EUROPEAN MECHANICS SOCIETY

Colloquium Final Report

N. 605 – Damage and failure of engineering materials under extreme loading conditions

Dates and location: **21/05/2019 - 24/05/2019, Madrid, Spain**

Chairperson **Jose A. Rodríguez Martínez**

Co-Chairperson **Daniel Rittel, Sébastien Mercier**

Conference fees

- Regular registration fee **425.0 €**
- Student registration fee **250.0 €**

What other funding was obtained? **we received financial support from Mecamat (the French Mechanics of Materials group) and the University Carlos III of Madrid through the project 2019/00137/001. The colloquium also received funding from the European Union's Horizon 2020 research and innovation programme, through the projects OUTCOME (GA-675602), QUANTIFY (GA-777896) and PURPOSE (GA-758056).**

What were the participants offered? **The registration fees included:**
- A bag with the conference schedule, list of participants, list of session chairmen. They also received tourist information about Madrid.
- Welcoming cocktail-dinner on Tuesday evening in the rooftop of the hotel ME Madrid Reina Victoria.
- 3 coffee breaks on Tuesday, 3 coffee breaks on Wednesday and Thursday, and 1 coffee on Friday. The coffee breaks included a variety of delicatessen, refreshments, beverage, cakes and fruits.
- 4 lunches at the Restaurant of the Hotel Puerta de Toledo, Madrid.
- Gala dinner in the Restaurant el Rincon de Esteban.
- A professional photographer took pictures of all participants during the opening, cocktail and banquet. The pictures were distributed to the participants.

Number of members of Euromech (reduced registration fee) **17**

Number of non-members of Euromech (full registration fee) **40**

Applicants (members)

- Curt Bronkhorst
- Vyacheslav Burlayenko
- Oana Cazacu
- Laura De Lorenzis

- Vikram Deshpande
- Antonio Gamez
- Odd Sture Hopperstad
- Xanthippi Markenscoff
- sebastien mercier
- Dirk Mohr
- Alain Molinari
- Alan Needleman
- Michael Ortiz
- Anna Pandolfi
- Anna Marina Pandolfi
- Daniel Rittel
- José Rodríguez-Martínez

Applicants (non members)

- Lisa BAKKALI
- Nicola Bonora
- Tore Børvik
- David A. Cendon
- Sagi Chen
- Luke Chown
- Irfan Habeeb Chuzhali Nilath
- Michel CORET
- Christophe Czarnota
- Manjunath Dakshinamurthy
- Daniel Eakins
- Skander EL MAI
- Juan Carlos Nieto Fuentes
- Juan Carlos Nieto Fuentes
- Kokouvi Gbetchi
- George Gray III
- Benat Gurrutxaga Lerma
- Navab Hosseini
- Nicolas Jacques
- Leslie Lamberson
- Qingming Li
- Patrice Longère
- Patrice LONGERE
- Bentejui Medina
- Bentejui Medina-Clavijo
- Komi Espoir N'souglo
- Oleg Naimark
- juan carlos Nieto Fuentes
- Shmuel Osovski
- Antonio Perillo Marcone
- Chun Ran
- Nicolas Ranc
- Gonzalo Ruiz
- Ankit Srivastava
- Manoj Subramani
- Claudio Torregrosa Martin
- Guadalupe Vadillo
- Álvaro Vaz-Romero Santero
- Patricia Verleysen
- Haim Waisman

Scientific Report

Damage and failure of deformable solids is a constantly evolving scientific field which poses a real challenge in terms of comprehension, control and modeling. Indeed, since the early notes of Leonardo da Vinci circa 1500 CE, where presumably the first mechanical tensile test was described, scientists are still seeking to properly understand, characterize and model the mechanical behavior of materials under various loading and environmental conditions. Solid structures, especially those subjected to EXTREME LOADING CONDITIONS (topic of the colloquium) – such as several aerospace components or protective armor elements for military applications – have to be designed to delay a potential damage and failure under service. Under certain conditions, the material may be exposed to an outburst of intense phenomena, that may cause e.g. a sudden increase of temperature, microstructural transformations, geometrical changes, or internal instabilities driven by inertial loads. As the experimental capabilities offer the possibility to have a deep observation of the evolution of the structure under extreme loading conditions, the efforts made by researchers in the past years have to be renewed in order to propose more advanced and dedicated modeling. In addition, driven by different industrial sectors (defense, automotive, aerospace), the research devoted to the analysis of the physical mechanisms responsible for damage and fracture under EXTREME LOADING CONDITIONS concerns all engineering materials like metals, polymers, ceramics and composite. Nevertheless, despite the significant efforts spent by scientists in increasing their understanding of the processes of strain localization, damage and failure, it is apparent that a number of questions remain open, notably on the origin of strain localization or dynamic fracture, how to control and prevent it.

The goal of the Euromech 605 held in Madrid was to discuss the latest achievements on the subject of dynamic failure of materials. In single-session presentations for 4 days, 49 participants from 13 different countries and 3 different continents (Europe, America and Asia) –36 presentations in total– had the chance to share their latest (mainly unpublished) results and advances on the topic. Fruitful and informal discussions between well-known researchers in the field and novice researchers were also encouraged.
The main topics discussed during the talks in the colloquium were:

The physics and mechanics of adiabatic shear bands

Characterized by areas of an intense shear localization, as those found in high speed machining chips, the onset of failure by adiabatic shear banding (ASB) is still debated. On the one hand, the high temperature rise developed in the localized area may soften the material and precede fracture. On the other hand, the microstructural evolution –such as dynamic recrystallization– may play an important role and precede the latter phenomenon. State of the art on numerical approaches and new experimental techniques were presented and discussed during the colloquium. It is still unclear whether temperature elevation induces the softening or whether microstructural changes, associated later with temperature increase induce the localization. Based on dedicated observation of various alloys, some assumptions were discussed but the origin is clearly material dependent. Under dynamic loading, the localization process leads to a narrow zone of intense deformation. This very thin area of intense deformation needs specific treatment when it attempts to be modeled using numerical methods. Several numerical approaches were discussed during the colloquium, showing the regularizing effect of thermal conductivity in the numerical results, which allow to predict shear bands of finite thickness. It was concluded that the shear band width can be linked to the thermal conductivity of the material. Nevertheless, some other physical

mechanisms which may lead to regularization (introducing a length scale) were discussed. In particular, further research is needed to elucidate the regularization mechanisms in dynamic problems dominated by inertia.
The effect of combined (shear dominated) loading was also discussed extensively during the symposium. Indeed, it was shown that prescribing a pure shear mode of deformation is almost impossible in experiments using the hat sample or the butterfly sample. A new device combining torsion and confinement was presented which opens new perspectives for the dynamic analysis of the mechanical behavior of metallic materials under shear-dominated dynamic loading. From a modelling standpoint, it was shown that a compressive component added to the principal shear loading may prevent to a large extent localization, delaying the onset of shear banding.

Inertia-driven structural instabilities

The formation of structural instabilities –e.g. necking, buckling or wrinkling– strongly depends on the rate of loading. Under static conditions, a circular bar subjected to uniaxial tension, develops a neck in the weakest section of the specimen, while under dynamic loading the role of stress wave propagation, or inertia itself, determine the number of necks and the location of failure, that can occur away from the weakest section of the specimen. For instance, the number of necks and fragments in rings subjected to dynamic expansion depends on the applied velocity, as extensively discussed in some of the talks. The influence of anisotropy on the formation of dynamic necks in metallic shells was also investigated. In this regard, new analytical, numerical and experimental approaches were presented to monitor and identify the loading conditions and materials behavior that control necking at high strain rates. For instance, a new two zone model was presented to model necking under biaxial loading. This model, which accounted for the stress triaxiality in the necked section using Bridgman approximation, was validated with finite element calculations. Nevertheless, the two-zone model predefines the shape of the defect, which raised several questions regarding the effect of the imperfection on the results. Necking is a geometric instability and as such depends on the specific structure investigated, which leads to the of what is the specific contribution of materials properties and boundary conditions on the formation and growth of dynamic necks. The problem of multiple necking under uniaxial tension was also addressed with a new linear stability approach that, unlike most of the currently available analytical models, captures the scatter in the dominant wavelengths which dictate the multiple necking pattern at high strain rates. Interestingly, the model relies on theories that were already developed in other fields of the physics: analysis of noise, of wave propagation on the ocean, and opens new routes to bring to light the role of surface roughness in the formation of necking instabilities in dynamic problems.

Micromechanics of dynamic ductile fracture

Dynamic ductile fracture is usually characterized by a three-stage process: nucleation, growth and coalescence of voids. To study the related phenomena, analytical yield criteria at moderate strain rates have been commonly used for the last decades. Thus, micro-inertia effects are frequently neglected, which in the case of high loading rates could be very important (up to take full control of the fracture process). Participants presented very recent progresses in analytical modeling and finite element simulations of dynamic void growth in porous materials, and the role of cavitation and internal pressure in the nucleation of voids in, initially, defect-free materials. The interaction between neighboring voids was also investigated with various numerical approaches. Depending on the spatial distribution of initial voids, different modes of deformation develop, which dictates the dissipation of energy in the material and thus the damage and fracture processes. There was a talk devoted to analyzing the formation of void-growth driven damage at intercepting beam devices used at CERN. These devices, usually made of heavy alloys, are exposed to high-intensity X-ray beams, which generate a large increase of temperature in the material, leading to enormous variation in hydrostatic pressure which leads to the rapid growth of voids. In this application the interplay between temperature rise and high stress variations makes the problem particularly challenging. Moreover, there were several discussions on the application of additive manufacturing to build metallic protective structures. This subject is currently attracting the attention of many researchers, which are modelling these materials with porous-plasticity theories to account for the internal porosity that 3D printing induces during the manufacturing process. Modelling dynamic behavior of 3D printed metals was identified as a new subject of research for the next few years. The void-growth process in single crystal material was also discussed during the colloquium. Some presentations were focused on the influence of anisotropy and tension-compression asymmetry on the development of damage in dynamically loading specimens. Some other talks revealed the effect of hydrogen-embrittlement, which is an important issue in many industrial applications, and a micro-mechanical model to capture the formation and propagation of cracks due to hydrogen-embrittlement was presented. Moreover, it was shown that when a honeycomb-type structure faces dynamic loading, the porosity evolution is governed by two length scales which strongly influence the mechanical behavior of the part. This type of honeycomb structures present interesting dissipation properties at very large strain rate, which is an important issue that requires further investigation and experimental validation. The role of grain boundaries and grain orientations on dynamic damage in various metals and alloys was illustrated by different numerical approaches. Intergranular fracture was modeled by considering cohesive elements. Weak and strong boundaries were modeled. It was shown that the dynamic toughness is strongly linked to microstructural features of the material. It was concluded that controlling the strength of the grain boundaries, the energy dissipated during dynamic loading process can be tailored.

Dynamic mechanical and thermomechanical behavior of metals across scales

It is well known that the dynamic mechanical response of a ductile material depends on the microstructural (density and type of defects) evolution during deformation. However, little is known about the thermomechanics enclosing these events. During the colloquium, it was shown that under dynamic (adiabatic) conditions the amount of energy stored by internal defects (microstructure) during deformation can be related with the macroscopic thermomechanical (heat to work ratio) response of the material. As discussed during the meeting, further numerical and experimental work to link thermomechanics across scales is still needed. At very large strain rate, dislocations dynamics are a very promising tool. In fact, results obtained at the level of dislocation dynamics can be used to feed meso-scale models. This upscaling is not yet widespread in the community and needs additional research. On the contrary, industry demands ready-to-use models that are reliable and enable to provide predictions in short periods of time. For materials presenting complex microstructural changes during loading (e.g. multi-phase steels used in automotive industry), the currently available models present important limitations to offer predictions of fracture for wide ranges of loading rates and stress states. In this regard it was suggested that machine learning may provide an effective solution for the previously mentioned industrial demands, as an alternative to traditional mathematical modelling. Nevertheless, it was concluded that further developments in machine learning are needed so that the results will be more physically sounded. Another key topic discussed in the colloquium was the dynamic effects that are found in high cycle fatigue process (gigacycles). In such scenario. quasi static tests cannot be performed, which compels to perform cyclic tests at large frequency and very low strain amplitude. It was shown that measuring self-heating during such tests can help to predict the material behavior in high cycle fatigue process. An overview of all experimental difficulties that are being encountered in this problem were presented, and some preliminary results were discussed.

Dynamic failure of brittle materials subjected to shock and impacts

Experimental and numerical techniques to study brittle failure under impact loading were presented. Multiscale modelling of the behavior of silica glass at high temperatures and pressures was the core of another presentation, which made apparent the importance of considering the microstructure of material to model dynamic brittle fracture and crack propagation in ceramics, polymers and rocks. There was another talk devoted to multiscale modeling of dynamic fracture of brittle materials, including thermal effects at the crack tip. A comparison with some earlier experiments shows that the temperature field measured during fast crack propagation can be quantitatively reproduced. The dynamic mixed-mode fracture of steel fiber reinforced concrete was investigated and (also) modelled using a multiscale approach. The performance of metaconcrete subjected to blast loading was discussed. It was shown that this material provides advanced protective capabilities that may not be obtained with classical fiber-reinforced concrete. Moreover, there was another presentation that showed that, while deep earthquakes can sometimes be considered as a slow process, inertia is playing a role, showing a link between earth sciences and traditional mechanics of materials. The constitutive behavior of foams, polymers and laminates under dynamic conditions was also discussed. There was a talk that illustrated the the influence of the specimen, the boundary conditions and the pre-stretch of the sample on the propagation of dynamic cracks in rubber. Using DIC, it was possible to measure the crack velocity and elucidate the loading conditions that lead to dynamic fracture of the structure.

A tremendously positive feedback from the participants was perceived during the colloquium. We expect new future international collaborations, since new comradeship had flourished between the participants, not only during the presentations, but during the social gathering. The dynamic behavior of materials was shown to be a hot topic on the field of mechanics, and further work is still needed to elucidate the physical phenomena that precedes material failure. Finally, it is noted that the Vice-President for Scientific Policy of the University Carlos III of Madrid opened the Colloquium. We thank the University Carlos III of Madrid for the very professional organization and support. We thank also EUROMECH for making the selection of the topic which has provided a nice possibility for fruitful exchange between all scientists.

Number of participants from each country

Country	Participants
Spain	11
Russia	1
France	12
Israel	7
Poland	1
United States	9
Italy	3
Norway	2
Germany	1
United Kingdom	5
Switzerland	3
Belgium	1
China	1
Total	**57**

Please send this report in electronic form to the Secretary General of EUROMECH, within one month after your Colloquium.