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A NOVEL TOPOLOGY OPTIMISATION METHODOLOGY FOR ROBUST DESIGN OF STRUCTURAL COMPONENTS CONSIDERING MATERIAL DEFECTS

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Abstract: *This work outlines a new Topology Optimisation methodology whereby material defects are introduced at the earliest stage of the structural design process, leading to more robust final design solutions. We couple the Levelset Method and the Floating Node Method to capture a moving material boundary explicitly on the Finite Element mesh. A continuum design sensitivity analysis scheme based on a measure of the energy release rate is used to quantify the impact of the defect. We show how the structure is optimised to reduce this measure and mitigate the impact of the material defect on the overall response.*

Keywords: Floating node method; Topology optimization; Levelset method; Energy release rate; Material defect

1. Introduction

Material defects – such as delamination, debonding, inclusions or internal cracks – occur during the manufacturing of composite structures. The smallest defects can be undetectable to current non-destructive testing techniques and may lead to premature structural collapse [1]. It is therefore imperative to account for such defects as early as possible in the design stage of a component.

The pre-inclusion of defects within a component during its design amounts to a quantification of the uncertainty relating to the impact of the defect on the response of the component; the uncertainty quantification allows for more robust design solution that mitigate the effects of the included defect.

The design of intricate structural components – such as a skin-stringer assembly of an aircraft (Figure 1) – is often sequential and iterative in nature; such a component must be studied under varied loading scenarios and with various material and geometric configurations, all of these constitute design variables that influence and depend on each other. Introducing into the design workflow material defects such as kissing bonds can make the already complex workflow to costly and time consuming.

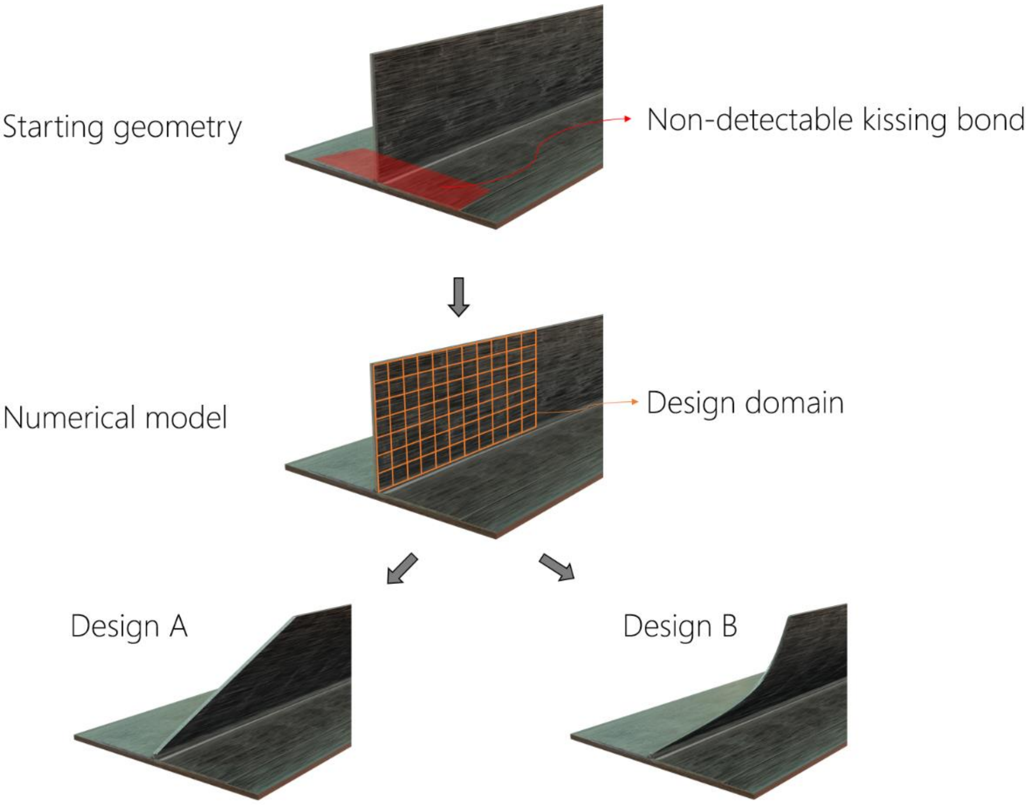


Figure 1. Optimisation concept of skin-stringer assembly with a kissing bond defect

Therefore, to alleviate these shortcomings a Structural Optimisation methodology can be used. Such a methodology can abstract design allowables and requirements as optimisation objectives allowing for multiple objectives to be included in a single design study.

Topology Optimisation (TO) is a Structural Optimisation methodology whereby the material distribution of a domain is optimized. The literature often categorizes TO methods based on the nature of the design variables; for example, density-based TO methods use cell densities to determine the solidity of a given region in space, and Levelset (LS) based TO methods use a scalar field that represents the moving material boundary and therefore dictates the regions within the solid domain [2].

Density-based TO methods have seen a recent proliferation in the literature and commercial applications but it suffers from a fundamental drawback – one that is more critical when we want to study the inclusion of material defects. Because the design variables are cell densities the material boundary resolution is limited to the density of the mesh and will often result in a blurry transition between material and void. In contrast, LS-based TO methods capture the material boundary through every design iteration as a scalar field [2] providing more granular design control.

Furthermore, LS-based TO methods allows us to employ continuum design sensitivity analysis based on the concept of shape derivative [3]. In this work we use this ability to develop a formulation based on the crack energy release rate and inform the optimisation algorithm of an embedded defect in the structure.

2. Methodology

2.1 Implicit boundary tracking

The Levelset Method (LSM) is a numerical method capable of representing and manipulating any arbitrary boundary as a scalar field embedded in a Finite Element (FE) formulation. The LS field, ϕ, can be define, depending on its value, whether a region in space is considered solid or void (Figure 2).

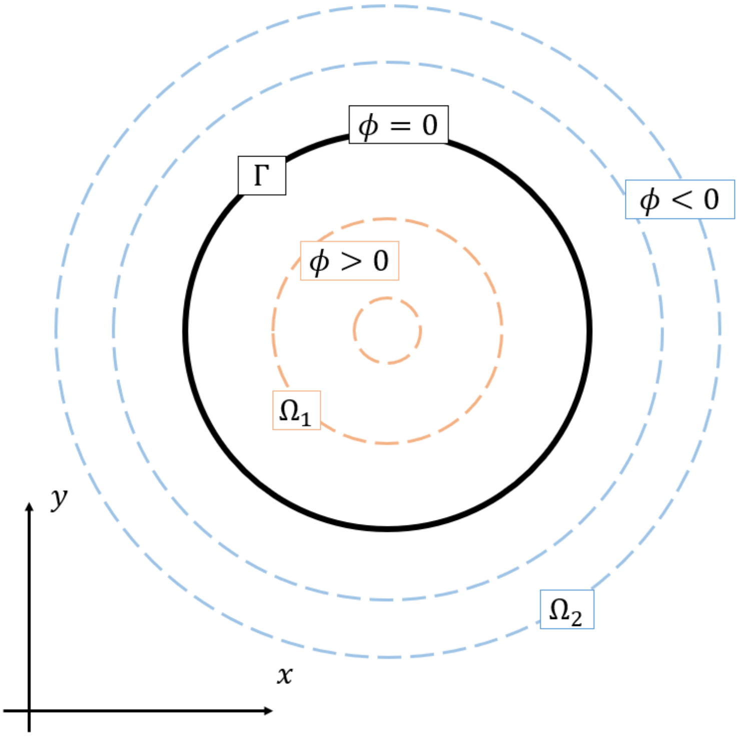


Figure 2. A 2D representation of the Levelset field, ϕ, of an arbitrary shape

The LS field, ϕ, can be manipulated in any way through an advection equation. This equation takes a velocity field as an input to move the boundary in the domain. The velocity field can be defined through the optimisation problem such that the LS field moves according to the design variables.

2.2 Element partitioning

The Floating Node Method (FNM) was initially developed to model crack propagation. It is a numerical method based on the Finite Element Method (FEM) that introduces extra nodes without a coordinate position at the start of the analysis – floating nodes (Figure 3).

These floating nodes can be tied to topological features such as edges, areas, or other nodes, although this is not mandatory. The connectivity of the element reflects the inclusion of floating nodes such that the element formulation does not change, and the partitioning algorithm is only tasked with activating/deactivating the correct combination of floating nodes.

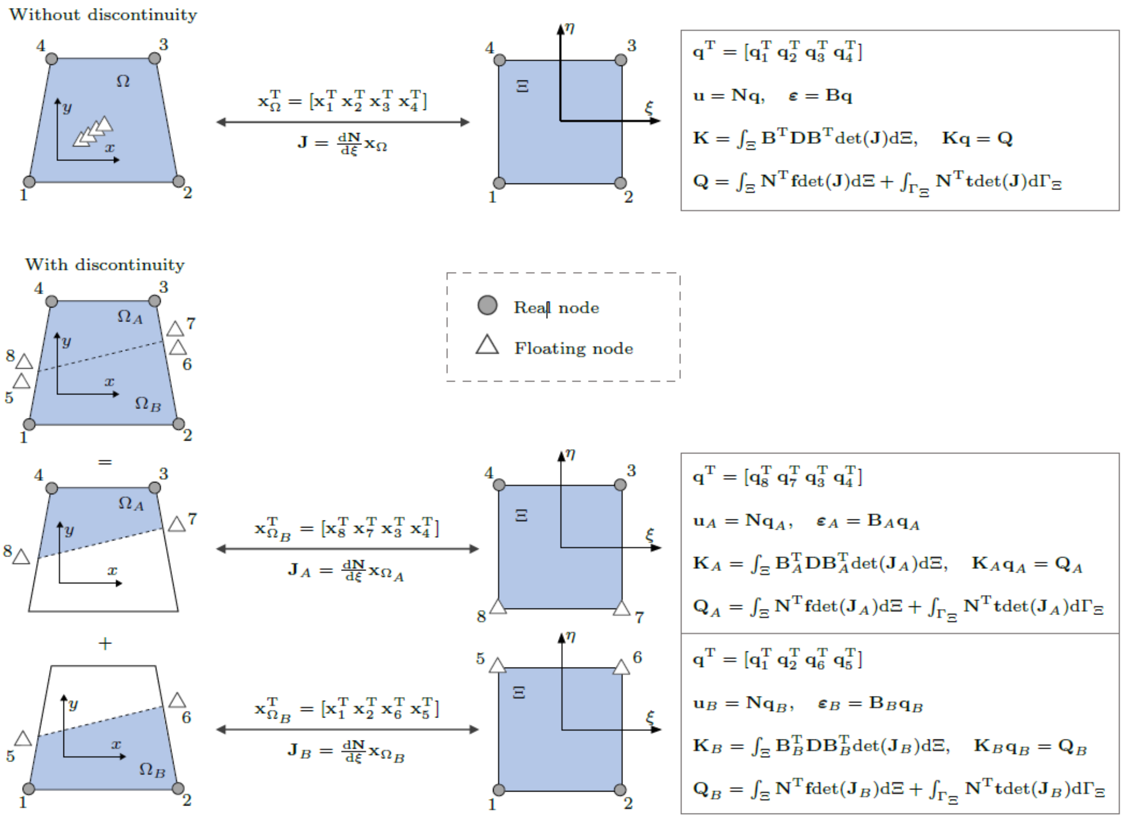


Figure 3. The Floating Node Method

2.3 Boundary-conforming mesh update

By coupling the LSM and FNM one can get both the implicit capabilities of boundary tracking and explicit element-wise partitioning. The partitioning can be done base on the LS field so as to capture the zero LS curve within each element (Figure 4).

To that end, each real node will have an additional degree of freedom (apart from the displacement ones) that represents the LS field in that point in space. The position at which each edge should be partitioned can then be computed by means of linear interpolation.

The partitioning algorithm is performed at the element level. So long as a given element has knowledge of its LS degrees of freedom it can partition itself independently of others. Therefore, the algorithm is highly parallelisable and scalable.

The partitioning cases are defined before the analysis and optimisation begin and can be as simple or as complex as the problem necessitates. The examples shown in Figure 4 are but an

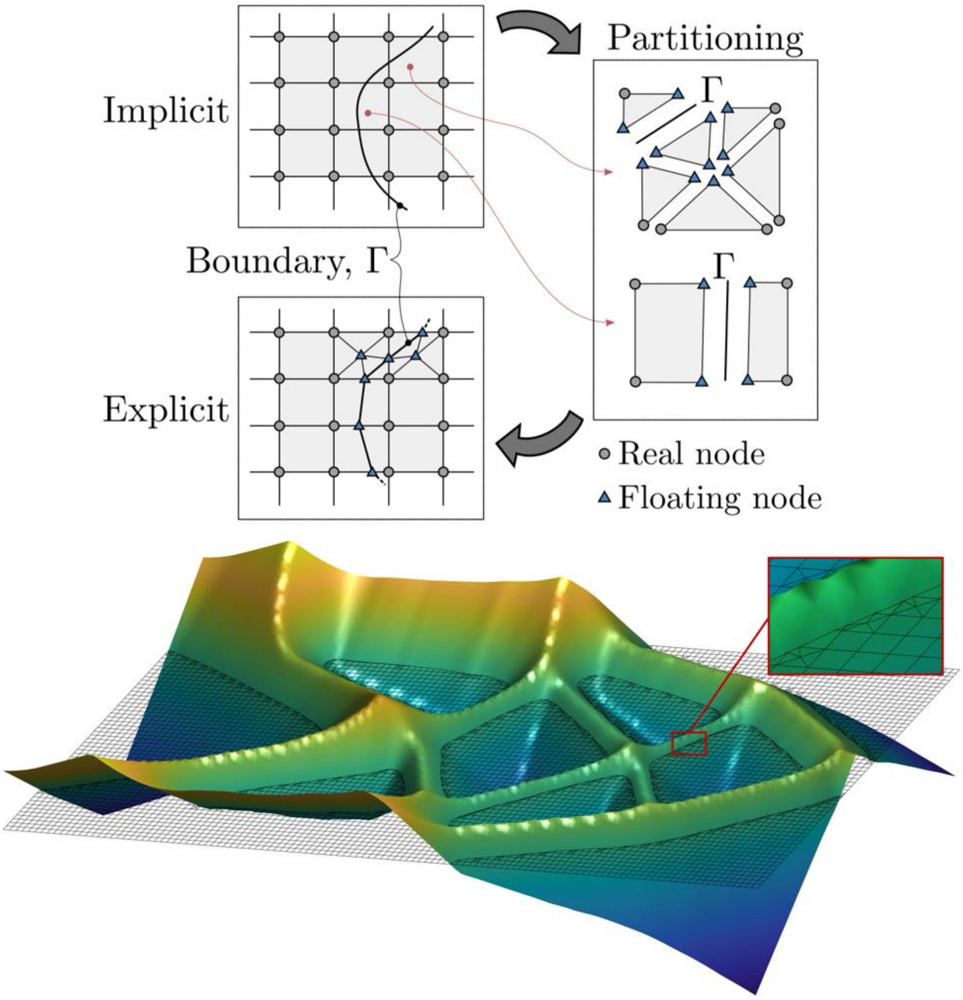


Figure 4. Coupling of the Levelset Method (implicit) and Floating Node Method (explicit) to achieve a conformal mesh partitioning scheme

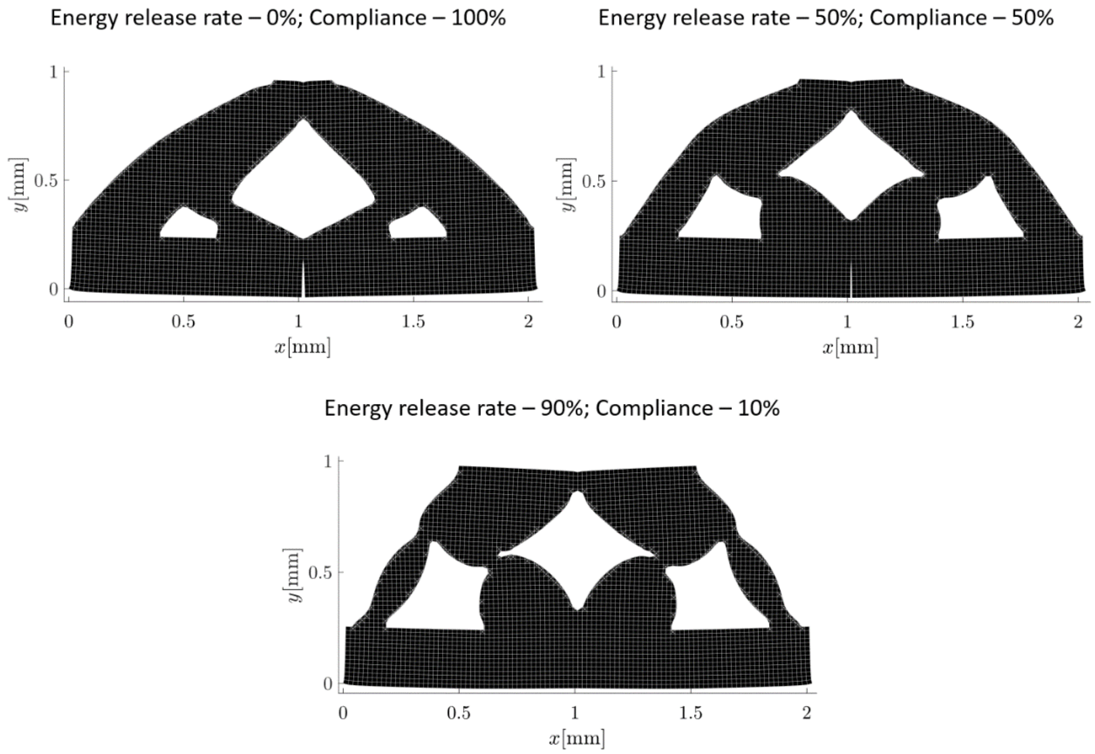
example of the simplest cases – single partition linearly representing the boundary within the element.

3. Results

The proposed methodology was assessed on a variety of problems with embedded cracks. The problems are variations of the MBB beam problem which is a common benchmark in topology optimisation problems.

Figure 5 contains the results for the MBB variation with a centred crack, specifically it shows the final design solutions for different weights of the energy release rate term. It is possible to observe that for higher weights of energy release rate the structure creates weakened structural members to divert load away from the crack tip – effectively reducing the effect of the crack on the overall response.

Figure 6 shows the evolution of the design measures through the design iterations and showcases the convergence of both of the measures.



Energy release rate – 0%; Compliance – 100%

Energy release rate – 50%; Compliance – 50%

Energy release rate – 90%; Compliance – 10%

Figure 5. Design evolution of a MBB beam with a centred embedded crack for various weights of the energy release rate objective function

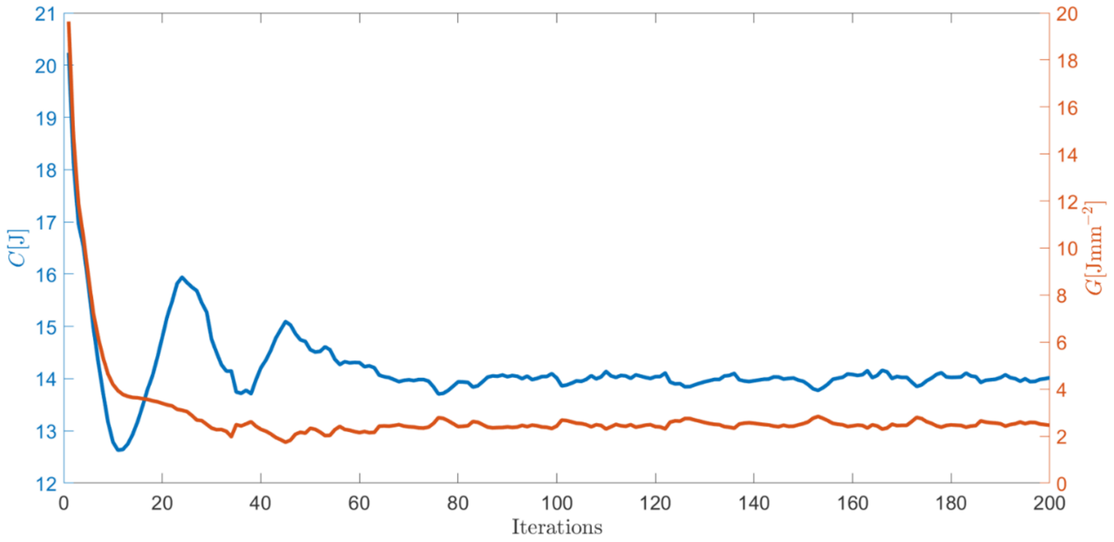
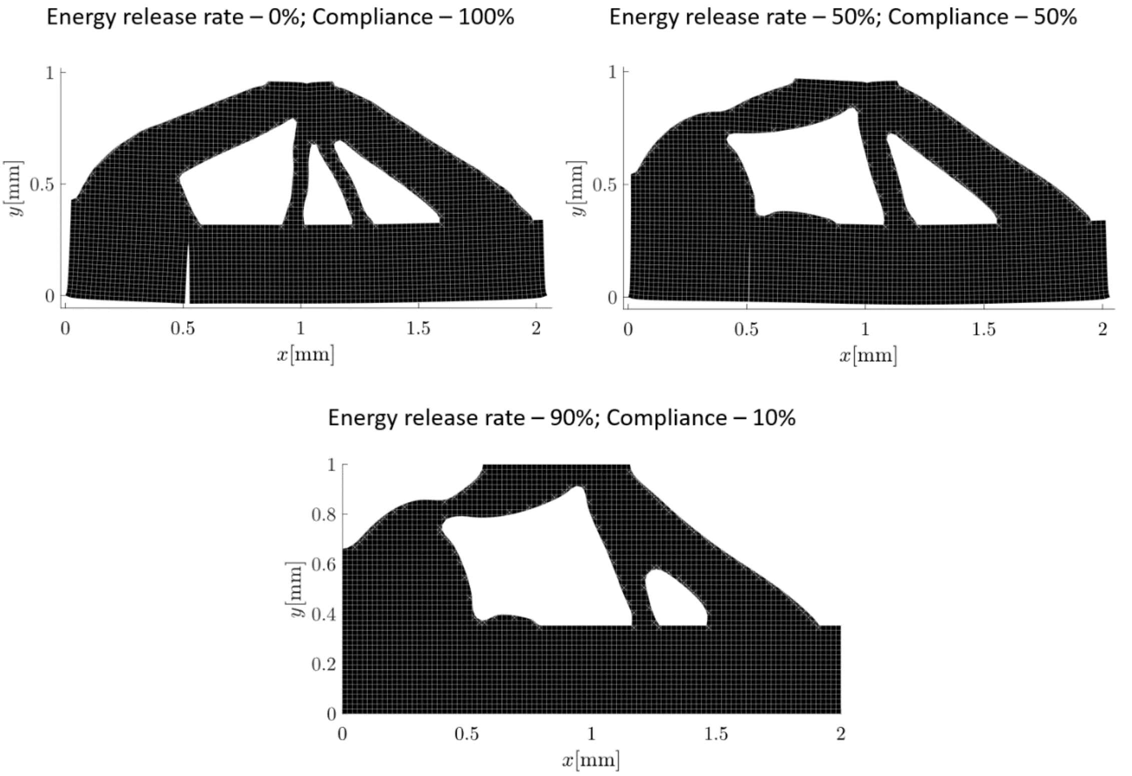


Figure 6. Evolution of the compliance (C) and energy release rate (G) terms as the design iterations evolve

Figure 7 contains the results for the MBB variation with an offset crack, specifically it shows the final design solutions for different weights of the energy release rate term. It is possible to observe that for higher weights of energy release rate the structure creates weakened structural



Energy release rate – 0%; Compliance – 100%

Energy release rate – 50%; Compliance – 50%

Energy release rate – 90%; Compliance – 10%

Figure 7. Design evolution of a MBB beam with an offset embedded crack for various weights of the energy release rate objective function

members to divert load away from the crack tip – effectively reducing the effect of the crack on the overall response.

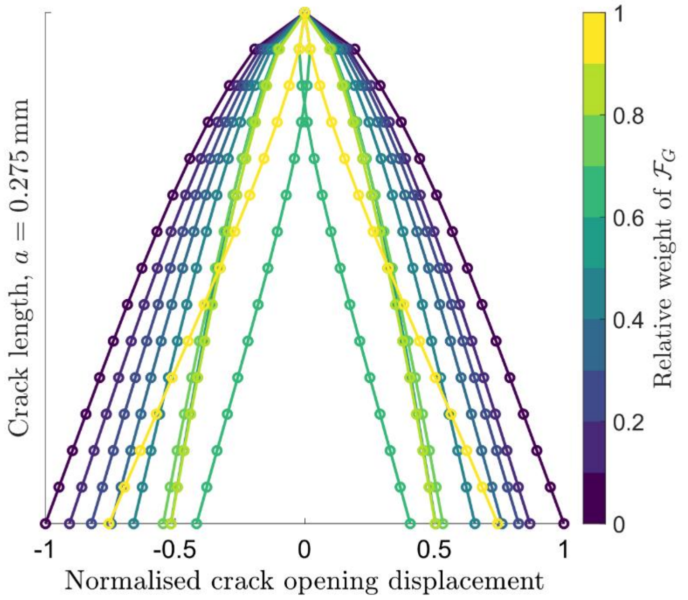


Figure 8. Effect of the energy release rate objective function (Fg) on the crack opening displacement

It can be observed from Figures 5 and 7 that the crack seems to close for the bigger weights of energy release rate. Figure 8 shows this effect in more detail and highlights the effect of the energy release rate term on the crack opening displacement

4. Conclusions

In this work we developed a Topology Optimisation methodology that couples the Levelset Method and Floating Node Method with a design sensitivity analysis formulation based on the energy release rate. Its key features include:

- the ability to include material defects in the model definition;
- an optimisation algorithm capable of reducing the impact of the material defects;
- an element partitioning algorithm capable of tracking the material boundary of the different designs;

We can conclude that this methodology can be applied to domains with embedded material defects for:

- studying design solutions that mitigate the impact of the defect while satisfying other design objectives and constraints;
- achieving more robust design solutions;
- simplifying the design process of intricate structures;

In summary, the proposed methodology provides a new framework for the robust design of composite structures with embedded material defects such as cracks and kissing bonds. This is achieved in a way that is highly scalable and easily configurable to fulfil unique design requirements and allowables.

5. References

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