Based on the statistical information gathered, the digital behavior of the adaptive pneumatic formwork system was added to the already existing algorithms. Figure 2 illustrates the design process.

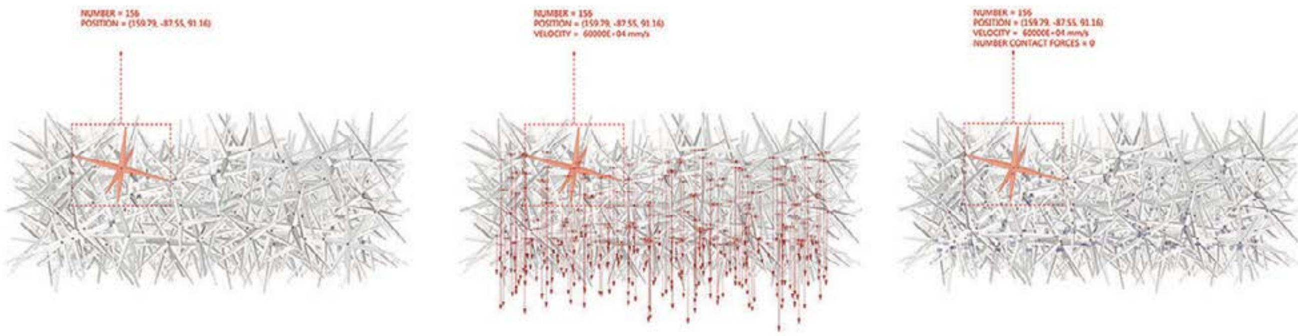
METHODS

The computational and analytical methods described in this paper demonstrate a mixture of observation techniques from both material and machine computation (Dierichs and Menges 2012). These two categories are inseparable when investigating the behavior of aggregates. The main goal was to collect information about the material system through numerical and physical prototyping. As speculated in this paper, the data gathered can be later used to inform the design process.

Machine Computation Method 01: DEM Simulations

In the DEM-software, each individual aggregate (clump) is represented by a number of bonded spheres (pebbles), which allows for time-saving calculation. A confining space is defined and a formwork mesh-geometry is imported. Aggregates are randomly distributed and gravitational force is applied to each of them, simulating their fall. The model state is time-based where series of calculations cycles are conducted. Each cycle consists of a sequence of operations finding the solution to Newton´s laws, which updates the position of the particles and consequently the next cycle is introduced (Pöschel and Schwager 2005). The calculations run until the particles find an equilibrium state. After that the formwork is removed and a second self-stabilizing process takes place until final settlement. The variables in the simulations executed are material friction, damping, particle surface geometry, pebble number per model and cycling. The calibration of the material properties for the simulations is described in an earlier publication (Dierichs and Menges 2015).

The parameters observed from the simulations were the position of each aggregate as x, y and z values; the clump velocity represented by colors ranging from red to blue indicating high to low velocity respectively; and the number of clump contact forces



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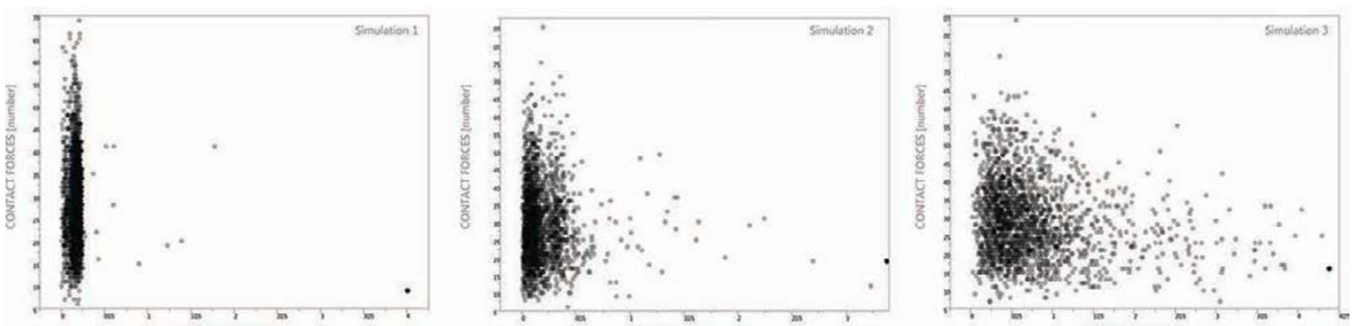

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(see Figure 3). In the context of this project, it is speculated that a simulated aggregate formation exhibits a marginal stable state when the majority of aggregates have short velocity vectors and high number of contacts with their neighbors.

Machine Computation Method 02: Analyses

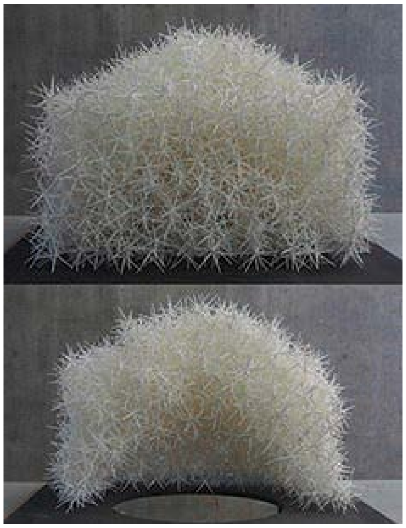
Two different software platforms were used during this research project—a 3D-modeling platform and a DEM-simulation program. A computational tool for analysis of the simulation results was developed to link them. First, the formwork mesh-structures were created and exported to the DEM-software. After the completion of the simulations, the output values were exported as *.csv-files to the 3D modeling environment where the behavior of the formations was traced and documented. Additionally, the simulated clumps with their final position and rotation in space were also imported as mesh-objects in the 3D modeling software. Figure 4 illustrates the results achieved with the tool developed.

Machine Computation Method 03: Statistical Analyses

Because of the stochastic behavior of the material system, statistical analyses are a key aspect of the observation technique. Figure 5 shows the relationship between numbers of contact forces and lengths of velocity vectors for three numerical studies of the same simulation setup. In the algorithm, a generate-function was used for defining the initial clumps' positions before they start falling. These were different for both cases, simulating the fact that in reality no aggregate composition can be built twice exactly the same way. Thus, despite the same bounding conditions for both tests, the simulation values after the same settling time were different. However, statistics enable the opportunity for estimating patterns of behavior after analyzing data sets. Therefore, large information collections of experiments were managed using a statistical software. The mean values extracted from the data formed the IF/THEN statement which activated a feedback-loop in the simulation process.

Material Computation Method 01: Physical Models

The second branch of methods used within this research is material computation. Physical models were built and the number of inflatables and their position in the confining space were varied for design and stability purposes. Two types of non-convex particles were used throughout the conduction of experiments: ten-armed with a diameter of 120 mm, and six-armed with diameter of 300 mm. The high degree of friction due to the particle geometry and the large amount of resources available were the main reason for this particular material choice. The physical prototypes built with both material systems are considered crucial to preparing the project, since they are essential to illustrating the material's behavior. Additionally, physical experiments were necessary in order to verify the reliability of the simulation and computational methods used. Figure 6 illustrates an example of a prototype built with 2500 ten-armed aggregates. The space formed after removing the inflatable remained stable even



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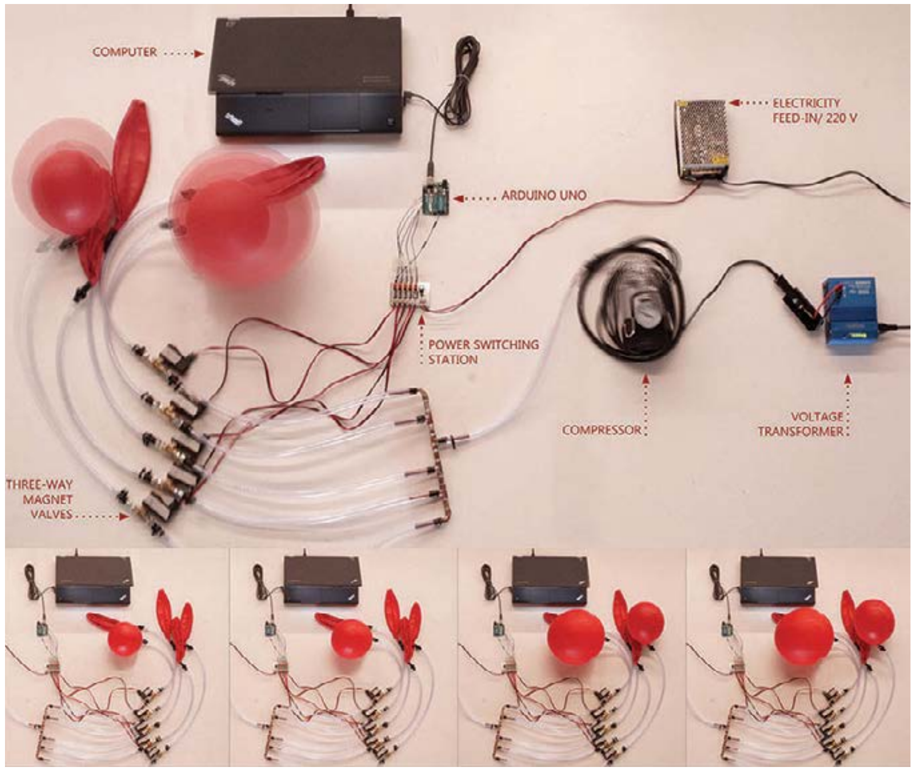

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after destroying half of the model. The stability of formations built with non-convex particles is based upon their interlocking behavior under compression forces. Therefore, enclosed spaces, for example dome-like structures are preferred for the global design of the formations. The design strategy of all experiments, including the final prototype, follows this logic.

Material Computation Method 02: Photogrammetry

A set of physical prototypes were documented using photogrammetry techniques which allowed for more precise analyses of physical models. The formations were photographed from all sides, and sets of 80 pictures for each were imported in a photogrammetry software. The program generated a dense point-cloud for each experiment with approximately one million points. A close view is illustrated in Figure 7. Each point holds the values of its x, y and z coordinates. This information was used for quantitative and numerical comparison of physical and digital prototypes.

Material and Machine Computation: Adaptive Pneumatic Formwork System

A direct connection between machine and material computation was established with the development of an adaptive pneumatic formwork system, following the concept illustrated in Figure 8. The tool was designed to be activated via computer.

The balloons were attached on the one side to plastic pipes and an electrically powered compressor that constantly pumped air in one direction, and on the other side to three-way magnetic valves. The three outputs of the valves allowed for both inflation and deflation of balloons individually. The system was controlled via an Arduino Uno board connected with a USB-cable to a computer. A power-switching station was designed for converting the 5 V output signal of the Arduino board to 12 V for each valve.

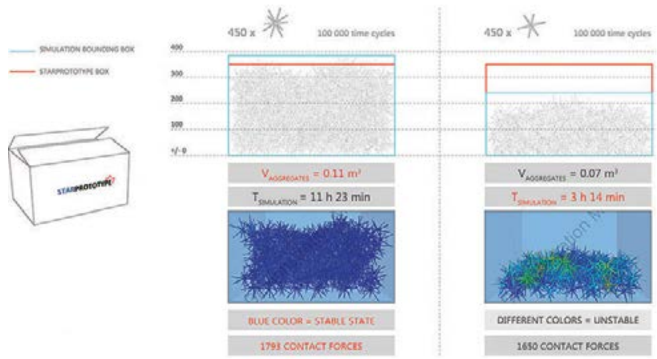
The system developed allowed for adaptation of the physical formwork based on the behavior of its digital representation during on-going simulations.

CASE STUDIES

Case Study 01: First Experiments with DEM Simulations

A series of simulation tests were needed to gain knowledge about the numerical representation of both particle-particle, and particle-formwork interactions. These first studies were of great importance for the development of further methods.

One investigation was dedicated to the comparison between two types of physical particles: six-armed and ten-armed, both with diameter of 110 mm. Four hundred and fifty particles from both material systems were separately poured in two identical boxes. The same settling cycle number was set for the two samples (see Figure 9). The first expected outcome was that the



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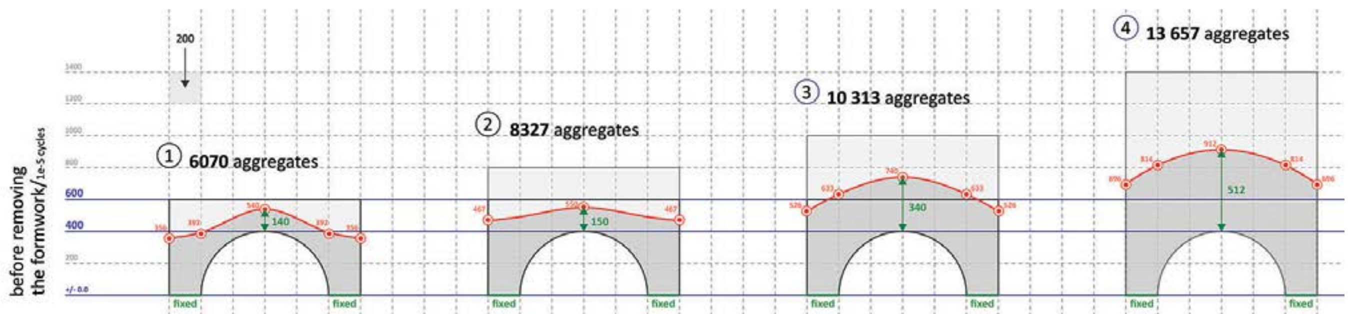

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6 Physical prototype constructed with ten-armed aggregates.

7 3D-scan of an aggregate composition.

8 Adaptive pneumatic formwork system and sequence of picture demonstrating the individual inflation of different balloons.

9 Simulation results of case study 01: ten-armed vs. six-armed particles.

10 Section through formations with different amount of aggregates.

volume occupied by the six-armed particles would be almost the half of the volume occupied by the ten-armed particles. The second conclusion was that after the same settling duration, the ten-armed particles would exhibit more static and stable behavior. However, a crucial parameter was also the time needed for both calculations. This case study proved that the simulations of six-armed particles are less time-consuming than those of ten-armed particles (3 hours 14 minutes vs. 11 hours 23 min on a PC equipped with a 4th generation Intel® Core™ processor). Since a regular computer was used in this project, it was decided to continue all experiments with the six-armed aggregates.

Another important examination is documented in Figure 10. It is a case study on the amount of particles needed to achieve a stable aggregate formation with a hemispherical void in the center. Before starting a simulation, one has to estimate the number of aggregates needed to achieve a stable configuration after their fall. Based on a number of experiments, the count was defined as a function of both the formwork´s and the particles´ volumes.

Case Study 02: Statistical Sets of DEM Simulations

The next two sets of simulations focused on observing the stochastic behavior of the material system. Two different setups were defined (see Figure 11). The first one consisted of a test container and two spheres, which allowed the formation of a column. One thousand six-armed aggregates with diameter of 300 mm were poured into the test container. The cycle time before and after removing the formwork was set to 1e+5. The second setup was similar to the first one. The two formwork spheres were designed to intersect each other and to allow a larger span in the middle of the formation. The fall of 800 six-armed particles was simulated with the same duration conditions as in the first setup.

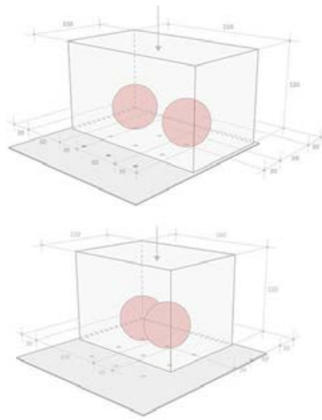
To analyze the behavior of the material system, each setup was tested ten times with different start positions for the aggregates. The output values for the clump velocity and the number of contact forces were first analyzed with a computational tool. Images of the top, right and front view were generated for each formation showing the last movement of the aggregates in the simulation (see Figure 12). The color and length of the arrows indicate the clump velocity. The critical parts of the formations are marked in red. Each formation, even within the same simulation setup, exhibits unstable behavior in a different place. This conclusion is of great importance for the feedback-driven design approach suggested.

The information gathered from the two simulation setups formed two separate statistical data sets (see Figure 13). Mean values were extracted for both parameters, the clump velocity and the number of contact forces. As expected and according to these parameters, the second simulation set showed more unstable behavior after the same amount of settling time. This is primarily due to the absence of a column in the middle, which requires the

11 Simulation setup 1 and 2.

12 Collection of front, side, and top views from simulation setup 1.

13 Comparison of the results from setup 1 and 2 after statistical analyses.



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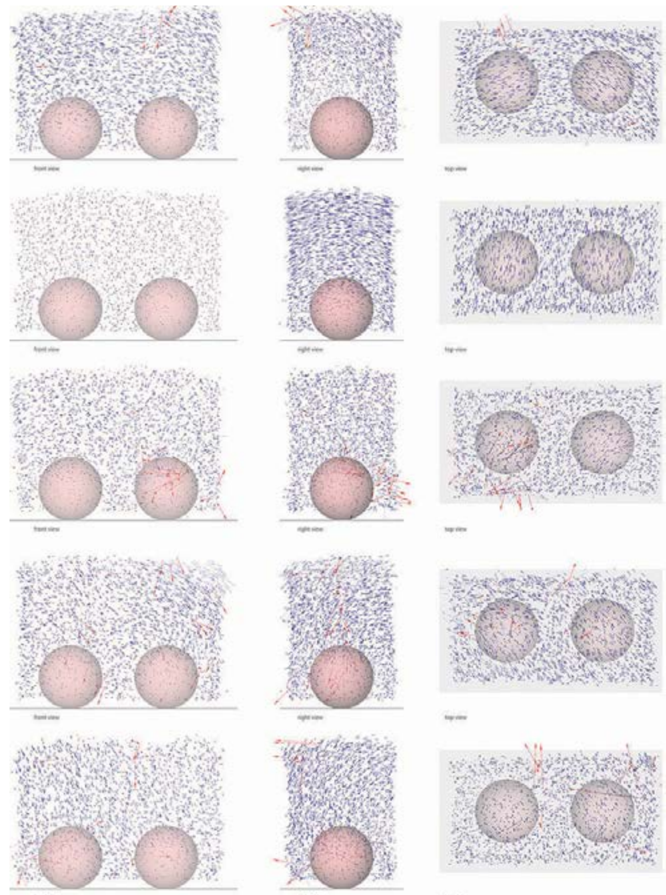

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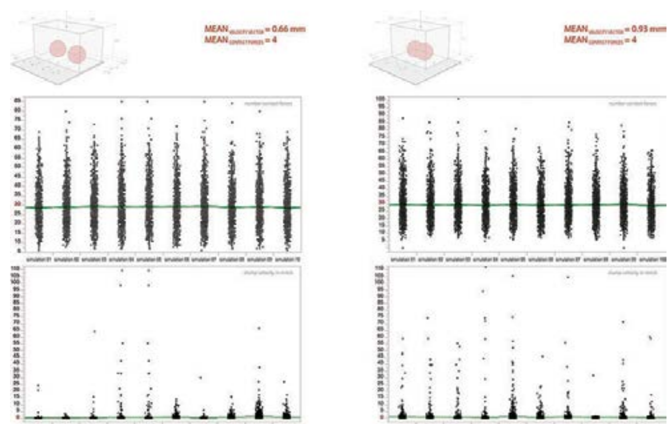

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aggregates to span two dome volumes instead of one as in the first simulation set.

The second set of simulations was also quantitatively compared to a statistical set of ten physical prototypes. Each model was 3D-scanned using photogrammetry. The generated 3D point-clouds of the physical prototypes were compared with the mesh-geometries exported from the simulations. Figure 14 shows that from a visual perspective, the results were identical. Additionally, the x-, y- and z-coordinates of the points for one point cloud were extracted in mm. The z-values of the points situated in the middle of the span were numerically compared to a mesh-model from one of the simulations (see Figure 15). The value deviation is considered acceptable for the stochastic nature of the material system.

Case Study 03: Feedback-driven Design Approach

The proposal for a design approach can be described as a feed-back-driven looping process consisting of four individual steps:

- Simulation of initial aggregate formation.
- Analyses of the results according to the two parameters.
- Adaptation of the digital formwork according to the actual stability state of the simulated formation.
- Activation of the physical formwork system.

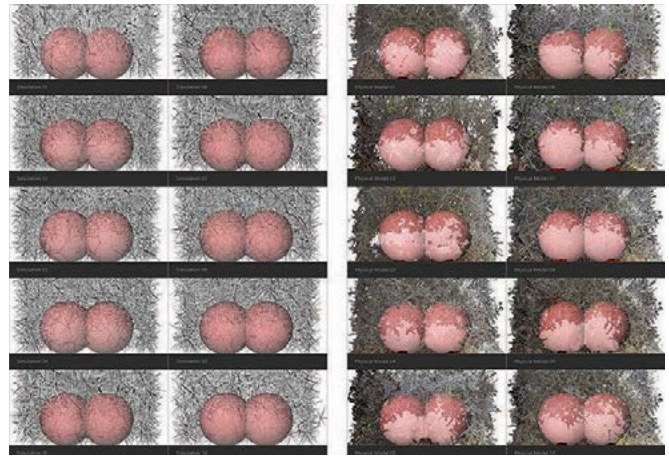
The setup for this last case study for both the simulation and the physical prototype consisted of four spherical inflatables, two intersecting each other and two with a column between them. The initial aggregate formation was simulated. Aggregates were designed to fall in the predefined boundary space and to settle on top of the inflatables. The initial formwork was removed and the second self-stabilizing phase started. This point of the process was crucial, since it was the appropriate moment for the feedback-loop to take place and for the adaptive inflatable system to be triggered. The digital balloons were designed to observe the aggregates´ behavior during the simulation and to react to it by inflating or deflating in the simulation. The behavior of the individual balloons was calculated directly in the simulation software. The feedback-algorithm was based on the actual state of matter of the numerical aggregate formation. It was designed to measure the length of the velocity vector for each aggregate in the system and to count the number of contacts with its neighbors. The mean values extracted in case study 02 formed an IF/THEN statement that triggered the inflation of the balloons needed. The code calculated the x and y centroid coordinates of the aggregates moving with higher velocity and having least number of contacts. If an instable group of particles was found, the nearest digital balloon was activated to support the structure (see Figure 16). The information about the position of the next inflation point was saved as a *.txt file and forwarded to the according balloon in the physical world. This process was designed to be iterative until a final stable state of the overall aggregate formation was achieved (see Figure 17).

RESULTS AND REFLECTION

This study builds upon the concept of discrete designed particles as a building material system and contributes to the investigations in the field by developing a simulation model which works as a complex adaptive system (CAS). This digital representation consists of two parts: the behavior of the aggregates and the behavior of the formwork. The adaptation occurs online and during the simulation. The feedback-loop is regulated through an IF/THEN statement based on mean values estimated via statistical simulation sets. Once the adaptation takes place in the digital environment, a signal is sent to the physical formwork (see Figure 2). Thus, the methods described here, lead to two main results.

First, a set of tools for direct connection between physical aggregate formations and their simulated representations was developed. This allows for a simultaneous observation of both digital and physical prototypes and, therefore, enables a straightforward comparison between them. However, due to the material´s stochastic behavior, a one-to-one recreation of the physical model in the simulation, and vice-versa, is clearly impossible. As a further development, a series of experiments could be conducted and analyzed using statistical methods. In this way behavior patterns for both the simulated and the real aggregates could be estimated with a focus on better understanding the material system.

Second, the project combined the self-organization capacity of aggregates to demonstrate emergence with the ability of the pneumatic formwork system to react according to the material state of matter. The outcome is the development of a CAS. This design strategy builds upon one of the most important advantages of aggregates as a building material system, namely their ability to reconfigure. The designer is driven to work with a design tool and material system, both of which remain outside of his/her complete control. Given this context, a consequential question needs to be answered: should the formations discussed find a final equilibrium state, or will they remain in a constantly self-adjusting mode, shifting periodically between static and flowing states?



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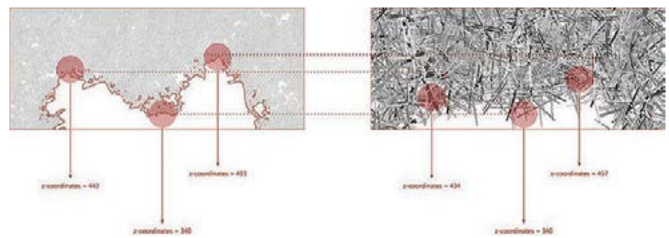

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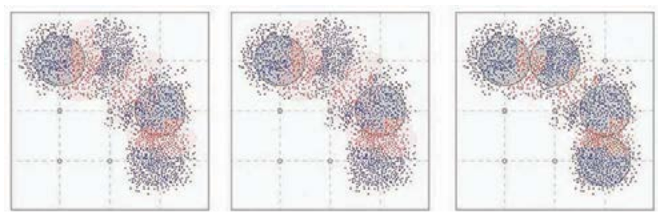

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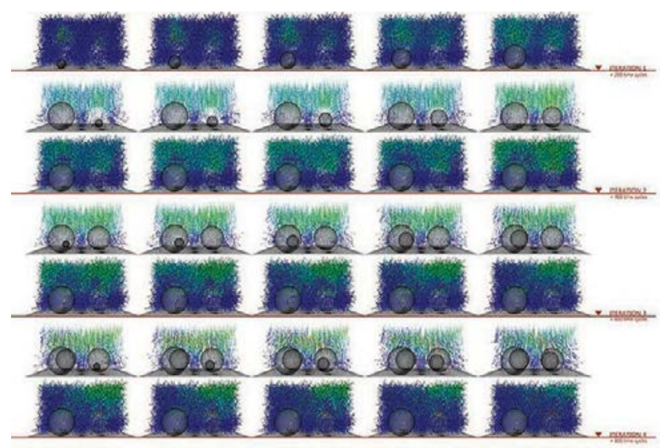

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14 Physical vs. numerical prototypes.

15 Numerical comparison.

16 Diagram for the calculation of the next inflation point.

17 Simulation results from case study 03.

FURTHER RESEARCH

The findings discussed here present opportunities for further development in two directions.

On the technical side of the project, the methods suggested could be improved. For example, the current version of the algorithm developed for the formwork actuation does not take the physical properties of the inflatables into account. A possible line of investigation could include measurements of pressure on the surface of the balloons in the physical model during construction and incorporation of this variable into the code. Otherwise, improving synchronization between the digital and physical models may also be of benefit, since the whole process is set online.

The second project branch with possibility for further investigation is the design process. The work presented here concentrates on the micro-mechanical behavior of the material and on the fragile stability of the formations as a design generator. All investigations were based on the self-supporting capacity of the structures. In a following step, static and dynamic loads, such as wind or directed air flows could be introduced into the system. This would allow for a design strategy based on the material properties and their interaction with the surrounding environment.

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IMAGE CREDITS

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