# Study and simulation of fragmentation phenomena of concrete structures under stuffy explosion

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**Summary**

This study comes from an industrial problem. The aim is to estimate the consequences of a gas explosion inside a bunker type concrete structure. The explosion is the results of a hydrogen leak mixed with air that forms an explosive cloud. Fragmentation mechanisms lead to strong discontinuous problem. Our investigation lead us to develop an adapted model which can integrate discontinuities and allows us to be able to describe fragmentation and particle ejections. From the observation of the size and the global shape of the fragments, we can build a meshed numeric model constituted with elastic discret elements connected by an adhesion law.

**keyword**: Rupture, fragmentation of concrete, experiment explosion, structures vulnerability, dynamics, discrete elements, cohesive interface.

## 1 Introduction

The topic of this paper is the fragmentation of concrete wall due to confined explosive load. The industrial problem being considered is the protection of concrete structures in a case of an accidental explosion (figure 1). The explosion is the result of an hydrogen leak that, mixed with air, form an explosive cloud. The first problem approach lets think that this accidental request will lead to the complete ruin of the structure. This particular study of civil protection concerns nuclear power station, but its application domain is wider. Besides knowing accidental explosion cause and determining a unique scenario and all parameters of baiting, we choose a determinist method that puts in correspondence accident causes and structure consequences, see [1]. The load due to a stuffy explosion depends on numerous parameters.

Fragmentation phenomena are observable on the numerous test campaigns resulting from the literature. Production of blocks, scales and dusts depend on different loads, see [3] and [4]. We note also a specific material behavior under dynamic load: concrete resistance increases according to strain speed and material internal structure destruction induces a compaction phenomenon (refer to [5] [6]).

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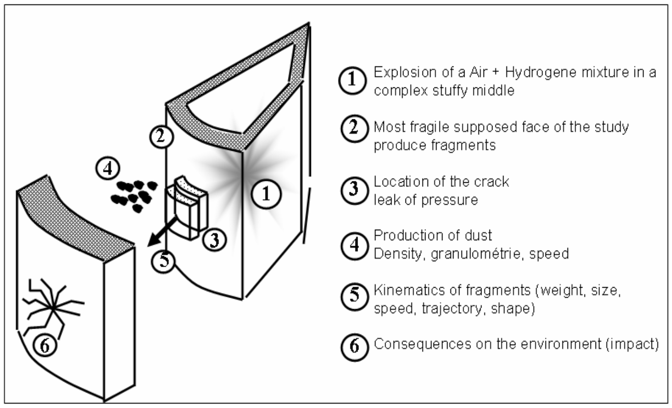


**Figure 1:** Accident scenario mechanisms

A lot of models express damage or cracks location, but not this strong rupture discontinuity. Our investigation leads us to an adapted model which can integrate all discontinuities and is able to describe particle ejection.

## 2 Explosion and load

The shape of the signal, its spatial distribution and pressure intensity, strongly depends on the initial conditions. A 1/20 scale experimental model reproducing the geometry of the structure allows us to observe the signal pressure versus time on a face in several conditions of combustion. The hypotheses on the explosion behavior and combustion type observed (slow or accelerated deflagration, detonation) allow us to get condition explosion parameters and load on the structure face.

The experiments, which we developped, were conducted in the Bourges Energie, Explosions et Structures Laboratory. We will be interested in this paper only in the load to be considered for a dynamic study. From first studies realized on the mockup, we propose here two representative types of combustion of real conditions in the case of an explosion hydrogen + air and a weak baiting and in the case of an explosion hydrogen + oxygen and a strong baiting (figure 2) [2].We retain the following observations:

For a deflagration explosion type (figure 2.a), we observe that the combustion is slow. Geometry and obstacles have a strong influence on the speed of combustion. The signal pressure / time distributed on the various faces of measure depends on this speed. The experimental study allows us to determine significant parameters independent from the volume.

For an detonation explosion type (figure 2.a), we observe a damped oscillating pressure and locally a pressure peak. The presence of aisles and sous spaces due to the complex shape of the volume concentrating the pressures of gases and increasing temperature during the combustion. Strong local explosions can result from it.

The passage to real scale and test repeatability were developed in this study (refer [2]).

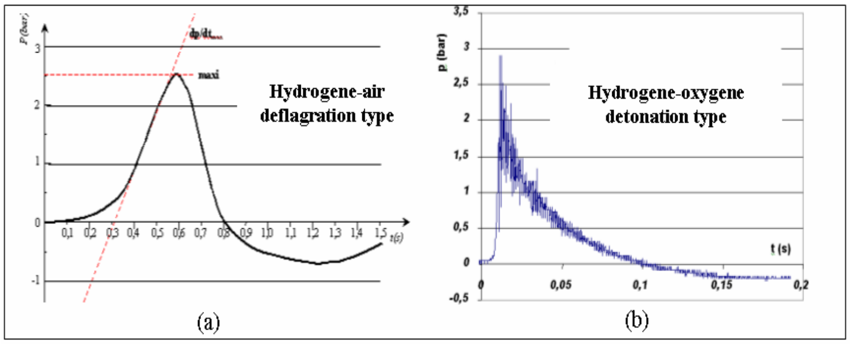


**Figure 2:** Pressure/time signals for a stuffy deflagration type (a) and a stuffy detonation type (b)

## 3 Discret elements method

If we consider fragments after break, we can imagine that these blocks were initially bound by a connection which disappeared during the fragmentation. From the the observation of the size and the global shape of fragments, we can build a meshed numeric model constituted with elastic elements connected among them by an adhesion law.

Initially, the discret elements method was developped to model granulars materials (see [6]). The middle was modeled by a set of rigid solids connected by interface laws. The adaptations realized in [8] allowed us to model continuous middle until the ruin and to observe dynamic phenomena of fracture. The main idea was to replace the rigid elements by elastic elements. The elasticity of the material is taken is account in finite elements. The interface is only used to describe the local fracture. It's a new approach in comparison with other formulation like in [16]. The finite elements are connected by cohesive interfaces. The cohesion phenomenon can be defined as the faculty for two bodies to stay in contact as long as the separation force does not exceed a given normal separation force. In a first approach, this separation force Rc is taken into account only on the normal part of the reaction of contact $R_N$ ( $R_N \geq R_C$). To model an energy of break, a gap of separation ($W_{eth}$) between elements before break is introduced. The area ($R_C.W_{eth}$) is then bound to an breaking energy. Resistance in shear is assumed by the Coulomb dry friction through the coefficient of friction $\mu$ (figure 3). In tangent plan, The shear resistance $R_T$ opposes at the slip tangential speed $U_T$.

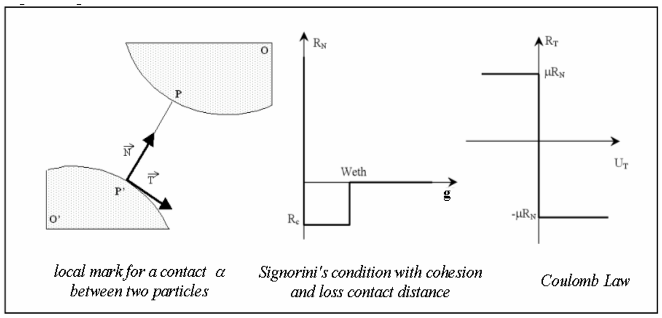


**Figure 3:** Normal cohesive model with fracture energy and coulomb law

First tests with this cohesive model leads to a too fast damage because the shear resistance is not strong enougn. To limit these phenomena, we suggest integrating into the model a progressive damage of the interface between elements and the consideration of an elasticity in traction and shear. This formulation is developed from the notion of damage intensity of the unilateral contact introduced by Cangémi L. [9] and Fremond M. [10]. A big part of the study of this model was detailed by Monerie Y. [11]. He proposes a progressive passage of the continious state to the fractured state by the introduction of a damage variable $\beta$ ($1>\beta>0$). The elasticity of the interface is introduced by the stiffness $C_N$ and $C_T$. The interface local energy of break is represented with the variable $w$ (figure 4). The numerical solver is realized by the method "*Non smooth contact dynamics*" (see [7] [8]). Initially used for rigid solids, it was adapted to elastic bodies [12] and become widespread [13] in multibodies with cohesive interface. It is an implicit treatment of the cohesive interface conditions by an algorithm of non linear Gauss Seidel type. This method was applied to our problem of fragmentation of the concrete and programmed in the LMGC 90 platform developed by Dubois F. and Jean M. [14].

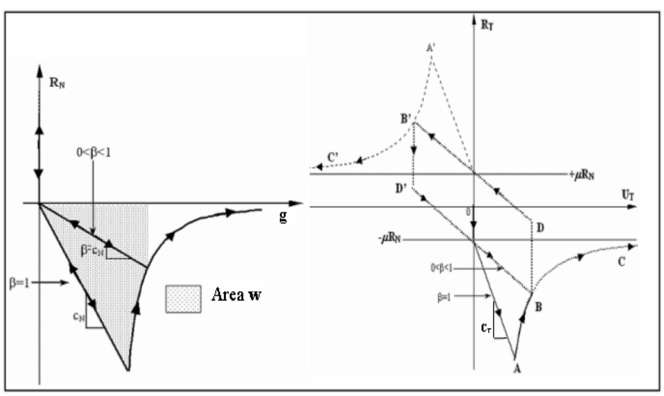


**Figure 4:** Cangémi-Fremond model – charge/discharge cycle for normal and tangential load

## 4 Simulations in the case of a dynamic drive

The first application of the model concerns fracture under dynamic traction observed during wall fragmentation test. To observe and to quantify break in dynamic drive, the modified Split Hopkinson Pressure Bar test is used.

The figure 5 shows a plan of the experimental device. A missile impact an entrance bar, giving place to a wave of compression in the bar, which propagates in the sample. It is reflected in a tensile wave on the free edge of the sample. The superimposing of the compression wave and the tensile wave breaks the sample.

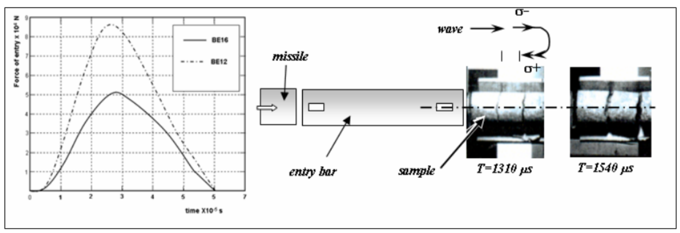


**Figure 5:** Modified Split Hopkinson Pressure Bar test - Incidental pressure signal– BE12 test with two high tension failure

| Test | maximum pressure load (Mpa) | deformation speed ($s^{-1}$) | maximum dynamic strain (Mpa) | break position X (mm) |
|---|---|---|---|---|
| BE16 | 36 | 21 | 19 | 65,8 |
| BE12 | 58 | 22,5 | 33,5 | 69 et 41 |

**Table 1:** Dynamic tensile experimental results from Brara A. [6]

We confront two representative experimental results of modified Split Hopkinson Pressure Bar test with simulations realized on 248 elements in plane and large strains. The concrete has the following characteristics: Young's modulus $E$=35GPa, density $\rho$ =2350 kg/m$^3$, traction static resistance $\sigma_t$ = 4 MPa. The diameter of the sample is 40mm, the length is 120mm. The figure 5 shows the efforts of entrance for two test, only given result available. The BE16 test, slowest, leads to a single break situated at 65,8 mm of the free edge, while BE12 test, faster, leads to two breaks at 69 mm and 41 mm of the edge (table I.). In the case of multi-breaks, the first to appear should the only one to be considered experimentally, other waves are caused by superposition and reflection. Second break, occurring at a short distance of the first (30mm), is due to several short waves provoked by the first break.

For our numerical model a damage of interface is determined according to an energy of break of the interface between elements. The value of this energy w returned on the length the interface depends on the constraint of break σc and on the elasticity of the following interface $C_N : w = \sigma_c / C_N$ . The elasticity of the interface in traction and in shear is estimated as ten times superior to the elasticity applied in the element. We preserve so an almost fragile break without punishing calculation and implicit formulation. We take a breaking stress in traction of 4 MPa then increased it until the fragmentation appears.

In the BE16 test, for a breaking stress in traction of 21 MPa, the distance of the fracture situated at x=65mm is very close to that found experimentally (figure 6). Also the relative speed of ejection between two blocks (measured between the centres of gravity of blocks at $t=8.10^{-5}$ s) is about 2 m/s.

For the BE12 test, the traction breaking stress of 28 MPa. The simulation shows, in agreement with the experimental observation, that the first crack that is situated closer of the free edge at 42 mm is followed by a second at 64 mm of the edge (figure 6). The time of appearance between two fractures is difficult to estimate experimentally; it is, in the numeric simulation, near $3.10^{-7}$s. The speed of ejection between the nearby blocks is 2,4 and 2,9 m/s at $t=8.10^{-5}$s.

In order to have a second comparaison, an elementary model can gives a relation between the speed of ejection $V_e$ of fragments and the breaking stress $\sigma_C$. This relation is $V_e = \sigma_C / \sqrt{\rho E}$ .

In our case, applied dynamic breaking stress are $\sigma_C$ =21 and 28 MPa for each test. Then, the speeds of ejection $V_e$ are equal to 2,3 and 3,08 m/s. These results are closed to those found by the simulations. These results of dynamic tensile constitute a first stage towards the revealing of the potentialities of the model concerning fragmentation phenomena.

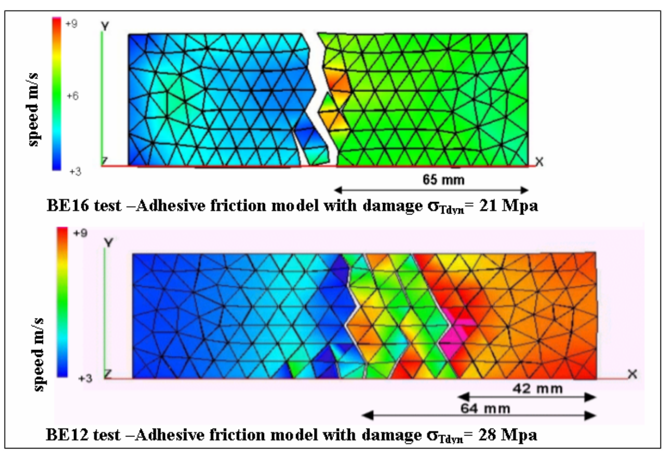


**Figure 6**: Rupture and axial velocity isovalues for BE16 and BE12 tests

## 5 Simulations in the case of a concrete wall under explosion

Simulations are realized on a reinforced concrete wall of dimensions 1m x 1m x 10 cm under uniform pressure. The armatures are modelled by elastic cables fixed in the material and work only in traction. The characteristics of cables are those of steel. We observe two known phenomena: the scaling of the free surface of the wall and the flexion of the structure.

In the case of high strain rates, we observe, on the figure 7, the transition of a wave in the thickness of the wall. This phenomenon is closed to the dynamic traction studied in the previous paragraph. The compressive wave is reflected on the free face of the wall in tensile wave which breaks the material by forming a scale. We find the speed of the scale of about 2,6 m/s and a thickness of about 2cm for the considered load. In a deflagration explosion type, the time of application of the pressure is about 0,1s. This load does not create a scaling. However, the oscillations of pressure around the value of the peak have a frequency spectral contents bigger than the global signal. Frequencies found during experiments are of the order of 45 to 78 Htz. These oscillations can generate a scaling.

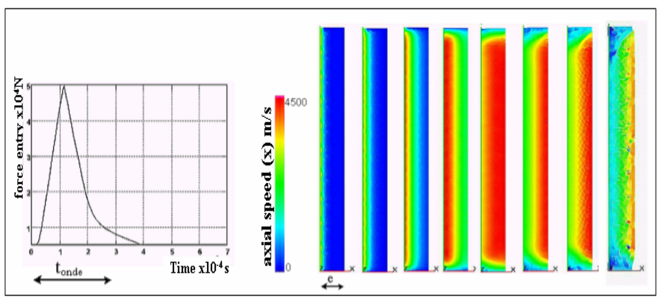


**Figure 7:** Wave transmission in a concrete wall and scaling

The flexion of the structure depends on chosen boundary conditions. The choice of a modelling by encastrement leads to a stress concentration and break the wall in shear (figure 8). The ejection phenomenon of a part of paving stone by shear at support level was also observed in shock tube test realized by Pontiroli C. [15] on reinforced concrete wall. Using the conditions of a deflagration, we find a deflection before break of about 0,07m and a wall ejection speed of 0,6 m/s. These values are closed to the estimation realized with simplified method. For example, the wall speed after break can be estimate has the flexion speed of the wall before break (found with finite element method).

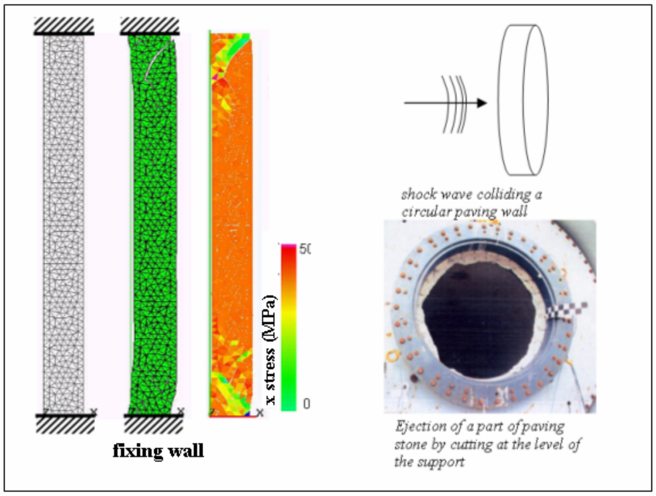


**Figure 8:** Bending of concrete wall and support condition influences. Slab ejection by shear failure on a shock tube test

## 6 Conclusion

The experiment of a stuffy explosion offers a rich data base for various configurations of explosion and allowed to put in evidence the main parameters of load.

Our approach by the observation of fragmentation elementary physical mechanisms allowed us to model the various aspects of the concrete rupture. We have proposed a model to determine the rupture of the structure according to the explosion type load. The simulation by discret elements of a modified Split Hopkinson Pressure Bar test, allowed to determine the main physical parameters of our model. We saw also the influence of the dynamic material behavior.

The simulation of a reinforced concrete wall under several loads and various boundary conditions show that our model is able to simulate the fragmentation phenomena (dynamic load, flexion of the structure, stress concentration).

The proposed model is limited to 2D simulations, however LMGC90 software allows 3D simulations in the case of rigid elements. An adaptation is in development for elastic bodies. We noticed the importance of 3D effects in the behavior of the structure. The future development will allow us to model more complex forms of wall, complete structures and realistic armatures. The compaction phenomenon and the increase of the resistance according to the speed of deformation must be directly taken into account by the model. The computation time remain prohibitive in the case of a long duration load. The elasticity of the interface punishes computation. A new implicit formulation of the interactions laws is curent studied to overcome these computation time limitations.

**References:**

[1] Bailly P. (1995) : Dynamique des bétons et des roches : modélisation et bilan scientifique du GRECO Géomatériaux 1994. In : Mécanique des Géomatériaux, Darve's edition, Hicher et Reynouard Hermes, Vol.2, Paris.

[2] Romero H. (2003) : Fragmentation du béton sous explosion : Etude d'une explosion confinée, PhD, University of Montpellier.

[3] MABS10 (1987) : Tenth international symposium on military applications of blast simulation . In : Bad Reichenhall, Germany, 21-25 September .

[4] Technical Manual n°5-1300 (1969) : Structures to resist the effects of accidental explosions, departement of the army, the Navy and the Air Force. In : Air Force manual, Navy publication NAVFAC 397/ AFM 88-22.

[5] Klepaczko J. (1990) : Dynamic Crack Initiation : Some experimental methods and modelling. In : Springer-Verlag Vienna, New York.

[6] Brara A., Camborde F., Klepaczko J. R. and Mariotti C. (2001) : Experimental and numerical study of concrete at high strain rates in tension. In : Mechanics of Materials, Volume 33, Issue 1, January, pp. 33-45.

[7] Moreau J.-J. (1994) :Some numerical methods in multibody dynamics: application to granular materials. In : Eur. J. Mech. A/Solids, Vol. 13, pp.93-114.

[8] Jean M. (1999) : The non-smooth contact dynamics method. In: Computer Methods Appl. Mech. Engrg. Vol. 177, pp.235-257.

[9] Raous M., Cangémi L., Cocu M. (1999) :Consistent model coupling adhesion, friction and unilateral contact. In: Computer Methods Appl. Mech. Engrg.,N°177, pp. 383-399.

[10] Fremond M. (1982) : Adhesion et contact unilateral. In: Contact Mechanics and Wear of Rail/Wheel Systems. British Columbia University of Waterloo Press, Vancouver 6-9 July, pp. 63-77.

[11] Bretelle A.S., Cocou M. and Monerie Y (2001) : Unilateral contact with adhesion and friction between two hyperelastic bodies. In : International Journal of Engineering Science, N° 39, Issue 18, December, pp. 2015-2032.

[12] Jourdan F., Alart P., Jean M. (1998) : A gauss-Seidel like algorithm to solve frictional contact problems. In : Computer Methods Appl. Mech. Engrg.,N°155, pp. 31-47.

[13] Jean M., Acary V., Monerie Y. (2001) : Non smooth contact dynamics approach of cohesive materials. In:Proceedings Royal society, London pp. 2497-2518.

[14] Dubois F., Jean M. (2003) : LMGC90 une plateforme de développement dédiée à la modélisation de problèmes d'interaction. In : Actes du colloque CSMA de Giens, France, pp. 111-119.