ON FRACTURE MECHANICS IN GENERAL AND DISCRETE CRACKS IN PARTICULAR

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Abstract
The author reflects on the progress, challenges, and limitations of fracture mechanics in general, and on the discrete crack model in particular.

1 Introduction

Conferences such as FramCos should not only to be reunions in which we show and tell about our latest research, but also times in which we ought to reflect and ponder on our overall progress. Hence, it is essential that we collectively pull out from the details of a research component, and try to look at the forest rather than at the individual leaves.

As such, the conference organizers should be complemented for providing such an opportunity through the specialized workshop and whereas it appears that almost each one of us had a different opinion of what should be discussed in them, I would like to hope that there is still room for a philosophical discussion, and that details should be left for the conference itself. As I am about to complete a comprehensive seven year project on the applicability of fracture mechanics to concrete dams (through which I have had numerous contacts with practitioners), (Saouma 1995) I would like to share some of my thoughts and concerns. First I will address the role of Fracture Mechanics in general, discussing the role of testing, models, applications, and the interactions among those key components. In the second part, I shall focus the discussion on the discrete crack model and its implication.

2 Role of Fracture Mechanics

Whereas fracture mechanics of concrete has been assiduously studied for over fifteen years, we ought to recognize that so far very few, if any, practical applications have emerged. Whereas such a time gap between development and application may not be unusual (limit state design being a notable example), I am doubtful as to whether such a change is likely to occur.

2.1 Applications

So far, our community has had difficulty in identifying specific code provisions where fracture mechanics could be used, and convincing not only practitioners, but our very own colleagues (such as those in ACI-318 Committee). This is certainly not caused by our lack of understanding, but rather by our inability to consider the problem as a whole and recognize that there are numerous factors which contribute to the failure of a structure, and that it is quite presumptuous to assume that a fracture mechanics based solution, by itself, can provide the mean to investigate such a failure. In general, a multi-disciplinary approach is warranted, and unfortunately as academicians we are called to specialize within our narrow discipline and find it difficult to interact with colleagues across the hall.

In its simplest and most elementary form, we can not indefinitely ignore the presence of reinforcement. We can not pretend that beams are without shear reinforcement, and that most concrete structures do not have steel (the ACI code specifies a minimum amount of reinforcement for both flexure and shear.) Which brings me to the next point, how relevant is fracture mechanics in the case of reinforced concrete? this remains an open question.

This negative view should be tempered by the potential application of the Size Effect Law in limited code provisions. Should such a revision take place, it is unlikely to be within the same frame-work in which the original law was cast. Finally, it is regretful that, as far as I know, there has not been a clear identification of ACI code provisions which can be revised on the basis of fracture mechanics, and for which clearly written substitutions are presented.

2.2 Standards

Lately, there has been numerous concerted efforts to develop a "standard" for fracture mechanics testing. Whereas such a noble endeavor should be welcomed, I am not convinced about the urgency nor the need of such a standard(s?). To the best of my knowledge, there has certainly not been pressure from practitioners for such a test, as we have not yet convinced them about its need in the first place. Instead we appear to be heading toward a situation where numerous "competing" organizations are seeking such a test (RILEM, ACI/SEM, ASTM), and within each one, some (but not all) individuals appear to be simply pushing "their" testing method. As such, there is pressure to adopt all major tests on the ground that they are really all measuring the same physical quantity (apparently forgetting that a Standard is usually unique!) Given the lack of guidance from practitioners, it is not surprising that the development of a standard has proven so far to be so arduous.

Furthermore, three methods are proposed to determine the fracture energy: the direct or work-of-fracture-method, the two-parameter-model and the size-effect-law. All of them appear to give different results for the same concrete, hence until we resolve those differences, there can not be "standard".

Whereas I would disagree on the need for a standard, not only for the above mentioned reason, but also because it may cause a sclerosis of our intellectual effort, I can also appreciate the argumentation in favor of one. As such, should there be a standard, I fail to understand why it would have to be as simple as possible. By the time we use fracture mechanics to analyze a structure, things must be really bad, and it is more than likely that we are dealing with a particularly complex problem to justify such a "sophisticated" approach. As to the thought of routinely applying fracture mechanics to design structural components, this is very unlikely to ever happen given the gross (over)simplification of numerous equations in ACI-318 design code. Hence, it is not sinful if a complex analysis requires a complex test. i.e. we should not oversimplify the test if this is what it takes. Last but not least, we as engineer should not be inhibited by codes, but the community ought to trust our judgement in our capability of analyzing complex structures with complex models.

2.3 Experimentalist "Blinder"

Furthermore, within the context of a test, we should have a clear idea of the importance of various parameters. Some would say it is the fracture energy, others the tensile strength, and others the softening curve. From an extensive parametric study undertaken by Plizzari and Saouma (Plizzari and Saouma 1995a-b), we determined that not only is the shape of the tension softening diagram (TSD) relatively unimportant (the model of Wittmann *et al* (1988), proved to be perfectly suitable for the numerous analyses we undertook) but the fracture energy also. The first linear segment of the TSD plays only a minor role in the prepeak response. What is instead of paramount importance is the tensile strength. In reaching such a conclusion, we had to evaluate the error in altering fracture energy and TSD with the one expected in an actual structure where the elastic modulus is known within 15% at best. In all models, sensitivity analyses should be undertaken to assess the importance of material parameters. I am not sure that arguing about small variation of G_F (which may result from different tests) is all that relevant if ultimately it may turn out that results are relatively insensitive to it. Hence, I would hope that more such analysis is undertaken.

Such an observation simply calls for greater interaction between experimentalist and numericians. In this instance, the experimentalist may be overestimating the importance of a quantity which (s)he can measure.

2.4 Analyst "Blinder"

With regard to analysis, many different methods have blossomed over the past decade. Each new year seems to bring a new parameter, and the complexity of these models is such that only few can really comprehend them. This search for a comprehensive model is certainly laudable as long as it confines itself within the walls of academia and does not pretend to be other than an academic exercise. I do have some concern when those models pretend to become effective predictive tools which can be used by practitioners. Indeed the complexity of these models is such that numerous parameters can not be directly extracted from simple experiments, but must be calibrated from tests. Hence, they can no longer be perceived as capable of honest pre-test prediction. In my opinion, it is irresponsible to have material parameters which can not be directly measured experimentally (and which eventually can not be explained in simple terms to an Engineer), and we should not confuse material parameter (which can be universally measured in the Laboratory), with model parameter (which may be cynically perceived as a "fudge" factor). Again, greater dialogue between experimentalists and numericians, who in this case overestimate our capability of measuring parameters in their models, is essential.

2.5 Practitioner's View

Also, we should keep in mind that it is practically impossible to convince an Engineer that the concrete has a finite non-zero tensile strength (an essential requirement for most models), and that there is a need for a post-peak prediction. Post peak prediction for an engineer is of very limited importance, and material post-peak response are very seldom measured in practice (one of the largest concrete laboratory in the United States, the one of the Bureau of Reclamation, only recently retrofitted an old testing machine in order to conduct post-peak compressive tests of concrete). Furthermore, there ought to be more statistical analyses of test results. i.e. what is the mean, standard deviation, and distribution of G_F, f'_t, K_{IC}. With such important quantities, not only more intelligent analyses can be performed, but we could really assess the safety of existing structures through their reliability index which is increasingly used by practitioners, (Saouma *et al.* 1995).

3 Discrete Crack

3.1 Discrete, Smeared, and "Discrete" Again

There was a time when discussions about discrete versus smeared crack models had the tenacity of a religious war. Here were two schools of thoughts, each trying to show the superiority of its own model. However, with the increased recognition that the smeared crack model remains quite sensitive to mesh orientation, a number of palliative emerged. Unfortunately, those remedies, introduced their own set of new parameters. Soon after, physical explanations were sought for variables which emergence was really caused to remedy a numerical deficiency. Hence, great care must be exercised in discriminating between those "fracture parameters" i.e. those truly rooted in the physical material response from the model parameter which were introduced to remove the mesh dependency. Within this context, some of the more recent "smeared" crack model are beginning to look a lot like discrete ones in disguise, and not only is the gap between those two models narrower, but the discrete crack may have gained the appreciation that it may have lacked.

3.2 Applicability of Discrete Crack

To the best of my knowledge no one disputes the applicability of the discrete crack model, however the usual criticism often voiced is that "it is too cumbersome". It should be quite evident, though many may dispute this assertion, that the discrete crack model is closer to the physical crack than the smeared one (as such it preceded it among our "founding fathers"). Hence, contrarily to the smeared crack model, the challenges that it introduces are not rooted in mechanics but rather in the topological representation of the model. This is, for obvious reasons, a discipline with which we do not relate too well. Nevertheless, enough progresses have been made in Boulder and Ithaca to counter the complexity argumentation against the discrete crack. In addition, it is safe to say that all the "complexity" associated with the remeshing pails in front of the complexity of certain models which are desperately trying to capture the localization of the crack in an objective matter. The pursuit of such a model has resulted in ever more complex computational algorithms which depend no more exclusively on simple physical parameters which can be measured in the laboratory and explained to an Engineer.

3.3 Pre and Post Test Predictive Capabilities

Almost by definition, the discrete crack model hinges on fewer parameters than its smeared cousin. As such, it would be natural to expect the discrete crack to fare better in pre-test predictions. Unfortunately, those are too few if any. Whereas it is by all means essential that a model be judged initially on the basis of its capabilities to duplicate existing test results, there is an almost incestuous relation between analysts and experimentalist (for both discrete and smeared crack proponents) through which we always analyze the same test problems. By the same token, there are very few, if any, practical problems used for model evaluation which would indeed convince the practitioner about the practical relevance of a fracture mechanics approach.

3.4 Reinforced Concrete

Whereas it has been argued that the discrete crack representation is very likely to surpass the smeared crack one in terms of pre-test predictive capability, such a claim can not be supported for reinforced concrete. This is not due to the failure of the discrete crack representation, but rather to the unpracticability of such an analysis. But then, one may ask her/himself how relevant is fracture mechanics in the presence of reinforcement when stress redistribution occurs? and if so wouldn't the simplest smeared crack representation be adequate enough?

3.5 LEFM and Discrete Cracks

LEFM, which is often closely associated with discrete crack, may have been prematurely rejected. I remain convinced that this is not only caused by the fact that test results appear to exhibit a size dependence, but also by the inability of the smeared crack model to simulate it. When the effective crack concept was adopted in our work, (Saouma *et al.* 1991), the variation in fracture toughness in terms of size appear to be of the same order as the variation of G_F with respect to size as reported by other researchers.

3.6 NLFM and Discrete Cracks

For many years, one had the impression that discrete crack was limited to LEFM, and that any serious NLFM analysis can only be performed by a smeared crack model. This is in part due to the fact that the discrete crack model is much closer to "orthodox" fracture mechanics, but also by the fact that the smeared crack model offers greater computational challenge to the analyst. This indeed has been true for quite some times. However, with the recent 2D and 3D linear and nonlinear fracture mechanics implementation, within the context of an incremental nonlinear algorithm, by Reich (1993) and Červenka (1994), this is no longer correct.

4 Conclusions

Some of my thoughts on fracture mechanics in general, and discrete crack models in particular were shared. Whereas they may be outright rejected by some, I hope that it will cause others to pause and ponder on the status of the research that we have all cherished over the past many years.

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