EUROPEAN MECHANICS SOCIETY

Colloquium Final Report

N. 635 – Finite fracture mechanics

Dates and location: **12/09/2023 - 15/09/2023, Lyon, France**

Chairperson **Dominique Leguillon**

Co-Chairperson **Vladislav Mantic, Aurélien Doitrand, Nicolas Carrère**

Conference fees

- Registration fee **120.0 €**

What other funding was obtained? **In addition to Euromech support, we thank INSA Lyon, MATEIS Laboratory, la region Auvergne-Rhone Alpes, MECAMAT association and Carnot Institute for providing financial support to the colloquium.**

What were the participants offered? **The goal of Euromech colloquium 635 was to bring together researchers from the fracture mechanics community. There were 34 participants and 28 presentations. Each presentation was allowed a 40 minutes slot in order to favor discussions. Ample time was also dedicated for informal discussions during the coffee break, lunches and social activities including welcome reception and colloquium diner.**

Number of members of Euromech (reduced registration fee) **6**

Number of non-members of Euromech (full registration fee) **27**

Applicants (members)

- Wilfried Becker
- Israel G. García
- Vladislav Mantic
- Vincent Maurel
- MAR MUÑOZ-REJA
- David Taylor

Applicants (non members)

- KARTHIK AMBIKAKUMARI SANALKUMAR
- Mattia Baldassari
- Pierre Bidaud
- Christophe Bois
- XI CHEN
- Aurélien Doitrand
- Thomas Duminy
- Rafael Estevez

- Francesco Ferrian
- Hugo Girard
- José Luis Guzmán Lóez
- María de los Ángeles Herrera Garrido
- Sara Jiménez Alfaro
- Andrei Kotousov
- Jérémy Le Pavic
- Dominique Leguillon
- Debora Linn
- Hela MENSI
- Gergely Molnar
- khouloud nagaz
- Roman Papšík
- Martin Pletz
- Renaud Rinaldi
- Mahsa Sakha
- Alberto Sapora
- Jean Vereecke
- Zohar Yosibash

Scientific Report

Several topics were addressed in the presentations and further discussed, both regarding theoretical or numerical implementation aspects such as analytical close form expressions, matched asymptotic expansions of full-finite element calculations. Confrontation of finite fracture mechanics to other models (such as e.g., phase-field, cohesive zone models, configurational forces) and confrontation and dialogue with experiments were also addressed. The CC applications were related to failure in adhesive joints failure, fiber-matrix interfaces in composites, bio inspired nacre-like composites, composite laminates at the meso scale, 3D printed composites, hydraulic fracturing, fatigue crack growth, additively manufactured samples, the influence of defects, residual stresses and thermal shock
Specific topics addressed and discussed are hereafter summarized:
The definition of crack nucleation in fracture models was questioned. It is clear that for the coupled criterion, crack nucleation corresponds to the minimum value of the load at which both criteria are fulfilled. Moreover, it adopts a binary description of cracking (either there is a crack, either not) and the crack is defined as infinitely sharp. However, the very definition of crack nucleation was questioned in phase-field models for instance when the internal length is comparable to the specimen size, which may happen when testing small scale specimens. In such a configuration, damage is thus diffused in the whole specimen rather than sharp as in Griffith's description. Comparing stiffness decrease, damage variable and force-displacement curve shed light on the fact that a stiffness criterion yields the closest results to the CC definition of crack nucleation. Otherwise, an overall good comparison between PF and CC was established, for instance under opening mode, in-plane shear mode and out-of-plane shear mode. Good comparison between CC and cohesive zone model was also shown. In some special cases where the process zone is relatively large, significant difference in the estimate of the shear critical energy release rate was noted.

Several discussions arose concerning the different lengths involved in fracture models:
The characteristic displacement jump in cohesive zone models
The length in the theory of critical distances
The internal length in phase-field l_PF
The initiation length in the coupled criterion l_c

It is clear that all these lengths are related to Irwin's length l_mat and can be expressed as a function of it. It is for instance usual that l_c=k l_mat, k being a coefficient smaller than 1. Also, l_PF is proportional to l_mat so that a linear correlation is found between l_c and l_PF. Nevertheless, it is not clear if these lengths actually "exist" in a real material, or can somehow be measured. In the coupled criterion, there is only one configuration where the initiation length could be measured, provided crack initiation is stable and only driven by energy. More often, there is an unstable crack propagation just after initiation that may lead to a further crack arrest. It means that generally, the only length that can be measured experimentally is this arrest length, and not the initiation length. Still, measuring an arrest length and confronting it to the numerical one predicted by the CC is an efficient way to establish an inverse identification of the fracture properties, and an indirect estimate of the initiation length.

The question of machining a natural crack for further fracture experiments arose. Whereas it can be easy to machine a V-notch, crack machining by a saw of laser cut results in a small tip radius instead of a sharp crack, and possibly residual stresses around the machined crack. Nevertheless, it is possible to initiate a stable crack ahead of a V-notch, for instance under compression in the V-notch bisector direction. The size of the created crack and the corresponding loading depends on the geometry (V-notch angle, depth) and on the material. It can be predicted using the CC, which could thus be used so as to design a V-notch specimen to obtain a desired initial sharp crack length after initiation, from which further fracture experiments are made possible.

Regarding the crack definition, an open question concerned the definition of the crack tip. While it is clearly defined in a theoretical LEFM analysis, it is not clear to determine it experimentally or from molecular dynamic simulations for instance. An approach based on William's series can be employed, which yields the equivalent LEFM crack tip. From such an analysis, it is possible to highlight the presence of any perturbations at the crack tip, such as a process zone or a plastic zone for instance. Another way to determine a small perturbation ahead of a main crack, or more generally ahead of a singular point, consists in using matched asymptotic expansions. Any perturbations (small crack, rounded V-notch tip, process zone or plastic zone) can also be detected through Generalized Stress Intensity Factor calculation. For MD simulations, a proposition was made to average the fields by a coarse graining method ensuring mass and energy conservation, and further calculate a damage variable as in phase field fracture. Interestingly, MD simulations of crack initiation showed local stress values larger than the material tensile strength (or more generally out of the material strength surface). The strength surface obtained by MD simulations resembles the strength surface obtained using a spectral split in PF fracture.

The application of the coupled criterion in presence of a small plastic zone/process zone was discussed. It was shown that a plane stress assumption yielded plastic zone shape and size closer to that observed in DIC than plane strain assumption. It was also shown that the plastic zone size was not too different either using a plasticity criterion as a post-processing of an elastic calculation, or by considering elasto-plastic behavior. It is shown that even in the presence of a small yield zone, linear elastic application of the CC tends to a significant underestimate of the failure forces. A suggestion was made that it is not the absolute plastic zone size itself that matters, but rather the increase in plastic zone size due to crack initiation. Two visions emerged from this discussion. The first one consists in trying to keep things as simple as possible and push the model as far as possible. The second one was to try to improve the application of the CC by considering plasticity in the energy balance and identify a plasticity and a failure criterion that enable reproducing the experiments. Regarding plasticity analysis during crack propagation using a remeshing approach, it was shown that it is necessary to use a proper field transfer approach based on nearest

The question of considering kinetic energy variation in the energy balance for crack initiation was also addressed. A key question concerned the way to described the crack velocity profile which has a non-negligible influence on the energy variation. An approach with progressive crack advance following a given velocity profile was compared to simultaneous unbuttoning of all the nodes along the initiating crack. It was shown that both approaches yielded similar crack initiation loading provided the crack velocity was small enough. A proper experimental characterization of the crack velocity profile during initiation is not trivial as i) it requires camera with sufficiently high acquisition frequency and ii) it is difficult to separate crack initiation from subsequent crack unstable propagation. Again, configurations in which the initiation length is also an arrest length could enable such measurement. A first application of the CC in the case of a frictional contact was also established to address shear crack propagation along an interface in edge notched specimen.

Regarding experiments, the use of the CC as a preliminary analysis for test design was highlighted for instance in the case of adhesively bonded specimen. Interface failure or cohesive failure were predicted for several testing conditions, and the CC enabled determining which configurations promoted one or the other mechanism, which was further confirmed by subsequent experiments. Another strength of the CC that was highlighted is the fact that solving the CC requires the calculation of different fracture scenarios including configurations that do not happen but that enable understanding why crack initiation occurs or not. It brings insight in understanding the reason for crack initiation, especially when there is a competition between several cracking mechanisms.

It was shown that scattering in experiments makes it difficult to study the influence of a V-notch on the fracture load for small angles. Indeed, there is theoretically a very flat variation of the failure load as a function of the notch angle for angles smaller than 90 deg. The failure load further increases with increase V-notch angles. As a consequence, it appears that experimental uncertainties (on the notch angle, depth, geometry similarity along the thickness, possible residual stresses) yields larger error bars than the failure load variation to be captured. Relatively large scattering in the failure stress was also observed when studying the failure size effect in sapphire, despite the absence of evident flaws at small scale. The interest of small-scale testing was highlighted, for instance for validation purpose of the size effect predicted by the coupled criterion. An intriguing aspect was evoked that the CC predicts different size effect depending on the type of loading, i.e. force- or displacement-controlled experiments, due to a difference in the incremental energy release rate obtained under imposed force or displacement. Performing in-situ force or displacement-controlled tests at small scale, for instance in scanning electron microscope would enable confirming or not the difference in the predicted size effects.

3D application of the CC was evoked, since it triggers a main additional difficulty regarding the crack surface definition. It was for instance shown that different topologies of 3D crack yield significantly different SIF distributions along the crack front. The 3D definition of the crack thus seems of primary importance for fracture analysis. Results arising from a 2D analysis show that in some cases (when the material characteristic length is small), crack shapes based on stress isovalues are actually the optimal crack shapes (i.e. the one minimizing the remote loading at initiation). For large material characteristic length, it seems that the crack shapes can be defined based on energy only. For intermediate material characteristic length, neither the stress nor the energy-based crack shape are optimal. Several ways to try to determine optimal crack shapes for the CC were discussed, for instance using 3D configurational forces that could also provide curved crack shape. A point of vigilance was however emitted in cases where mode II loading is dominant. An analysis based on phase-field modeling could also provide insight about the optimal 3D crack shapes.

Still about 3D cracks, the question of analyzing a crack impinging a free surface (which is encountered in many experiments where surface observations of the crack propagation are made) was discussed. At this point, the modes defined by 2D LEFM are no longer valid and it is essential to consider the point where the crack front intersect the free surface as a 3D singularity, which has its own characteristic exponent (different from 0.5) and eigenvector. As a consequence, neither plane stress nor plane strain assumption seem to be valid at this point.

Mode III crack propagation was evoked. If LEFM is used, straight crack propagation occurs. But experimentally small facets inclined with respect to the mother crack are observed, further resulting in a macroscopic rotation of the mother crack. In phase-field models, the nucleation of facets can be reproduced provided the use of tension/compression energy decomposition as well as small perturbation (such as small spatial toughness variation) to so as to trigger the instability. The tension/compression decomposition somehow penalize straight crack propagation as no tensile stress would act on a crack propagating straight, which resembles considering a stress criterion in addition to a purely energetic condition. It was thus highlighted that even if in 2D, the crack angle is generally correctly predicted by either a stress or an energy criterion, it is not true in 3D and especially in the case of mode III loading.

Whereas the community is unanimous about the energy criterion that results from an undisputable energy balance, there are still some interrogations regarding the use of a stress criterion that must be fulfilled all over the crack path or an average stress criterion. The stress criterion appears more restrictive than the average stress criterion since it must be fulfilled all over the path of the new crack before initiation. As a consequence, the stress criterion predicts that crack nucleation cannot occur in certain circumstances, such as for instance, a V-notch with an opening angle larger than 105 deg. loaded under pure mode II for which the stress tends towards 0 at the notch tip. The average stress criterion predict that crack initiation could occur at the V-notch tip since it provides an average positive value of the stress. Nevertheless, it was mentioned that the average stress criterion would probably predict that crack initiation is more favorable at another location than the V-notch tip in such a situation. When exploring the size effect at small scales, the classical stress criterion predicts failure stresses larger than the tensile strength whereas it is not the case for the average stress criterion. Unfortunately, no experiments were available to probe which of the approaches are closer to the reality. It was agreed that a proper comparison of both approaches requires that fracture properties have been independently identified on a separate set of data, otherwise it is difficult to determine which approach yields better results. The question of using strain rather than stress criterion could also be addressed.

The Generalized stress intensity factors are usually calculated using a contour integral. In Fracture mechanics, the contour integrals are often transformed to surface integral in a numerical integration. Even if the contour integral actually provides small sensitivity to the chosen contours (this sensitivity tends to increase when passing from 2D to 3D GSIF evaluation), it could be useful to explore the possibility of defining a surface integral equivalent to the contour integral currently used. Still regarding the GSIF, it is noted that when studying the influence of a V-notch angle on crack initiation for instance, it is difficult to reason in terms of GSIF since the unit depends on the angle. It is thus recommended to rather reason in terms of failure force or displacements, which can be compared in a straightforward way between different configurations and also measured experimentally.

We thank Euromech for the support in organizing the colloquium, as well as INSA Lyon, MATEIS Laboratory, la region Auvergne-Rhone Alpes, MECAMAT association and Carnot Institute for providing financial support to the colloquium.

Number of participants from each country

Country	Participants
France	16
Germany	2
Spain	6
Italy	3
Israel	1
Austria	2
Australia	1
Ireland	1
Switzerland	1
Total	**33**

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