Simulation of physical object construction featuring irreversible state changes

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Abstract : In this paper, we firstly assume that the physical properties of a physical object, specially transformations of these objects such as fractures or solidification, are the result of a initial changing of state called "the physical construction process". We secondly assume that the physical behaviour of the final object is better accounted for when the final physical structure of the object is produced by a simulation of this physical construction process, providing more realistic dynamics deformations and transformations. Then, we describe a method for physical construction, based on the simulation of physical model which represents a kind of "instantaneous cement set". We describe the physical models of the rigid or deformable blocks to be assembled. Then, we describe the matter for the assembly and the way of its state changes. Finally, we perform simulations of these objects to produce rigidity, deformations and irreversible fractures.

Key words : fracture, simulation, physical modelling, deformable objects, physically-based construction

1. Introduction : physical construction of physical elements

1.1. Related works and the new problem to be solved

Computer Graphics and Computer Animation have developed a lot of models of physical objects such as rigid or deformable objects. In CAD, most of the objects modelled are geometrical [RM92]. Deformations have been added to this kind of shape modelling such as the Free Form Deformations or the Extended Free Form Deformations [Coq91]. More generally, using simulation methods, such as simulation of dynamic properties, the dynamic behaviour of rigid objects (whose shape is quite constant related to time) [Bar89][Bar90][Bar91], as well as deformable of objects are well understood today. But, "deformation", doesn't mean "transformation". Rigid or deformable objects are first modelled as a whole piece, discretised with finite elements method or particle methods [LM93][LJR91]. They are modelled without taking into account the changes in their physical states. In works which deals with transformations such as fractures or changes in the physical states, we have to distinguish between reversible changes of states, such as for fluids or pastes models

[DG95][Ton91][LJR91] and irreversible ones [NTB91][TPF89]. But in these models, the changing of states is not the result of a physical building of the object. It is described as a nature of the object, for example, the consequence of a physical heterogeneity, "genetically" written in the physical structure of the object. However, the capability of a physical object to change its physical state is the consequence of a physical building process. For instance, a column is finally an heterogeneous object because it is composed of physical elements assembled by either a physical process or a physico-chemical process. Likewise, a pebble can be seen as an heterogeneous piece, a set of physical mineral components that has gone through a state changing. Taking into account the physical nature of construction has a great influence on the dynamic behaviour of an object. Each of the component of the construction can be more or less rigid, deformable or transformable. And then, the micro-deformations, even non visible, of these components may have consequences on the visible deformation of the whole piece. In addition, the physical assembling may be of a different physical nature from its components. In this way, the resistance of the assembling can be lower (or greater) than its components. This leads to less or more fracturable and more or less heterogeneous objects.

1.2. Atoms and assembling

A component of the object can be seen as an heterogeneous physical system obtained by assembling smaller physical components. There is a recursive construction process in which it is possible to define the lowest level of the divisibility wanted. The components of this level will be called " atoms". So if one is not interested in the fracturability of its components, a block of granite will be constituted of non-fracturable atoms of quartz, mica, feldspath, assembled by a physical component. But if one is also interested in the fracturability of the components, then these will also be modelled by smaller physically assembled components. This reasoning can be done for a big object, which can be either a non fracturable atom, or a fracturable physically built object. The atom or the elementary component of the physical assembling defines the scale at which the user-constructor want to work.

1.3. Physical assembling process : a dynamic and dissymmetric process

Our assembling process is characterised by the fact that assembling "is" the result of a physical process. Then, the resulting shape and physical structure of an object are produced by simulation. The user provides the atoms and the physical links between the atoms. The operator can take part in the assembling process as a mason. Nevertheless, he doesn't decide of the result of the assembling. The physical assembling is characterised by three different stages : a construction stage, a structurally stable stage, a possible irreversible destructuration.

Construction stage

The construction stage requires an energy greater than the other stages as a granite block constituting under high pressures, or a wall constructed using specific linking materials, such as cements, in which a state changing is caused by a physico-chemical process. This implies irreversibility of the process : if a fracture arises, the object will not be re-built by itself.

Stable stage

In its usual state, an objet may remain in a structural stable stage during which its shape and its structure are not deeply modified. The external (or internal) forces exerted to (or in) the object will be smallest than the ones exerted during the construction stage. They can lead to light structural modifications (micro-fractures, micro-packing down ...) whose scale will be quite-small.

Breaking stage

The breaking stage deals with intermediate scale internal or external forces, caused by an infrequent event in time and/or space such as an impact, or by the summation of shared constraints of low amplitude constraints (acoustic vibrations) or else with a physical state change (micro-fractures). Then the macrostructure of the object can vary from deformations to deep transformations : cracks, fractures, explosions...

2. CORDIS - ANIMA

The *Cordis-Anima* physical modeller-simulator, based on point physics [CLF90][CLFR91]. *Cordis-Anima* is a formal representation systems to build physical models. Objects are modelled by networks composed of two types of automata (figure 1) : MAT and LIA. In these networks, all the nodes are MAT automata and the arcs are LIA automata.

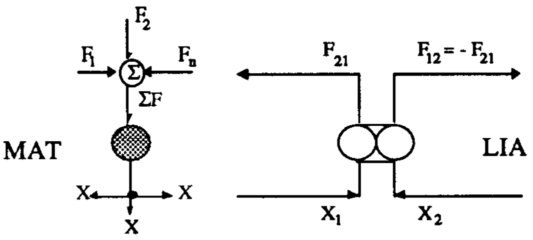

Figure 1 : the two basic atoms MAT and LIA of the *Cordis-Anima* modeller-simulator

In the standard implementation, one MAT automaton represents one punctual mass. One such automaton reads a force F and produce one position X. The algorithm implemented in MAT automata is based on Newton's second law (m is the mass of the punctual mass).

$$F = m.\ddot{X} \Leftrightarrow X = \frac{1}{m}\iint F\,dt^2$$

which give, after time sampling

$$X(n+1) = 2X(n) - X(n-1) + \frac{F}{m}.T^2$$

In the same way, LIA automata read two positions X_1 and X_2 (and/or two velocities) and produce two opposite forces F_{12} and F_{21}. The underlying algorithm represents physical interaction (elasticity, viscosity, plasticity ...).

Next we present the expressions of the basic visco-elastic interaction functions. k represents stiffness of the interaction, z the viscosity and d_0 represents the rest length.

Linear visco-elastic interaction

$$F_{12} = -F_{21} = \left(-z_0 \cdot \frac{\partial}{\partial t} |X_1 - X_2| - k_0 \cdot \left(|X_1 - X_2| - d_0 \right) \right) \cdot u_{12} \quad \text{where} \quad u_{12} = \frac{X_1 - X_2}{|X_1 - X_2|}$$

Thresholded elastic interaction (buffer interaction)

$$\text{if } |X_1 - X_2| \geq d_{e0} \qquad F_{12} = F_{21} = 0$$

$$\text{if } |X_1 - X_2| < d_{e0} \qquad F_{12} = -F_{21} = -k_0 \cdot \left(|X_1 - X_2| - d_{e0} \right) \cdot u_{12}$$

Thresholded visco-elastic interaction (visco-elastic buffer interaction)

This is equivalent to an elastic and a viscous interaction, acting in parallel, between two MAT automata.

3. The physical atoms

3.1. Typology of the atoms

In the presented recursive physically-based construction process, we call " atoms" the unbreakable components, homogeneous or not, with which the object will be constructed. As rigid or deformable physical objects, a CORDIS-ANIMA model of unbreakable atoms can be composed of a set of punctual 3D masses linked by permanent physical interactions (visco-elastic, plastic...). For the present demonstration as well as for the simulations we performed, only visco-elastic interactions were used. The topology of the Cordis-Anima network as well as the values of the parameters of the elements <MAT> and <LIA> define the deformation modes of the object. Note that this object is not necessarily homogeneous.

According to the fact that the shape is a determining criterion of the object behaviour, we classify the shapes into typical shapes. The purpose doesn't lost its generality as soon as other shapes will be accessible by construction. Specially, we can distinguish punctual, lineic ("stem"), surfacic ("cell"), and volumic ("block") atoms meaning that they have or not dimensions greater than others.

3.2. Modelling the atoms

The three types of atoms are modelled in the same way by punctual masses linked with visco-elastic unbreakable interactions. All these blocks are prestressed to minimise the number of rest positions of the block and give them a regular aspect.

Volumic atoms

To choose volumic pertinent structures, we explored topologies based on crystallography such as cubic and compact-hexagonal networks [MQ88], or the structure of the fulren atom. For legibility, all the links are not all drawn on the figure 2.

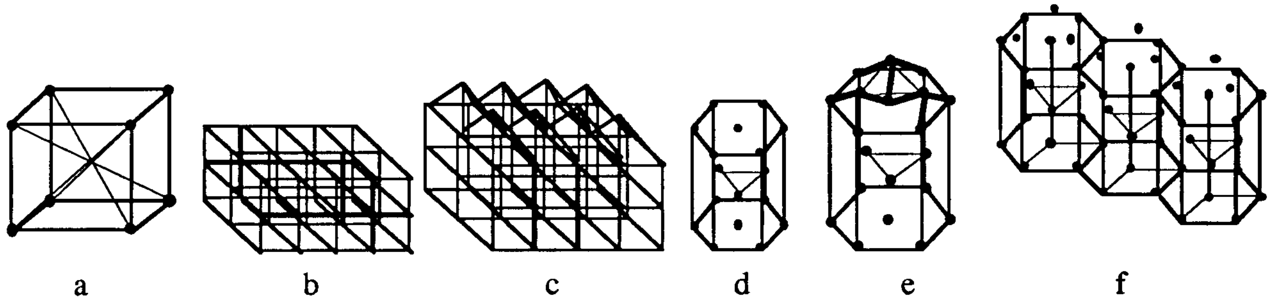

Figure 2 - Some structures of unbreakable atomes
(a) Cubic block 8 masses, 16 visco-elastic links with 2 different lengths - (b) Parallelipipedic block 45 masses, 160 visco-elastic links with 2 different lengths - (c) "Lego" block 53 masses, 192 visco-elastic links with 2 different lengths - (d) Hexagonal compact block 17 masses, 61 visco-elastic links with 3 different lengths - (e) Auto-piled hexagonal compact block 20 masses, 70 visco-elastic links with 3 lengths - (f) Triple auto-piled hexagonal compact block 52 masses, 191 visco-elastic links (3 lengths).

Surfacic atoms : lath

The figure 3 shows an example of surfacic atom composed of 12 masses and 38 liaisons visco-elastic links with 4 different lengths. Even without rigidification rod this lath is highly rigid and has a correct deformation behaviour. The rest length of the X1,X2, X4 links are $\sqrt{2}$, $\sqrt{5}$, $\sqrt{17}$ time the mesh length.

Lineic atoms : stem or helix

To obtain an helicoidal stem or an helix (figure 4), we assemble recursively tetrahedron meshes. We placed a prestressing visco-elastic interaction to determine a global rest position.

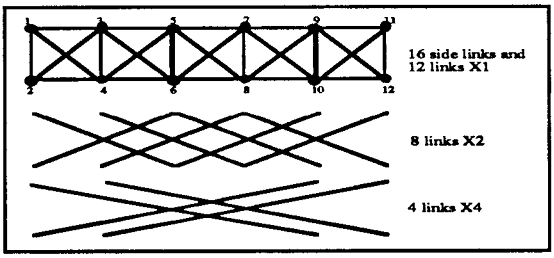

Figure 3 - Lath model (Top view)

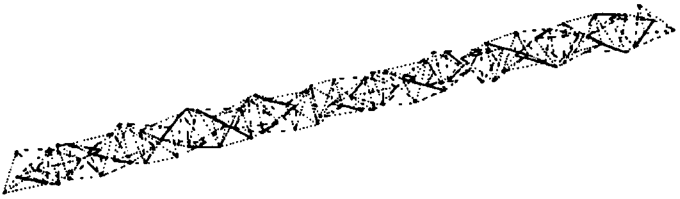

Figure 4 - a resulting "100 masses" helix.

4. Assembling and dismantling the blocks

4.1. The construction stage : the "instantaneous cement set"

The assembling process must satisfy the three following properties :

P1 : in the resulting model, the relative positions between the "cemented" blocks will remain always the same in average.

P2 : the rest length of the "cement" links must be equal to the distance between the masses it links, at their rest piled state.

P3 : Two blocks linked by the cement must not reassemble together after separation.

The cement we use is modelled by a single specific CORDIS-ANIMA interaction link called "instantaneous cement set", depending only on the distance between the blocks to link. This means that the changing of state will occur between two steps of simulation. A simplification consists in designing this link with a physical interaction function without inertia. This hypothesis doesn't limit the process general nature as nothing prevent from improving the "cement" component, considering it as a subpart of the " atoms" type, linked by "immaterial" interactions. The function on figure 5 satisfy to the three properties of assembling given above.

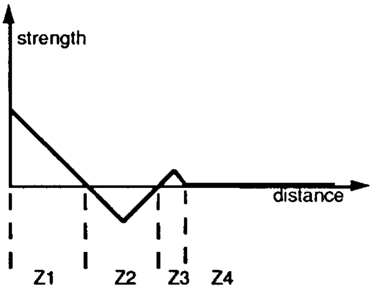

Figure 5 - "Cement" interaction function profile computing the intensity of the force between the punctual masses.

The abscissa is divide into four zones with four different purpose : zone 1 generates force that repulses the two masses. This is a buffer behaviour. Zone 2 creates force that attracts the two masses, creating a cohesion. Zone 3 is an other repulsive zone whose role is to prevent the reassembling of the masses after a break by a capillarity phenomenon. In zone 4 the link doesn't produce force so that the masses moves freely. The robustness of the cohesion depend on the slopes of each zone, on the thresholds defining the zones and the ratios between them.

The assembling of the blocks consists in setting links between each mass, at contact points. The initial state corresponds to the assembled state : the masses positions lie in such a way that at initial state the links are in zone 1 or 2.

4.2. Simulation stage : the links breaking.

A link break arise when its distance comes from zone 1 or 2 to zone 4. The zone 3 give a very few energy to the motion compared to the other energies. The purpose of zone 3 is to prevent from masses (therefore objects) reassembling.

The objects are put into a very low viscosity medium (near air's viscosity) with a gravity, lie on the ground or are dropped. The ground is modelled with only one mass placed underneath the objects. It is linked with each mass of the objects with a collision (visco-elastic bumper) and a dry friction interactions [Jim93]. All the atoms of the build objects are interacting together [JL93][LJR91].

5. Results and interpretations

About the visualisation : The visualisation we use is very simple, some masses are joint by lines, some have a circle on it, depending on the buffer threshold. In the figures showing columns, the upper block is linked to an invisible block, representing the ceiling of a room. The destroyer is a heavy pendulum.

5.1. Columns examples

A large set of behaviours (deformation, cracks...), has been obtained. The figures 6, 7, 8 show triple hexagonal blocks columns with different parameters of cement, hitted by the same pendulum.

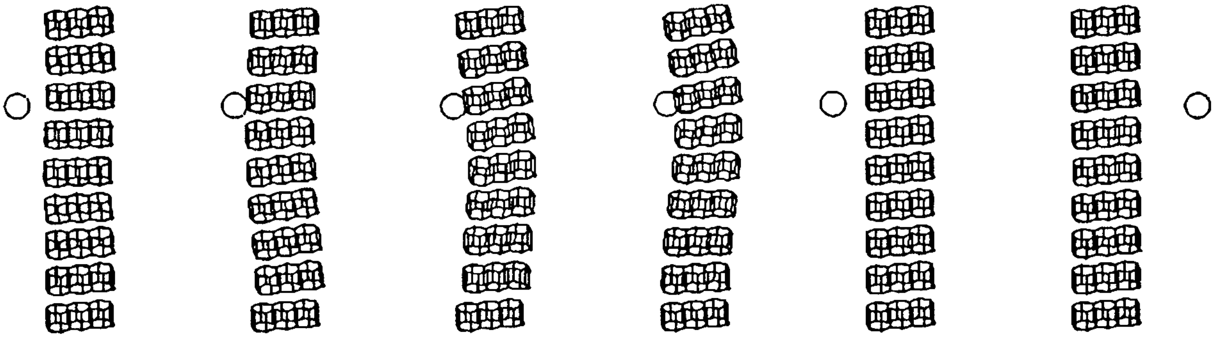

Fig 6 - Triple hexagonal block column resisting to an impact. Images n° 6, 83, 86, 91, 96, 250 .

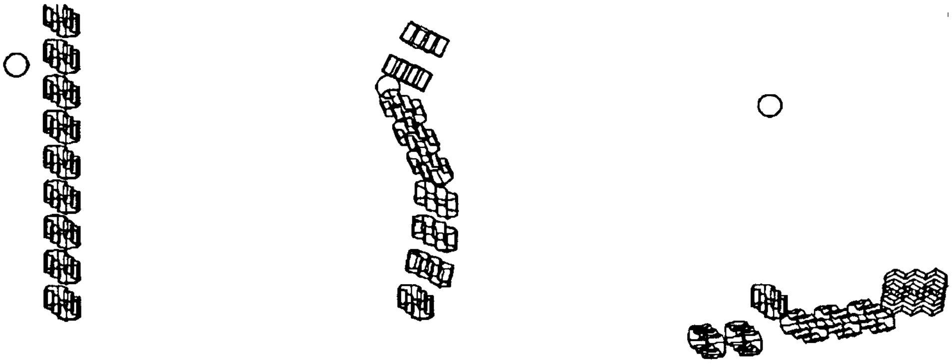

Fig 7 - The column breaks into three parts at impact time and each part remains entire reaching the ground. Images n° 70, 95 and 190 .

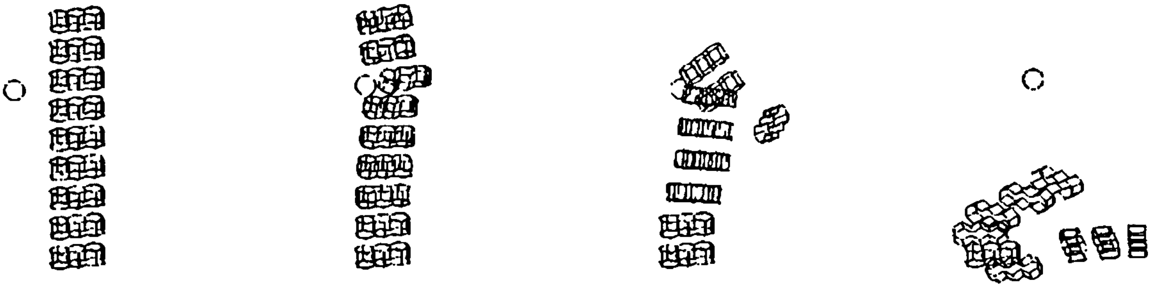

Fig. 8 - The initial hit unties an element of the column that breaks into three parts. When touching the ground, some parts break into smaller parts, others remains intact. Images N° 75, 83, 102, 199.

5.2. Wall examples

Figure 9 shows a hexa wall is composed of 30 auto-pilable triple hexagonal atoms. The wall is not fastened to the ground, and the ground/blocks link has no dry friction component, so that the blocks slide along the ground and the wall rotates after the impact. Figure 10 shows a "lego" wall has 24 "lego" atoms. The lower row is fastened to the ground as would be wall foundations. The blocks/ground interaction is a dry friction [Jim93]. Reaching the ground, the blocks quickly stop.

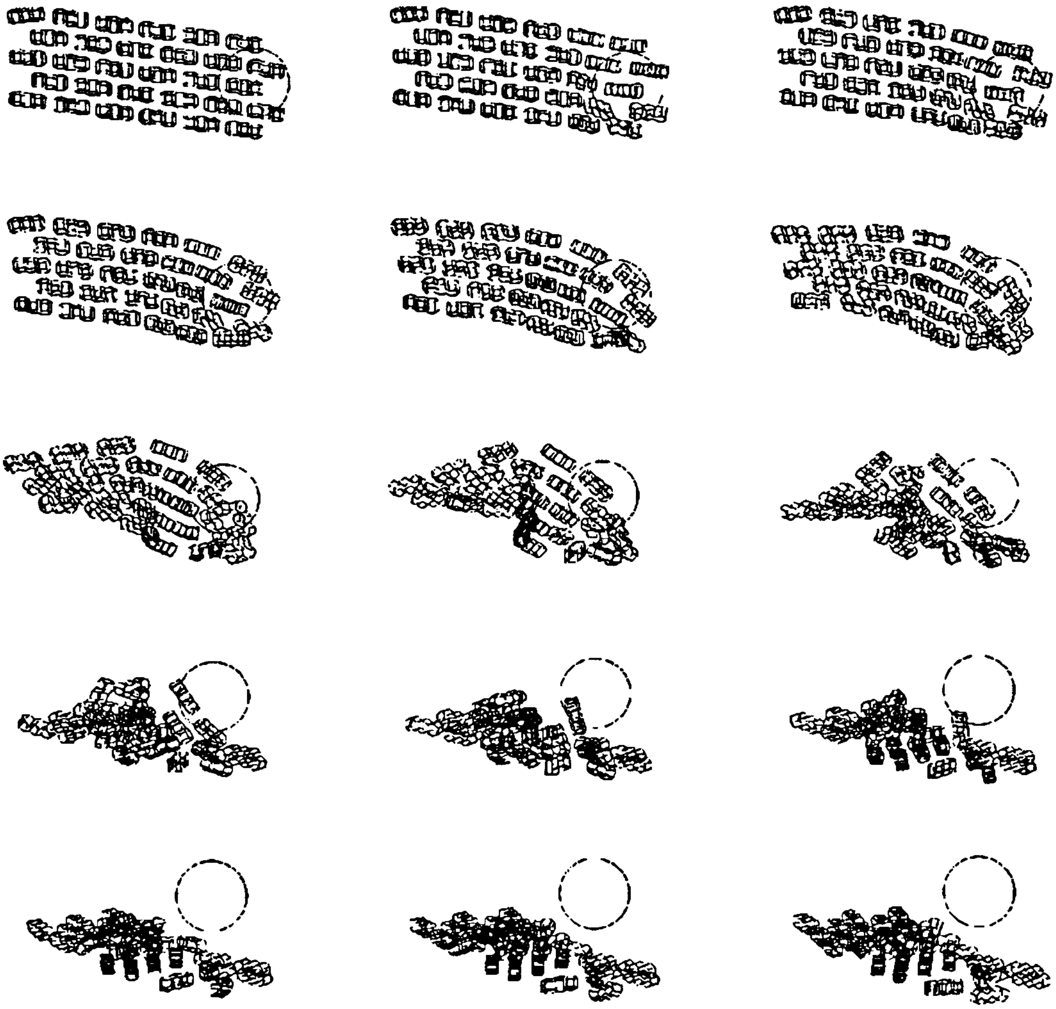

Fig 9 - Hexa wall : 1563 masses - 5/25th of sec. between each picture.

6. Conclusion

The method presented here allows the physical construction of deformable, fracturable and breakable objects. The construction is based on unbreakable elements called atoms, hierarchically put together to create more complex objects that are breakable. The construction stage as the simulation stage are twice physical and use the simulator Cordis-Anima. The fracture zone are not predetermined. Non visible deformations causes irreversible changes of state. We could weaken or reinforce a material at a given place only by modifying some cement links. In this modelling method, we control the object by describing its own internal characteristics rather than the behaviour we want it has.

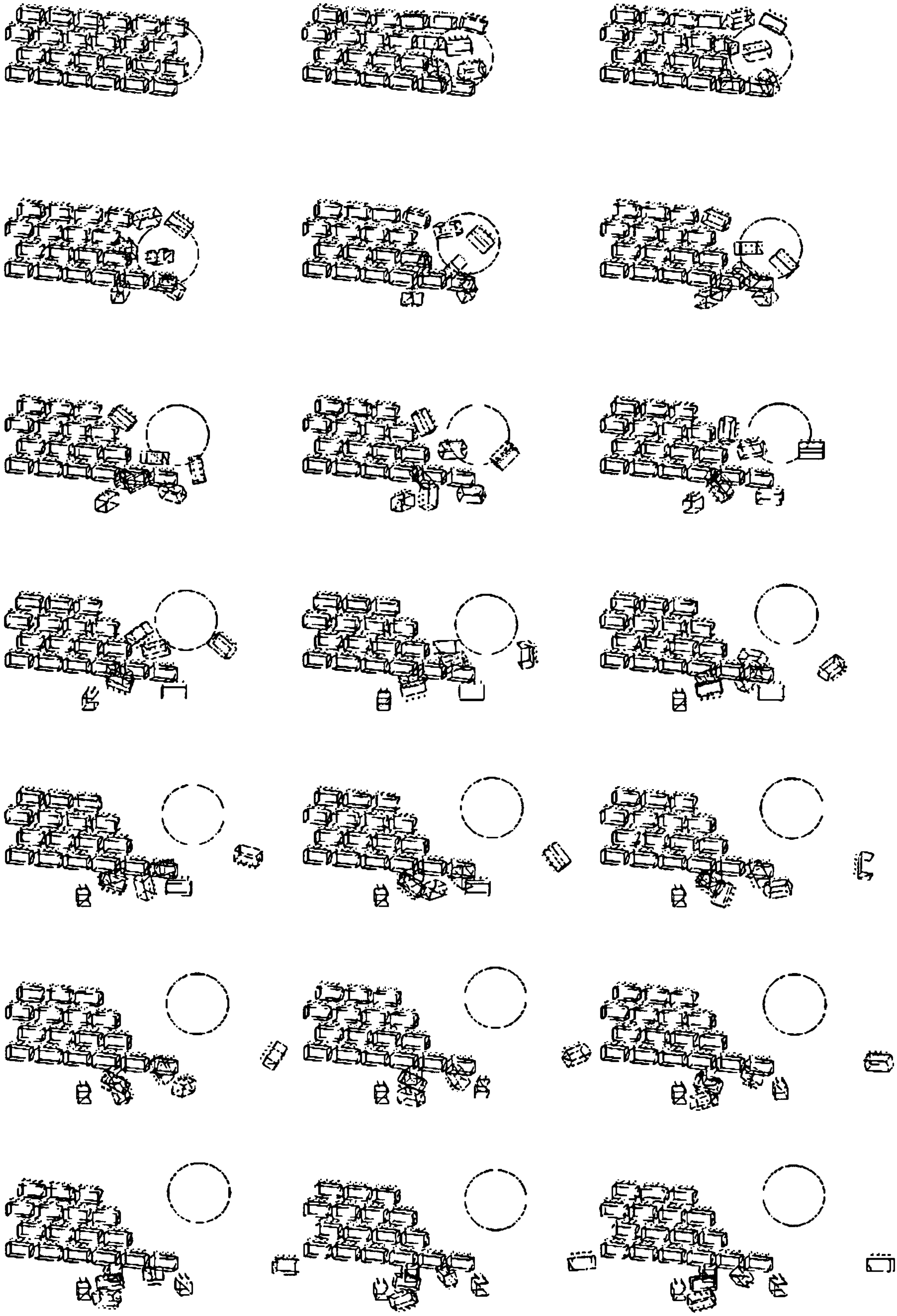

Fig 10 - Lego wall with dry friction : 1275 masses - 3/25th of sec. between each picture.

7. References

[Bar89] D. BARAFF - “Analytical methods for Dynamics Simulation of Non-Penetrating Rigid Bodies.” - Computer Graphics, 23 (3) july 1989, pp. 223-232 (Proceedings of SIGGRAPH’89).

[Bar90] D. BARAFF - “Curved Surfaces and Coherence for Non-penetrating Rigid Body Simulation.” - Computer Graphics, 24 (4) august 1990, pp. 19-28 (Proceedings of SIGGRAPH’90).

[Bar91] D. BARAFF - “Coping with Friction for Non-penetrating Rigid Body Simulation” - Computer Graphics, Volume 25, Number 4, July 1991, p. 31-40 (Proceedings of SIGGRAPH’91).

[CLF91] C. CADOZ, A. LUCIANI, J.L. FLORENS, O. RAOULT - “Physique discrète, discrétisation du temps et de la matière” - 1er Colloque Géométrie en Imagerie: Fondement et Application, Strasbourg, 26-27 septembre 1991.

[CLF93] CADOZ (C), LUCIANI (A) & FLORENS (JL), "CORDIS-ANIMA : a Modeling and Simulation System for Sound and Image Synthesis- The General Formalism", Computer Music Journal, Vol 17-1 spring 1993, MIT Press

[Coq91] Sabine COQUILLARD - "Extendet free-form deformation: A sculpturing tool for 3D geometric modeling." *Computer Graphics (SIGGRAPH '90 Proceedings)*, volume 25, pages23-26, July 1991.

[LJR91] A. LUCIANI, S. JIMENEZ, O. RAOULT, C. CADOZ, J.L. FLORENS - “An unified view of multitude behavior, flexibility, plasticity and fractures Balls, Bubbles and Agglomerates” - Modeling in Computer Graphics (IFIP series on Computer Graphics), pp. 54-74 - IFIP 1991 (Springer Verlag Ed.)

[Jim93] S.JIMENEZ - “Modélisation et simulation physique d'objets volumiques déformables complexes” - Thèse INPG _ Grenoble - France - 1993.

[JL93] S. JIMENEZ, A. LUCIANI - “Animation of Interacting Objects with Collisions and Prolonged Contacts” - Modeling in Computer Graphics (IFIP series on Computer Graphics), pp.129-141 - Springer Verlag 1993.

[LM93] X. LI, J.M. MOSHELL - “Modeling Soil: Realtime Dynamic Models for Soil Slippage and Manipulation” - Computer graphics proceedings, Annual Conference Series, 1993, p.361-368 (Proceedings of SIGGRAPH 93).

[MQ88] J. MESPLEDE, J.L. QUEYREL. - “Précis de chimie” - Eds Bréal 1988.

[NTB91] A. NORTON, G. TURK, B. BACON, J. GERTH, P. SWEENEY - "Animation of fracture by physical modeling" - The Visual Computer (1991) 7:210-219

[RM92] F. RACHEL MARTY - “Contribution à l'étude d'un modeleur géométrique pour la CAO des systèmes mécaniques” - Thèse de physique et informatique - Aix-en-Provence, 1992.

[Ton91] D. TONNESEN - "Modeling Liquids and Solids using Thermal Particles" - In *Proceedings Graphics Interface*. Graphics Interface, 1991.

[TPF89] D.TERZOPOULOS, J.PLATT, K. FLEISHER - "Heating and Melting Deformable Models (From Goop to Glop)" - In *Proc. Graphics Interface* . Graphics Interface, June 1989.