DTU Library

Crack Tip Flipping: A New Phenomenon yet to be Resolved in Ductile Plate Tearing

Nielsen, Kim Lau

Published in:
Proceedings of the 30th Nordic Seminar on Computational Mechanics (NSCM-30)

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Nielsen, K. L. (2017). Crack Tip Flipping: A New Phenomenon yet to be Resolved in Ductile Plate Tearing. In J. Høsberg, & N. L. Pedersen (Eds.), *Proceedings of the 30th Nordic Seminar on Computational Mechanics (NSCM-30)* (pp. 30-33)

30th Nordic Seminar on Computational Mechanics
NSCM-30
J. Høgsberg. N.L. Pedersen (Eds.)
2017

CRACK TIP FLIPPING: A NEW PHENOMENON YET TO BE RESOLVED IN DUCTILE PLATE TEARING

KIM L. NIELSEN

Department of Mechanical Engineering, Solid Mechanics Section, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark
Email: kin@mek.dtu.dk - Web page: http://www.mek.dtu.dk

Key words: Plate Tearing, Flipping Mechanism, Crack Tip Condition, Micro-mechanics.

Summary. Conclusive insight to the mechanics that govern so-called "crack tip flipping" remains to be revealed, but details continue to fall into place as researcher dig deeper. The work presents an overview of the latest findings and the next steps to be made.

1 INTRODUCTION

Strong evidence exists that a number of unexplained transitions in crack surface morphology, that appears in mode I tearing of ductile plates, can be assigned to the so-called "crack tip flipping" mechanism, or element here of. But, little effort has been devoted to getting to the bottom of this intriguing plate tearing phenomenon despite numerous researchers reporting it. Crack tip flipping reveals itself when a slanted tearing crack, propagating in a ductile plate, shifts its orientation from one 45-degree angle shear band to the other. That is, the mechanics at play during crack tip flipping is strongly tied to the well-known slant crack propagation, where two equally active shear bands travel ahead of the leading tip, within a heavily strained region, such that plastic flow and damage evolution localize in one shear band and leaves the other band inactive. Figure 1 display a mode I crack that repeatedly flips back and forth in a very periodic manner and with high frequency – leaving a "shark teeth"-like surface. The flipping frequency is, however, dependent on the set-up (the constraints), the plate thickness, and plate material. For example, El-Naaman and Nielsen (2013) reports high frequencies for steel, whereas the same tests performed on aluminum shows a lower flipping frequency. In fact, a slant crack can display flipping spaced apart on the fracture surface such that the


Figure 1: Repeated crack tip flipping in large scale testing of a normal strength steel plate subject to mode I loading.

slant crack has propagated some distance before making a new flip to the other 45-degree shear band. The mechanics involved are now understood to span multiple length scales – from the micro-mechanics governing ductile damage evolution, through the plastic flow localization into shear bands and thinning ahead of the crack tip, to the competition between the near tip plasticity and the far-field elastic plate response. A status on current insight to the crack tip flipping mechanism is given.

2 INVESTIGATIONS

In a first study dedicated to the crack tip flipping mechanism, El-Naaman and Nielsen (2013) conducted an experimental investigation, where extensive crack propagation in plate metal (both steel and aluminum) was achieved. Through their effort it was cemented that; *i) the flipping mechanism develops in a very stable and controlled manner being easily traced by the naked eye on the outer free surface, ii) steel displays a higher flipping frequency compared to aluminum (the difference is roughly a factor three, when keeping the plate thickness constant), and likewise will the plate dimensions and constraints influence the flipping. Relax the constraint and the flipping frequency has been observed to drop.* The asymmetry in the mode I tearing problem, that develops once the crack slants to propagate in one 45-degree shear band, must give rise to an out-of-plane deflection and it has long been speculated to be the driving force behind the flipping mechanism. In a recent study, Nielsen and Hutchinson (2017) attempt to quantify this out-of-plane action by considering a slanted through-crack propagating in a symmetrical mode I loaded plate strip of elastic-plastic material. Here, relying on a 3D steady-state code tailored to reveal the crack tip conditions under the assumption of small strain. This is an approximation to the complex plate tearing, but the numerical framework allows extracting results without going through the long transient regime. This fundamental study brought out that; *i) a competition between the elastic far-field and the near tip elastic-plastic field unfold during slant crack propagation. Essentially, a purely elastic solution displays an out-of-plane action to one side, whereas a plate dominated by the plastic response displays an out-of-plane action to the other side, ii) a constraint on the out-of-plane bending imposes a significant influence the mixed mode behavior along the crack front (the mode III loading on the crack front increases), iii) the asymmetry in the tearing problem manifests itself in the plastic zone ahead of the crack tip and the stress distribution, in the acute angle corner where the slant crack intersects the plate outer surface, appears to be consistent with initiation of a re-orientated shear crack in the flipping direction.* Such shear cracks (also referred to as “shear-lips”) are often observed in plate tearing and they are a key ingredient in making the slanted crack flipping. Nielsen and Gundlach (2017) recently studied a slant crack tip, undergoing flipping, by use of X-ray tomography to access the plate interior (Fig. 2). While undergoing a shear band switch, such that the flipping mechanism is active, the plate tearing test was interrupted and the crack tip extracted for further investigation. Their study reveals that the failure process ahead of the flipping crack tip closely resemble that of ordinary ductile slant crack growth governed by local thinning and moderate crack tip tunneling, and that; *i) the initiation of the flipping is* *governed by the formation of shear-lips (Fig. 3c) at the both outer free surfaces simultaneously such that the flipping process poses 180-degree rotational symmetry about the growth direction (x_1-axis), ii) during flipping the crack tip consists of two leading edges – one being the edge of the primary slant crack face and one being the edge of the evolving shear-lips (Fig. 3b and d) – and upon further loading, the shear lips grow to catch up on the primary (slant) crack front such that they overtake the growth to complete the flipping and re-orient the crack face, iii) the flipping process contrasts existing tearing modes, where the orientation of the crack front remains stationary, and the near tip stress/strain field continuously chance and never settles in a steady-state.* A full 3D numerical study, employing the Gurson material model and taking into account finite strain deformations, has been presented in Felter and Nielsen (2017). In their work, a slight out-of-plane action is imposed to assist the crack tip in flipping – and it really does (Fig. 3).

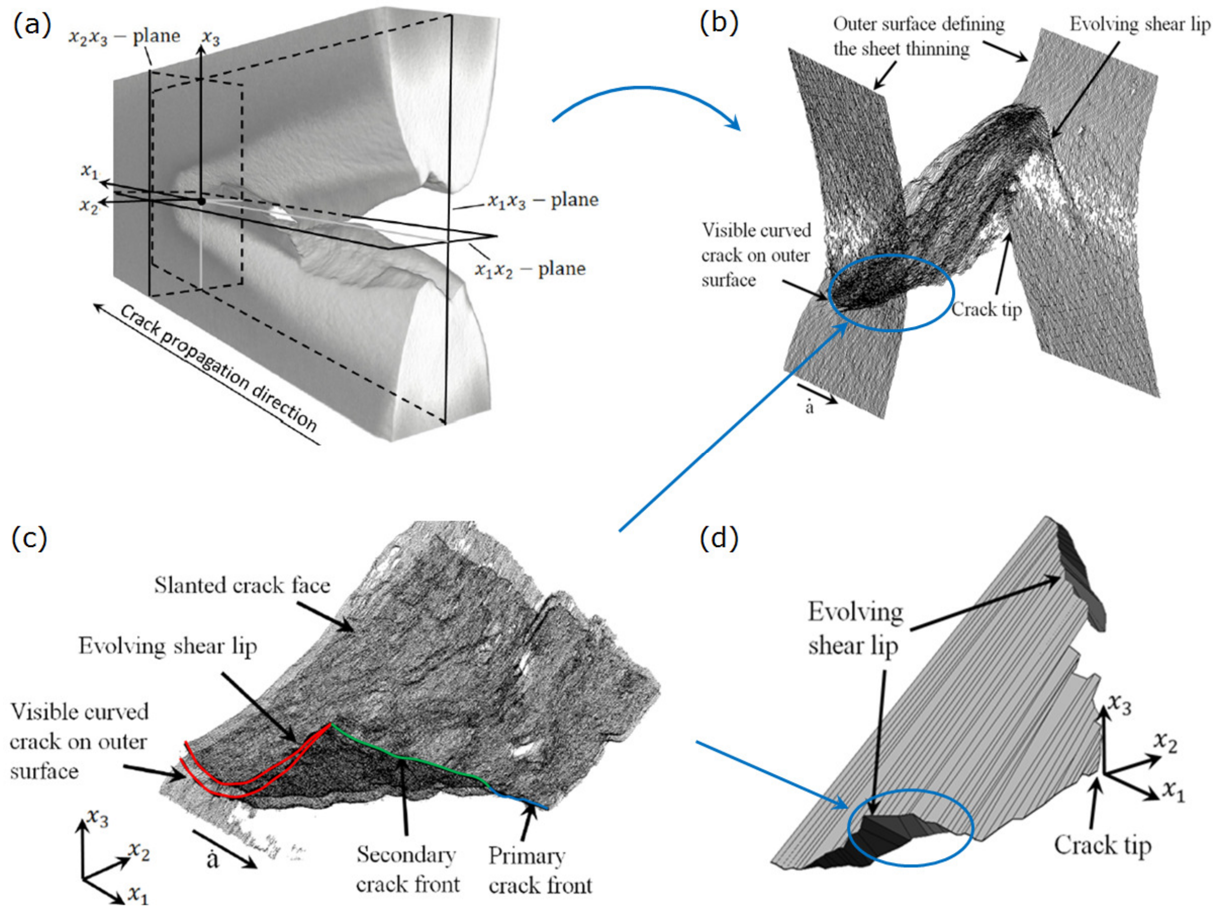

Figure 2: X-ray tomography scans of a crack tip flip underway, showing; (a) a 3D perspective of the flipping crack with growth direction along the positive x_1-axis ($\sim 100\mu$m resolution), (b) flipping crack face and outer surfaces that define the thinning region ($\sim 20\mu$m resolution), (c) details on one shear-lip close to the outer free surface within the thinning region, and (d) manual reconstruction of the flipping crack tip ($\sim 6\mu$m resolution) from the data in Fig. 2(b).

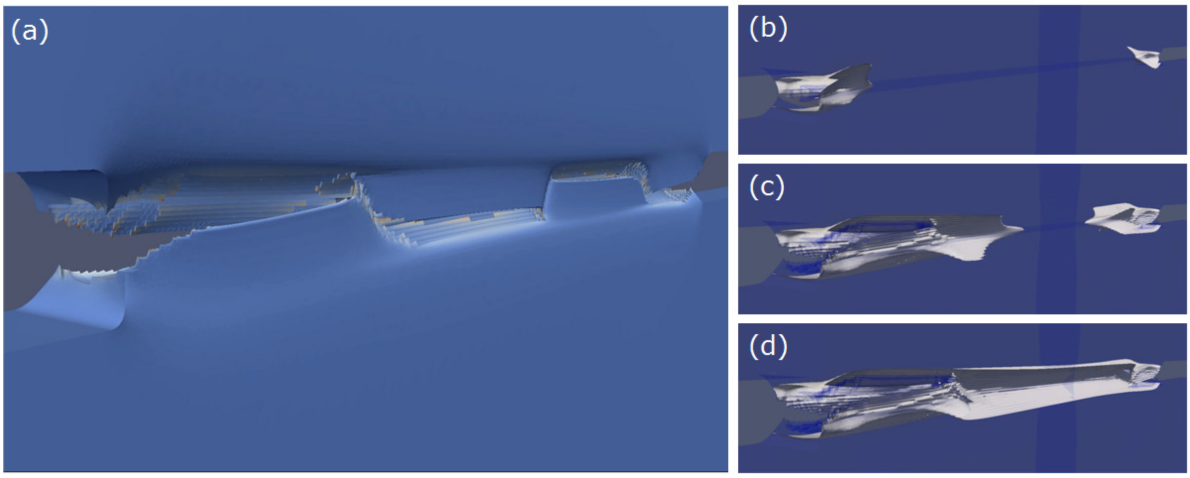

Figure 3: 3D simulation of assisted crack tip flipping using the Gurson model, showing; (a) crack surface at end of simulation, (b-d) contours of void volume fraction, with transparent geometry, at different deformation stages.

3 CONCLUSIONS

- The mechanics governing the crack tip flipping phenomenon is multi-scale as it relies on the constraint effect from the surroundings (e.g. an elastic far-field) to facilitate a favorable asymmetry in the near-tip plastic stress/strain field for damage to evolve.
- The loss of symmetry, when the crack slants, manifests itself as an out-of-plane action of the top/bottom part of the plate and drives the asymmetry in the near field.
- The crack first diverges from the slant orientation at the outer free surface as shear-lips evolve and grow to overtake and govern further advance of the crack tip.

ACKNOWLEDGEMENTS

The work is financially supported by the Villum Foundation Young Investigator Programme, grant VKR023451. Fruitful discussions with colleagues are highly appreciated.

REFERENCES

[1] K.L. Nielsen and J.W. Hutchinson, “Cohesive traction-separation laws for tearing of ductile metal plates”, *Int. J. Impact. Eng.*, **48**, 15-23 (2012).
[2] K.L. Nielsen and J.W. Hutchinson, “Steady-state, elastic-plastic growth of slanted cracks in symmetrically loaded plates”, *Int. J. Impact Eng.*, **108**, 286-294 (2017).
[3] S.A. El-Naaman and K.L. Nielsen, “Observations on mode I ductile tearing in sheet metals”, *Eur. J. Mech. A/Solids*, **42**, 54-63 (2013).
[4] C.L. Felter and K.L. Nielsen, “Assisted crack tip flipping under mode I thin sheet tearing”, *Eur. J. Mech. A/Solids*, **64**, 58-68 (2017).
[5] K.L. Nielsen and C. Gundlach, “Crack tip flipping under mode I tearing: investigated by X-ray tomography”, *Int. J. Solids Struct.*, **118**, 119-127 (2017).