CMEX PROJECT :DEVELOPMENT OF A CONSTITUTIVE MODEL FOR CAST PLASTIC BONDED EXPLOSIVES

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The mechanical behavior and failure properties of the cast PBX B2211D (RDX/AP/Al/HTBP) have been investigated throughout a large set of experiments : static tensile test, SHPB test, reverse Taylor test and Brazilian test. In addition, some experiments on other energetic materials are also reported for mechanical behavior comparison. A nonlinear viscoelastic model implemented in LSDYNA was developed. This model is based on non-linearity observed in static tensile experiments and includes a damage variable representative of the dewetting of solid particles. The CMEX model gives reasonable results in comparison with uniaxial static and dynamic experiments. The numerical results for 2D/3D experiments, the reverse Taylor test and the dynamic Brazilian test, are discussed.

INTRODUCTION

Solid energetic materials are used in many different defense and space applications. These materials are subjected to mechanical loading during functioning of the systems that used it and can be subjected to high dynamic loading in accidental impacts.

For solid propellants, most of the functional loads are in the quasi-static or low frequency regime: thermal loading, pressure rise at ignition or pressure gradient. In the field of interior ballistic of guns, propellant grains may be subjected to dynamic loading which can lead to potential accidental situations by development of anomalous burning surface area. The increase of performance for future munitions such as penetrators implies severe mechanical loading of the explosive charge and can cause shearing, failure, friction and then premature ignition. In safety problems, mechanical damage increases sensitivity of energetic materials and plays an important role in initiation and violence of reaction. The large field of applications explains the interest of experimental and numerical studies on mechanical behavior of energetic materials.

In this paper, we present experimental results looking at the mechanical behavior and failure properties of the cast cured PBX B2211D (RDX / AP / Al / HTBP). The experiments include quasi-static tensile test at different strain rates and temperatures, SHPB dynamic compression, reverse Taylor test and dynamic Brazilian test. The inelastic behavior of B2211D as revealed by reverse Taylor test is also compared with experimental results of some other energetic materials : a NTO based PBX, two gun propellants and a solid propellant.

A numerical model CMEX (Constitutive Model for cast Explosive) under development is used to analyze experimental results. This model is based on a generalized Maxwell viscoelastic model with n components and includes a damage variable representative of debonding between binder and solid particles.

BACKGROUND

It can be considered that pioneer work on mechanical behavior on high filled polymers has been done on solid propellants in the early 70's by a group conducted by R.J. Farris, R.A. Shapery, L.R. Hermann, J.R. Hutchinson[1] who has developed a non linear viscoelastic model based on vacuole formation and an implicit finite element code utilizing these relation. SNPE has experienced this model[2,3] but poor performances of computers at this time (FEM code was running with 64K storage memory) restrict the use of this too complex model for engineering design. Nevertheless, some basic ideas are still remaining in recently developed models[4,5]. All these efforts are for structural assessment of solid propellant grains and are mainly devoted to static loads. On an other hand, detailed mechanical models have been developed for safety assessment of energetic materials. SNPE has been involved in the improvement of the micromechanical damage model BFRACT[6] necessary to be applied to energetic materials and this version of BFRACT has been also used[7] elsewhere.

In this paper, we are focusing on intermediate strain rate for design of explosive charge submitted to functional acceleration or deceleration and so it is not necessary to detail fracture mechanisms as for safety analysis. Some non linear viscoelastic models exist and are suitable for this kind of applications[8,9]. One of the key for modeling mechanical behavior of composite energetic materials is the definition of the continuum field governing damage process. We have recommended[10] that damage be firstly initiated by the strain field in accordance with a vacuole formation model. We may imagine that the growth of damage is governed by the stress tensor as in the classical mechanics of fracture but it is not clear if the full stress tensor or the deviatoric stress tensor has to be considered. For example, failure of composite energetic materials in tensile test under pressure occurs with the three principal stresses being negative. This difficulty to distinguish tensile or compression in a multi-axial state is similar for geomaterials and some insight in this problem is given by a three invariants model[11]. Considering the complexity of the mechanical behavior of composite energetic materials, the CMEX model was kept simple with few parameters in order to be applied in the future to help engineering design of real systems.

EXPERIMENTAL

Quasi static tensile data

Tensile static experiments were performed at different strain rates and different temperatures. The temperature range is from -40°C to + 60°C and three strain rates were used: .1215, .01215 and .001215 s^{-1}. The data is analyzed with time-temperature superposition principal as described by Williams, Landel and Ferry[12]. The Young modulus is plotted as a function of the reduced time (time to reach the maximum engineering stress of the strain-stress curve) in figure 1. The reduced time is the real time divided by the shift factor usually noted a_T.

High strain rate compression testing

Dynamic mechanical properties were assessed by split Hopkinson pressure bars experiments (SHPB). To improve impedance matching with the material studied, the striker and the incident and transmitter bars are in polymeric materials : polymethyl-methacrylate (PMMA) and in polyamide (Nylon) for a system developed more recently. The polyamide system allows longer bars (3m for the incident bar and up to 1.13m for the striker bar) and then larger compression of the sample. The large diameter (40 mm) of the bars insures a sufficient stiffness. The incident, reflected, and transmitted waves are measured by strain gauges mounted on the incident and the transmitter bars. The strain measurements are used to calculate forces and velocities at the sample–bars interfaces. The shifting technique[13] based on 3D Fourier stationary harmonic wave analysis for viscoelastic bars implemented in the DAVID software is used. Different impact velocities and different sizes of the sample provide different strain rates varying from 400 to 1100 s^{-1}. The initial Young modulus obtained in two SHPB experiments are reported figure 1.

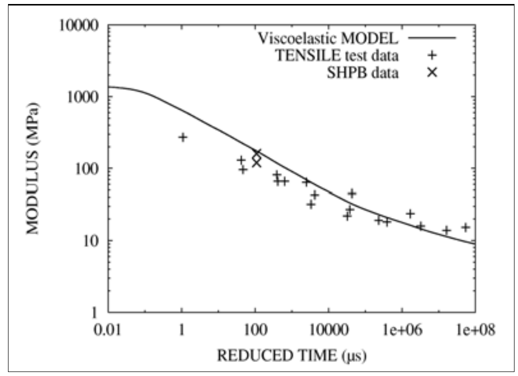

FIGURE 1. B2211 TENSILE TEST AND SHPB DATA

Reverse Taylor test

The reverse Taylor test used at SNPE is based on the configuration devised at SRI[14] and has been improved by a VISAR measurement of the rear surface velocity of the sample[15]. The test is briefly recalled. An aluminum rod is launched by a light gas gun and impacts a cylindrical sample. The well-controlled impact conditions lead to tilt less than few mrad. A soft recovery chamber allows examination of the sample after impact with no additional damage.

The reverse Taylor test has multiple goals. Firstly, it is used to observe macroscopic and microscopic dynamic failure and amount of damage as a function of impact velocity. The table 1 summarized experimental results on the explosive B2211D.

TABLE 1. REVERSE TAYLOR TEST-DYNAMIC FAILURE RESULTS ON B2211D

Shot Number	*Impact velocity (m/s)*	*Damage**
1/99	49.4	No/-
2/99	84.2	Yes
3/99	60.4	No/-
4/99	49.4 + 59.8	Yes
1/00	74.2	Yes
2/00	65.4	Yes
3/00	52	No/No
4/00	61	Yes
5/00	55.3	No/Yes
6/00	53	No/Yes

* Macroscopic Damage/Microscopic damage if investigated

A typical macroscopic failure with radial cracks at the periphery of the sample is illustrated figure 2. In some experiments, the recovered sample with no visual failure has been cut and scanning electronic microscope analysis revealed internal cracks. In table 1, an arbitrary threshold of about one mm is used to quantify microscopic damage. Cumulative damage has been investigated in shot number 4/99. A sample primary impacted at 49.4 m/s with no resulting apparent damage was reimpacted at 59.8 m/s. This second impact results in a very large damage of the sample with a conical plug which can be separated from the main part of the sample (figure 3). Although more experiments will be needed, it seems that microscopic damage occurring in a first load generates large macroscopic damage in a second load of the same magnitude of the first one. The shape of the damage plug may be attributed to tensile stress due to rarefaction waves originating from the lateral surface of the sample after the shock compression phase.

The reverse Taylor test has been also operated as the classical Taylor test. The deformation of the specimen is registered by a high-speed DYNAFAX camera and the digitalization of the photographs gives profiles of the sample at various times during the impact. For the experiments with no macroscopic failure, the deformation of the sample is very small and so the accuracy is too weak to get quantitative information in order to determine a constitutive model for the explosive. This information is then only used for checking that the numerical model gives the good stiffness of the material.

FIGURE 2. MACROSCOPIC FAILURE OBSERVED IN SHOT 4/00

FIGURE 3. CUMULATIVE DAMAGE AFTER TWO IMPACTS (SHOT 4/99) (left: after first impact, right: plug after second impact)

The mechanical behavior of the material is more investigated by the VISAR measurement which provides the viscoelastic response in a large continuum spectrum. The large time to reach the final velocity (about 200 µs) is mainly due viscoelastic properties and the value of this velocity is a measurement of the inelasticity of the material. The experimental results indicate a quite complete inelasticity for the B2211D PBXs. However, it must be emphasized that the reverse Taylor test involves, especially during the first microseconds after impact very high dynamic loading which is not quite relevant to the domain of functional loads on explosive charges but which is more similar to situations in safety analysis. The overall elasticity response can be resumed by the ratio:

$$R = \frac{V_f}{V_i} - 1$$

where V_i is the initial velocity of the long rod impactor and V_f is the final velocity of the sample as measured by the VISAR system. This ratio is equal to 1 in an ideal purely 0D elastic impact.

Table 2 summarizes experimental results for two PBXs B2211D and B2214 and for other energetic materials : two gun propel-lants and a solid propellant. The inelasticity of the two PBX compared to the two gun propellants in this high dynamic loading is probably mainly due to the heterogeneous nature of the PBX which have a high amount of solid charges.

TABLE 2. ELASTICITY RATIO IN REVERSE TAYLOR TEST

Material	*Impact velocity (m/s)*	*Elasticity ratio R*
B2211D PBX (RDX/AP/Al/HTPB)	48.6	0.0
	60.4	0.1
	84.0 (*)	0.0
B2214 PBX (HMX/NTO/ HTPB)	41.0	0.0
	51.0	0.0
Single base gun propellant (NC)	10.3	0.5
	32.6	0.5
	78.0	0.6
	82.4 (*)	0.3
	75.9	0.5
Double base gun propellant (NC/NG)	79.0	0.3
Solid propellant (AP/Al/ HTPB)	74.2	0.15

(*) Macroscopic failure of the sample

Dynamic failure testing

Split Hopkinson bars have been used to perform Brazilian test on brittle materials such as concrete or ceramic in order to investigate dynamic failure properties at high strain rate. We have applied this technique to the B2211D PBX. The two experiments reported here were performed with the Nylon bars and the long 1.13 m striker bar and samples were 36 mm diameter and 10 mm thickness. In addition to the strain measurement on the bars, the deformation of the sample and the initiation and propagation of failure are followed by a numeric high speed video (30000 i/s). The striking velocity in the experiments were 9.9 m/s. Figure 4 shows photographs of one experiment at initial time and the first beginning of failure which occurs 1250 µs after impact of the incident bar. This failure appears at the center of the sample but white cross traces seemed to indicate shearing of the sample as known in such configuration [16].

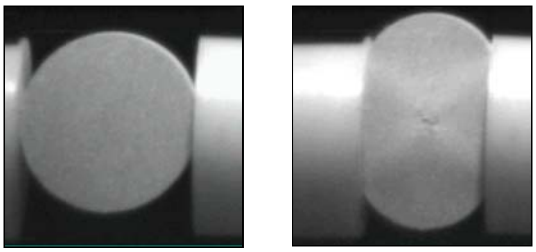

FIGURE 4. PHOTOGRAPHS OF DYNAMIC BRAZILIAN TEST (left: initial , right: first failure)

CMEX MODEL

Linear analysis

The skeleton of the CMEX model is a generalized Maxwell viscoelastic model with n components that we have implemented in LSDYNA3D code[15]. The spherical part of the stress-strain relation has not yet been developped and is purely elastic. This viscoelastic model is used for engineering design[17] and when it is restricted to a small domain of strain and strain rate, it may represent correctly some particular experiments such as SHPB compression or reverse Taylor test. However, it suffers of physical basis for large strain where it is known that non-linear effects occur, firstly by debonding between solid particles and binder. The objective of this work is an attempt to fill this lack of physics in the model.

The master curve of modulus from tensile test data is fit by a Prony series with ten components and the shear modulus is derived assuming incompressibility :

$$G(t) = G_{\infty} + \sum_{i=1}^{10} G_i e^{-t/\tau_i}$$

The initial Young modulus obtained in two SHPB experiments is also reported figure 1. As experimental results are from different material lots, it is difficult to say if the observed scatter in the data is due to usual scatter in mechanical properties measurement or material or has a physical meaning. The SHPB point obtained more recently with Nylon bars is thought the most appropriate for this study and is therefore enhanced in the fit. The resulting viscoelatic secant modulus in a constant strain rate experiment, expressed as a function of time :

$$E(t) = E_{\infty} + \sum_{i=1}^{10} E_i \frac{\tau_i}{t} (1 - e^{-t/\tau_i})$$

is reported in the figure 1. The fit preserves the decrease of E_i as a function of τ_i because it seemed more physical regarding to the complete curve E(t). This unique viscoelastic model is used throughout the CMEX computations presented in this work.

Non linear analysis

The master curve is roughly analyzed in an engineering way. Each tensile experiment is summarized by the three mechanical characteristics : the Young modulus E, the maximum (engineering) stress S_m, the maximum (engineering) strain e_m. The stress-strain curve is approximated by the reduced form [18] :

$$y = x\, e^{\frac{1}{n}(1-x^n)} \qquad \textbf{(1)}$$

using the reduced variables $y=\sigma/S_m$, $x=\varepsilon/e_m$.

The coefficient n which can be seen as an index of ductility is plotted figure 5 for the two PBXs B2211D and B2214. Despite some usual scatter of the data, we can observe as a general trend that n decreases with decreasing reduced time (or in some way increasing strain rate). Nevertheless, a constant value of n=1 is kept in CMEX model for simplification.

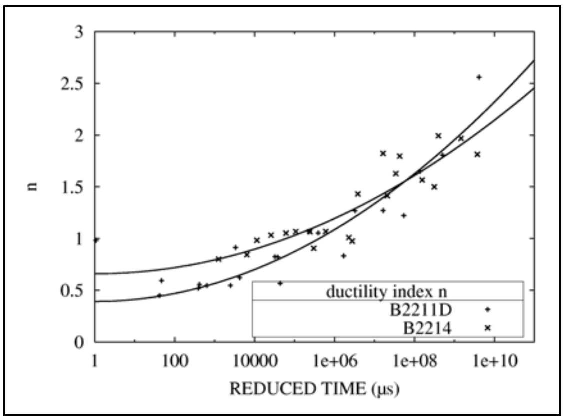

FIGURE 5. INDEX OF DUCTILITY VERSUS REDUCED TIME FOR B2211D AND B2214

The dewetting of solid particles which is the first non linear process is studied for the B2211D PBX on three tensile experiments at three constant strain rates. The non linear threshold is determined by the simple model derived from the previous analysis :

$$\sigma = e^{-\alpha \,\mathrm{Max}\,(0,(\varepsilon-\varepsilon_d))} \int E\,(t-\tau)\, \frac{\partial \varepsilon\ (\tau)}{\partial \tau} d\tau \qquad \textbf{(2)}$$

The results are given in table 3 and figure 6 shows the comparison between the experimental results and the model. It is observed that the non-linear threshold is decreasing with strain rate and that the maximum rate α is quite constant. These observations are consistent with basic ideas of mechanical behavior of such materials. The increase of strain rate leads to less spreading of efforts in the binder and then to more stress concentration at the interface between binder and solid particles. The constant value of α indicates that, in the domain explored, the final collapse of the material is mainly governed by the debonding process and not by binder or solid particles failure. Due to the lack of reliable data on high strain rate tensile testing, these results are extrapolated for dynamic loading : the non linear threshold ε_d is set to 0 and the α parameter is kept constant.

TABLE 3. NONLINEAR ANALYSIS OF 3TENSILE TESTS ON B2211D

Strain Rate (s^{-1})	*Threshold* ε_d	*Max rate1/*α
.001215	.115	.249
.01215	.084	.270
.1215	.041	.243

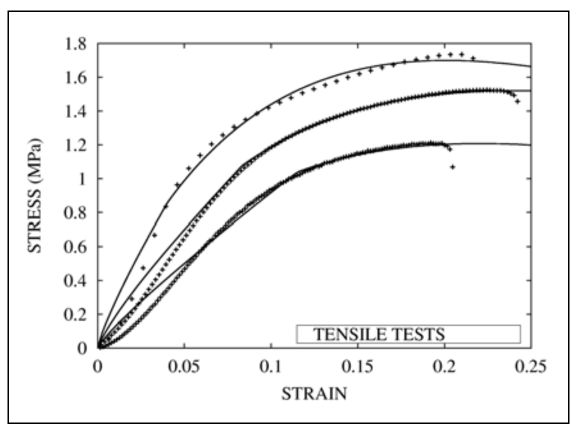

FIGURE 6. EXPERIMENTAL (points) AND NUMERICAL (solid lines) RESULTS
ON TENSILE TESTS FOR B2211D

With this assumption, equation (1) may be rewritten :

$$\sigma'_{xx} = (1 - D_d)\, \sigma'^{V}_{xx} \qquad \textbf{(3)}$$

$$\dot{D}_d = \alpha\,(1 - D_d)\,\dot{\varepsilon}_{xx} \qquad \textbf{(4)}$$

where the σ'^{V}_{xx} is the deviatoric viscoelastic part of the stress tensor. This form is more convenient for implementation in an explicit code.

One of the key of mechanical behavior modeling of high filled polymers is to distinguish tensile state from compression state. In one dimensional tensile test, equation (4) is rewritten :

$$\dot{D}_d = \alpha\,(1 - D_d)\,\hat{\dot{\varepsilon}}$$

$$\hat{\dot{\varepsilon}} = \sqrt{\sum (\mathrm{Max}(0, \dot{\varepsilon}_p))^2}$$

where $\dot{\varepsilon}_p$ are the principal strain rates.

This is the present form of the CMEX model currently implemented in LSDYNA code. Figure 7 shows the stress-strain curve of the SHPB compression test with Nylon bars reported in the figure 1 and CMEX model results for tensile and compression at the same strain rate. The comparison of experimental and numerical results is satisfactory regarding that the same model gives also nicely results for quasi static tensile tests corresponding approximately to strain rate 10^5 times lower and stress 10 times lower.

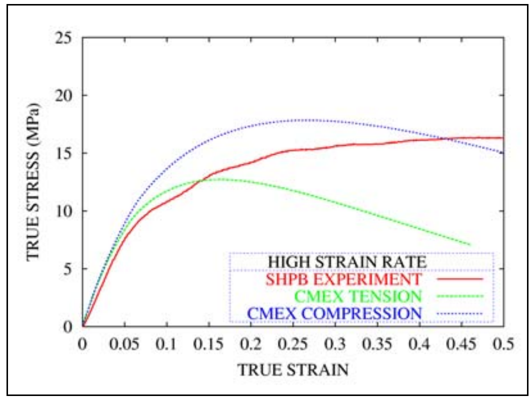

FIGURE 7. COMPARISON OF SHPB EXPERIMENT AND CMEX RESULTS-CMEX RESULT IN TENSION

Failure analysis

The linear cumulative damage theory of Miner[19] is used to model failure at different strain rates and temperatures. Failure is defined here as the maximum stress of a stress-strain curve in a tensile experiment. The uncoupled macroscopic damage, which includes debonding but also unknown mechanical processes of propagation and coalescence of microcracks between debonding sites is defined by :

$$D_f(t) = a\ \|\sigma\|_m\ ;\ D_f = 1 \text{ at failure}$$

a and m being material coefficients and :

$$\|\sigma(t)\|_m = \left(\int_o^t \sigma^m(\tau)\, \frac{d\tau}{a_T} \right)^{1/m} \qquad \textbf{(5)}$$

Using the reduced form (1) of a stress-strain curve for a tensile test and after some integral transforms, the calculation of the damage D_f along a tensile curve is straightforward. The damage at failure for each tensile test of the master curve is plotted figure 8 for the two PBXs B2211D and B2214. For a 3D stress state, the use of this damage variable needs a multi-axial criteria.

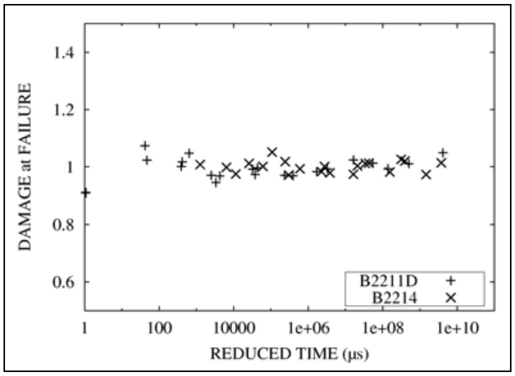

FIGURE 8. DAMAGE AT FAILURE VER-SUS REDUCED TIME FOR B2211D AND B2214

EXPERIMENTAL AND CMEX MODELING RESULTS

In a previous study[15], it was expected that the discrepancy between VISAR measurement and numerical simulation of the reverse Taylor test was due to non linear effects. The CMEX modeling gives reasonable results at the beginning of loading but do not really improve the result for the final velocity of the sample. The quite complete inelastic behavior observed may be reproduced by dropping E_i modulus which are out of the time range of the loading but it is not physically consistent. An other explanation of these results has been suggested[9] and supposes a non linear viscoelastic bulk behavior. We think that the high transient dynamic loading during the first microseconds leads to intense stresses and strains around the solid particles, especially for large particles and results in microcracks and bulk energy dissipation in the binder. This mesoscopic behavior due to the heterogeneity of mechanical properties of solid particles and binder is out of the scope of the CMEX model developed here. Numerical simulation gives reasonable value of damage D_d due to distorsion and is representative of damage observed in figure 2.

By added a very simple bulk damage model :

$$\dot{D}_k = 3\alpha(1 - D_k)\max(0, \dot{\varepsilon}_v)$$

$\dot{\varepsilon}_v$: volumetric strain rate

we observe a damage inside the sample which can be compared to the experimental plug of the figure 3.

In the dynamic Brazilian test, we use moving stonewalls with applied experimental velocities for modeling the input and output bars. It is well known that low impedance bars leads to oscillations in measured pulses [20] and which are here enhanced by the large diameter of the bars. The comparison of experimental results and CMEX modeling are then made on the output force. Figure 9 shows the good agreement between experimental and numerical results. The numerical model predicts high level of shearing before high tensile stress at the center of the sample. An analysis of failure was conducted using the damage model D_f and a Von Mises-Stassi multi-axial failure criteria[3] but we find that this model overestimates the damage in the sample compared to experiments. Instead, we have used the maximum in plane shear and tension as specific components of the stress tensor suitable for this test. This specific stress integrated in the uncoupled macroscopic damage D_f of equation 5 gives reasonable prediction of the time to failure. Detailed analysis of numerical simulations of the reverse Taylor test and the Brazilian test are currently in progress.

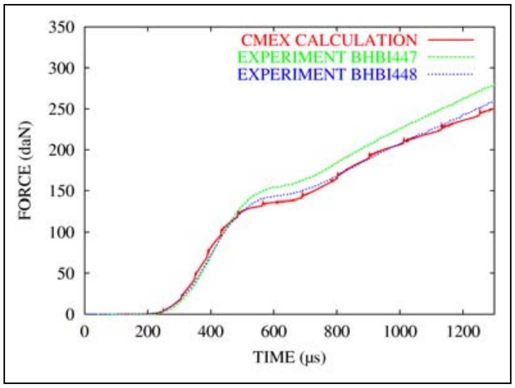

FIGURE 9. EXPERIMENTAL AND NUMERICAL FORCES IN BRAZILIAN TEST

CONCLUSIONS

A large experimental data on mechanical behavior of cast PBXs has been constructed and includes experiments from static regime to high transient dynamic loading. The CMEX model under development is intended to represent the viscoelasticity of this materials and the first non linear effects which are attributed to the binder-solid particles interaction. The model gives nicely results for different static and dynamic experiments but is found insufficient in some cases, involving highly transient loading for example. The major tasks to improve the model should be the development of a model which represents how the stress tensor drives the growth of damage in any fully 3D state, the development of a more realistic equation of state at low pressure and coupling spherical and deviatoric parts of the stress and the strain tensor. It is recognized that a complete mechanical model for such materials remains a challenge due the very different physical properties of the constituents and it may be asked what are the limits in the field of continuum mechanics. New methods such as direct simulation at the mesoscopic level with classical FEM codes or DEM (Discrete or distinct element methods) will probably give some answers in the future.

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