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Crack Opening Profile method for stress intensity factor estimation in notched and non-linear materials

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Introduction
The concepts of stress intensity factor (K) and a material's fracture toughness form the foundation of Linear Elastic Fracture Mechanics (LEFM): they provide a quantitative assessment of crack propagation risk. Most literature methods for calculating K rely on stress analysis or strain energy estimates [1], which, despite their accuracy, often demand complex calculations and detailed models. Displacement-based approaches [2] are more straightforward but limited to near-tip measurements, which are notoriously hard to obtain accurately in practice. Allahdiniyan and Taylor [3] introduced a simpler alternative: the Crack Opening Profile (COP) method, which estimates K directly from measurements of crack face displacements along the entire crack front. Grounded in the Westergaard equation [4] linking K to displacements, it has proven effective for sharp 2D cracks in linear elastic materials, though still constrained to those ideal cases. The aim of our work is to extend the COP method to more realistic scenarios, incorporating notches with finite root radius and material non-linearity. This would enable practical K estimation from direct measurements on real-world cracks, with broad applications from structural health monitoring to biological materials like bone.

Materials and Methods
To account for notches and material non-linearity, we adopt a combined Finite Element Analysis (FEA) and experimental approach. From FEA simulations we extract COP shapes and displacement-based K values, validated against stress-based K from literature methods. The experimental works serve as a demonstration of the practical applicability of the methods and to validate the results of FEA. For the analysis of the notch effect on crack propagation, FEA simulations involved U-shaped and elliptical notches in various 2D configurations and the experiments consisted in tensile tests on notched PMMA plates. For the analysis of the material non-linearity, both FEA and experiments focused on tensile tests on notched metallic specimens, with different notch shapes and dimensions. The experiments were carried out on aluminium alloy 6082-T6. For both PMMA and aluminium samples, the COP was measured via 2D Digital Image Correlation (DIC) with a simple USB microscope to prove easy applicability.

Results
The notch study showed that crack-based equations [3] predict COP and estimate K reasonably well for small notches (relative to plate dimensions) regardless of radius and for larger notches only if sharp. For large blunt notches, we proposed corrected formulas. This allows modelling COP with errors <10% and COP-derived K closely matches J-integral K in most cases.
For metals, the same crack-based equations capture the linear K-displacement relationship in the initial test phase, where behaviour is linear elastic. At plastic deformation onset at the notch tip, linearity is lost: COP increases while K stays nearly constant and the COP profile changes with tip blunting. Knowing material properties, we can reasonably estimate plastic onset, K at that point and corresponding displacement trend. It is a simplified model, so there are some uncertainties in predictions, but they still give good indicators for K values.

Conclusion
Our work takes a step forward in developing a simple crack propagation risk estimation method based solely on crack opening measurements. This has potential for real-world applications, from structural monitoring and material characterization to fracture assessment where loading conditions are hard to predict and direct testing is complex.

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