Designing for crack arrest - Discussion of fracture paper #15

Ståhle, P.; Ståhle, P.

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Discussion of fracture paper #15 - Designing for crack arrest

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Everyone loves an elegant engineering solution. It is particularly true when the alternatives are terrifying. In the paper:
"Brittle crack propagation/arrest behaviour in steel plate – Part I: Model formulation" by Kazuki Shibanuma, Fuminori Yanagimoto, Tetsuya Namegawa, Katsuyuki Suzuki, Shuji Aihara in Engineering Fracture Mechanics, 162 (2016) 324-340.
a team from University of Tokyo proposes a model for prediction of the arrest of propagating brittle cracks in steel plates. The approach, in spite of its simplicity, captures the physics of the fracture process. The model formulates the energy release rate in simple and comprehensible terms and gives accurate predictions. The theory is validated on several experiments described in a subsequent paper, a "Part II: Experiments and model validation" also in Engineering Fracture Mechanics. The characteristics are those of a pilot study with the goal to provide a design tool for predicting crack arrest in steel plates.
In the model, the energy to complete the fracture process is at most what is left of the released energy when the work of plastic deformation and the part of the kinetic energy that is reflected away from crack tip region have been covered. The energy dissipation at plastic deformation is reduced at increasing crack tip velocity while the opposite applies to the dissipated kinetic energy. The energy required for the fracture processes is supposed to be constant. If it at some velocity is more than required then the energy is in balance only at a single stable higher crack tip velocity. If crack growth is initiated then the crack accelerates until the energy balance is obtained. When the crack subsequently loose driving force or require additional work, caused, e.g., by elevated temperature which decreases the material viscosity or by whatever, the crack decelerates until zero velocity or until the minimum energy release rate is obtained and the crack arrest comes abruptly.
Surface-ligaments are assumed to consume a serious part of the available energy. The slower the crack grows the wider these ligaments become which rapidly increases the plastic dissipation. Finally the energy balance and the stability of the crack tip velocity cannot be maintained and the crack will come to a stop.

Considering that one has to keep track of the complicated sequence of processes that keep the crack growing, it seemed obvious to me that this would end up in a horrible and time consuming analysis. Then, to my surprise, the investigators present an ingenious solution that simplifies the analysis a lot. It is based on three assumptions: 1) that the crack front is assumed to be straight through the plate, 2) that the unbroken side-ligaments are regarded as integrated parts of the crack front, and 3) that the evaluation of the state of the crack front in done at the plate mid-plane.

In the subsequent part II the functionality of the model is verified. The validation is performed on different grades of steel that are exposed to different load levels. The authors believe that this model can be used to establish a design strategy for steel plates. I too believe that, even if more possibly needs to be done to qualify the method as a design standard.

I understand that the authors are familiar with the series of wide plate experiments on crack arrest in very large specimens (around 11x1x0.1 m3) reported by Naus et al., NUREG/CR-4930 ORNL-6388, Oakridge Laboratories, USA, 1987.

In the aftermath of the experiments a variety of models where proposed. An interesting observation made by D. Alexander and I.B. Johansson at Oakridge Labs when they examined the crack surfaces was that remains of plastic deformation framed the cloven grains. The guess was that this was remaining parts of broken ligaments between the crack surfaces and that these ligaments were ripped apart during the fracture process. The area covered by these remains was clearly increasing with decreasing crack tip velocity. Just before crack arrest they could cover as much as 10 to 20 % of the ”brittle” part of the crack surface. I have a feeling that this may mean something. The plastic ligaments per se consume large amounts of energy and with increasing fractions they might influence the crack tip velocity at arrest. Only 10% may seem as small or even insignificant, but considering that the plastic ligaments that bridge a crack may consume many times more energy than the pure cleavage of the remaining 90%, even 10% must be important. It would be interesting to know if the authors observed any remains of plastic ligaments. If so, did the fraction of them change in any systematic way during crack growth?

Any contribution to this blog is gratefully acknowledged.

Per Ståhle