STRUCTURAL OPTIMISATION FOR DAMAGE TOLERANCE

Rui O. S. S. da Costa[1, a], S. T. Pinho[1, b]

[1] Department of Aeronautics, Imperial College London, London SW7 2AZ, United Kingdom

[a] r.costa18@imperial.ac.uk

[b] silvestre.pinho@imperial.ac.uk

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ABSTRACT

Material defects are a widespread feature in the manufacturing of composite structures, especially in very large structures. These defects can lead to premature structural collapse; thus, it is important to design and optimise these large structures considering material defects. Structural optimisation methods enable targeting arbitrary design variables, such as defect tolerance, by incorporating carefully devised objective and constraint functions. In this work, we show an implementation of a topology optimisation methodology within a modelling framework designed for very large composite structures. The methodology has explicit boundary-tracking capabilities and relies on an objective function centred on the energy release rate of a crack or debond. We demonstrate how the optimisation methodology can successfully handle debonds in a model of a skin-stringer run-out assembly. We show that the method can decrease the energy release associated with the debond by changing the stringer run-out shape.

1 INTRODUCTION

The manufacturing of composite structures can lead to material imperfections and structural defects – for example, inter-plie debonding, kissing bonds (Fig. 1) and fiber misalignment. Current non-destructive measurement techniques have a lower bound on the dimension of defects that can be detected. Therefore, it is of extreme importance to account for the presence of defects in the design stage such that the final optimised design is more robust and less sensitive to defects that may be missed during structural inspection.

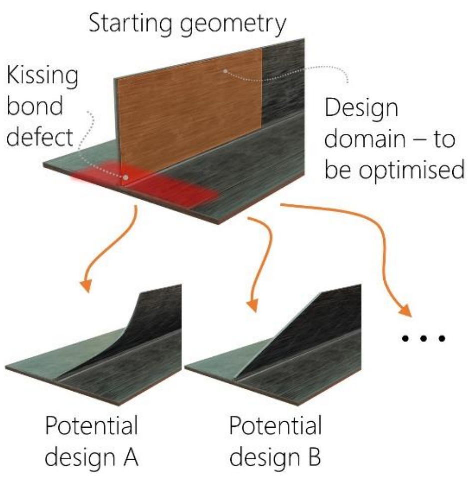

Figure 1: Schematic of shape optimisation of skin-stringer run out assembly

Structural design and analysis are traditionally separated as being two distinct subjects. The need for faster time-to-market, more competitive pricing and greater structural performance creates the need for innovative approaches to design. To this end, approaches which combine both design and analysis can convert an otherwise iterative process into a seamless concurrent one. These approaches allow for the consideration of structural defects during the design; moreover, they create the opportunity to optimise the design for damage tolerance.

Structural optimisation is a family of methodologies that aims to provide a seamless design and analysis experience through the evolution and optimisation of design variables and parameters. Topology optimisation is one of such methodologies which focuses on obtaining the best distribution of material along the domain.

In this work, we propose a new methodology capable of optimising the topology of a structure with a focus on damage tolerance. We present the 2D groundwork in which we consider an embedded crack defect in the domain; we then apply the methodology to a composite skin-stiffener runout with a kissing bond defect (as outlined conceptually in Fig. 1)

By employing a topology optimisation method, we can introduce complex design features into our models and find the design solutions that best fulfil a set of objectives around this design feature. For example, we can introduce debonds in component interfaces and evolve the design to minimise the energy release rate of this newly introduced defect. This design approach allows for faster design turnover and ultimately faster time-to-market. Additionally, by choosing objective functions carefully we can also achieve more robust and defect resistant designs.

2 BACKGROUND

2.1 Topology optimisation

Topology optimisation is a structural optimisation method in which the main design variable is the localised material density (normally localised to an element). Most topology optimisation methods are gradient-based methods whereby some form of design sensitivity analysis must take place in order to compute the effect of some arbitrary design change on the objective and constraint functions. The design sensitivity analysis normally materialises itself in the form of derivatives that need to be computed at every design iteration.

Often, topology optimisation methods are compliance-based, which means that the main objective function is some measure of the structure's compliance, and the method optimises to increase overall structural stiffness (it reduces compliance). However, we can devise other objective functions and constraints such that the behaviour of the method is specific to the problem we are trying to solve. Researchers have done this to study stress-based objectives, displacement-based objectives, and more.

2.2 Modelling evolving boundaries

The efforts to model evolving boundaries rely either on implicit tracking schemes or explicit tracking schemes. Implicit schemes, such as the level-set method (LSM, see Fig. 2), provide the means to efficiently model the boundary and its evolution, but cannot readily access information at the boundary [1]. Alternatively, explicit tracking schemes, such as the ones based on remeshing or partial-remeshing, are often computationally expensive and inherently complex to implement [2].

Some work has been done on alternative explicit schemes that alleviate some of the computational cost of remeshing. Namely, these include partial remeshing and trimming or cutting elements to locally conform to the desired domain [2]. While these methods succeed in obtaining conformal mesh more efficiently than remeshing, they rely on mesh deformation procedures and/or partial modification of elemental connectivity. Both are undesirable in the context of user-defined elements in a generic FE package.

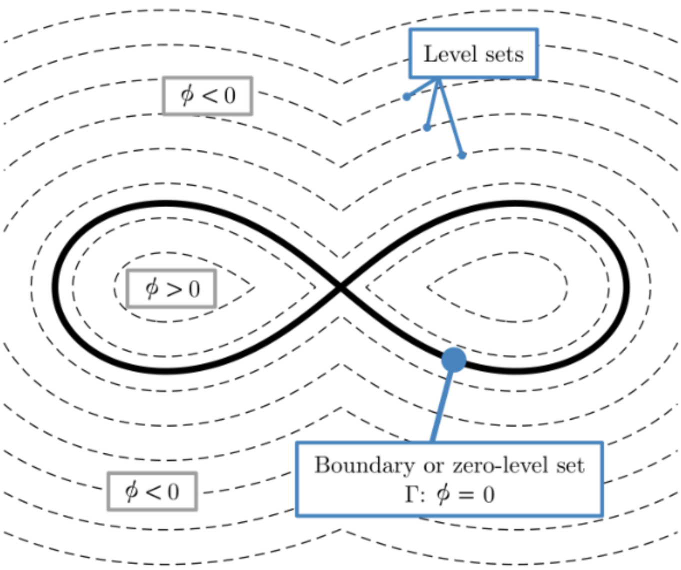

Figure 2: Schematic representation of the LSM and its implicit boundary representation capabilities, through the LS function ϕ [5]

2.3 Floating node method

The floating node method (FNM) is a method based on the finite element method (FEM) which creates floating nodes – nodes not initially tied to a coordinate position (see Fig. 3) – to provide the freedom of locally partitioning an element such that it conforms with a desired shape.

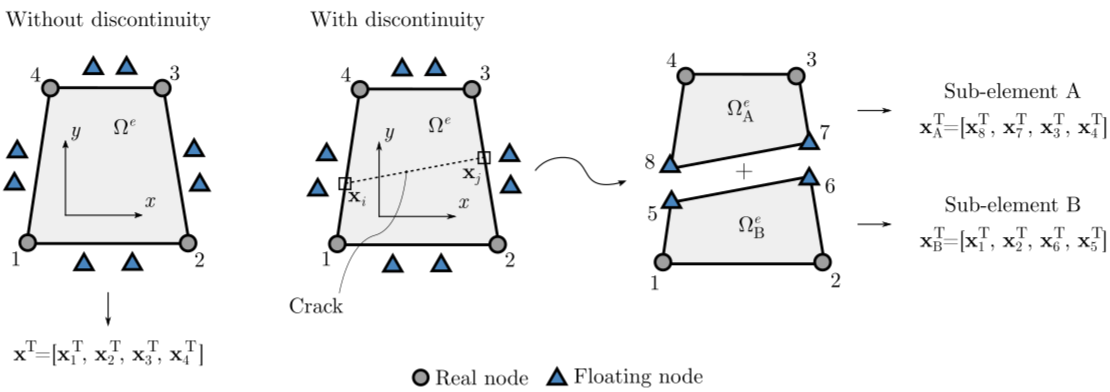

Figure 3: Floating node method discretisation of a strong discontinuity in an element [5]

Although FNM was initially developed to study crack propagation [3], it has also proven to be very powerful in realising polymorphic elements [4] and modelling evolving boundaries [5].

3 METHOD

3.1 Energy release rate sensitivity analysis

One of the most important aspects of this work is the development of a topology optimisation method based on the energy release rate. We propose a new objective function and derive its sensitivity in the context of continuum design sensitivity analysis (based on the shape derivative). Full details can be found in [6].

Considering a deformable elastic body, we can write the total potential energy (without considering body forces) as

$$\Pi = \frac{1}{2}\int_{\Omega} \boldsymbol{\sigma}_u : \boldsymbol{\varepsilon}_u \, \mathrm{d}\Omega - \int_{\Gamma} \mathbf{t} \cdot \mathbf{u} \, \mathrm{d}\Gamma . \tag{1}$$

From Equation (1) we can derive the expressions for energy release rate,

$$G = -\frac{\partial \Pi}{\partial a} = -\frac{1}{2}\int_{\Omega} \frac{\partial}{\partial a}(\boldsymbol{\sigma}_u : \boldsymbol{\varepsilon}_u) \, \mathrm{d}\Omega + \frac{\partial}{\partial a}\int_{\Gamma} \mathbf{t} \cdot \mathbf{u} \, \mathrm{d}\Gamma \; . \tag{2}$$

The traditional compliance objective function (resulting from Equation (1)) can be written as

$$F_C = \int_{\Gamma} \mathbf{t} \cdot \mathbf{u} \, \mathrm{d}\Gamma . \tag{3}$$

The proposed energy release rate (resulting from Equation (2)) objective function is defined as

$$F_G = \frac{\partial}{\partial a}\int_{\Gamma} \mathbf{t} \cdot \mathbf{u} \, \mathrm{d}\Gamma , \tag{4}$$

where a represents a crack length (for 2D problems) or a debond area (for 3D problems).

The full objective function is a combination of Equations (3) and (4),

$$F = (1 - \alpha)F_C + \alpha F_G , \tag{4}$$

where α is a weighting parameter controlling the ratio of the effect of each term of the objective function.

From Equation (4) we can define the optimisation problem such that we minimise function F when subject to a volume constraint.

The sensitivity expression of the compliance term expressed as a velocity for the level-set function can be written as

$$v_G = -\boldsymbol{\sigma}_u : \boldsymbol{\varepsilon}_u . \tag{5}$$

The analogous expression for the energy release rate objective function can be derived to reach the following

$$v_G = \boldsymbol{\sigma}_u : \boldsymbol{\varepsilon}_p , \tag{6}$$

Where the subscript p refers to the adjoint variable resulting from the derivative with respect to the crack length,

$$\mathbf{p} = -\frac{\partial \mathbf{u}}{\partial a} . \tag{6}$$

The combined sensitivity follows the definition in Equation (4) and can be written as

$$v = (1 - \alpha)v_C + \alpha v_G . \tag{4}$$

3.2 Floating node method for evolving boundary problems

The explicit boundary tracking capabilities of our proposed method are a direct consequence of using FNM to partition elements on-the-fly as they are intersected by the moving boundary. The partitioning algorithm operates on a 2D domain by employing the partitioning cases of a quadrilateral (see Fig. 4). Following this, the partitioning scenario is propagated through the thickness to achieve a 3D (or effectively a 2.5D) partition and a linear representation of the boundary on the 3D mesh [6].

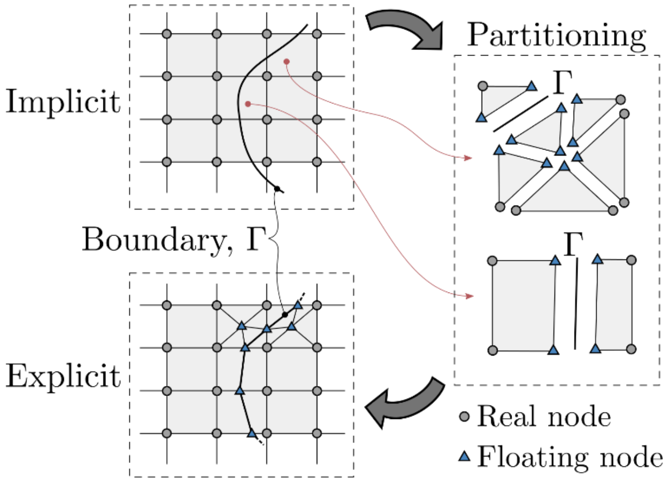

Figure 4: Floating node method discretisation of a moving boundary

3.3 Solid shell element formulation

In this work, we implement two layered solid shell elements: one hexadron and one wedge element. These are based on their solid element counterparts (with linear isoparametric shape functions) but we employ reduced integration (with several points through the thickness) and a modified plane stress constitutive law to achieve the shell behaviour [6].

The implementation of the shell elements is designed to allow for the LSM, FNM and optimisation methodologies to come together. This is done by introducing extra degrees of freedom and variables that represent all the problem types we need to solve (structural, adjoint, velocity extension and level-set evolution).

For simplicity of implementation we make use of Abaqus built-in hourglass control schemes by overlapping a built-in solid element type to our user element and sharing some of its nodes. The solid element is given an extremely soft material to influence the stiffness of shared nodes as little as possible.

3.4 Algorithm

The methodology presented in this work [6] is implemented in Fortran as a user-element for Abaqus. The implementation includes the custom shell element (with level-set, floating node and optimisation features) and all the logic necessary to manage and visualise the evolving mesh in ParaView through a simple VTK file exporter.

The algorithm is devised such that we have different problem types (structural problem, level-set velocity extension, level-set evolution and adjoint problem). Each of these types represents a single stage in a full analysis step; each stage being solved for sequentially in each step. The custom shell element stiffness matrix is populated, at each stage, with the correct matrix for the given problem type.

4 RESULTS

We apply the proposed methodology to the design of a skin-stringer run out assembly (see Fig. 5). The assembly, being a detail model from a full-scale wing-box model, is driven by a sub-modelling approach in which boundary conditions for the detail model are extracted from a global wing-box model [7] at the location corresponding with the boundary of the detail model. The results of the global wing-box model are a snapshot from a damage evolution simulation in which there was substantial buckling and material damage in skin region just in front of the stringer run-out.

The model was tested for different ratios of the mean compliance and energy release rate objective functions. We observed a clear trend whereby as the importance of the energy release rate term increased, the energy release rate of the resulting design solution approached zero (see Fig. 7).

Effectively, the energy release rate objective function led to design solutions more resistant to the growth of the debond. This was achieved by removing some of the material above the debond (see Fig. 6) from the web of T-stringer. This alleviates the localized stiffness of that particular region leading to debond to open less.

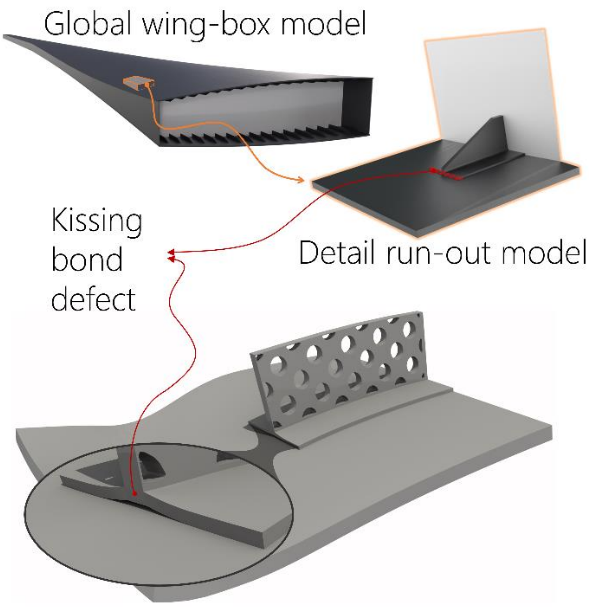

Figure 5: Sub-modelling approach. Results from a damage evolution analysis on the full-scale wing-box global model drive the analysis of a detail skin-stringer assembly with a kissing bond defect

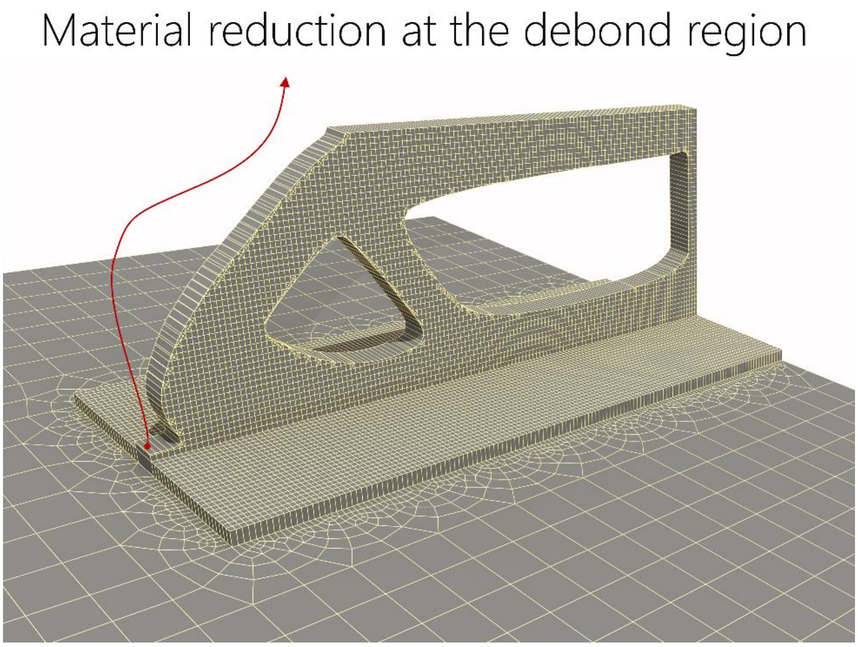

Figure 6: Converged solution for $\alpha = 0.5$ (50% contribution from compliance and energy release rate terms) with clear material reduction at the region where the kissing bond defect is present

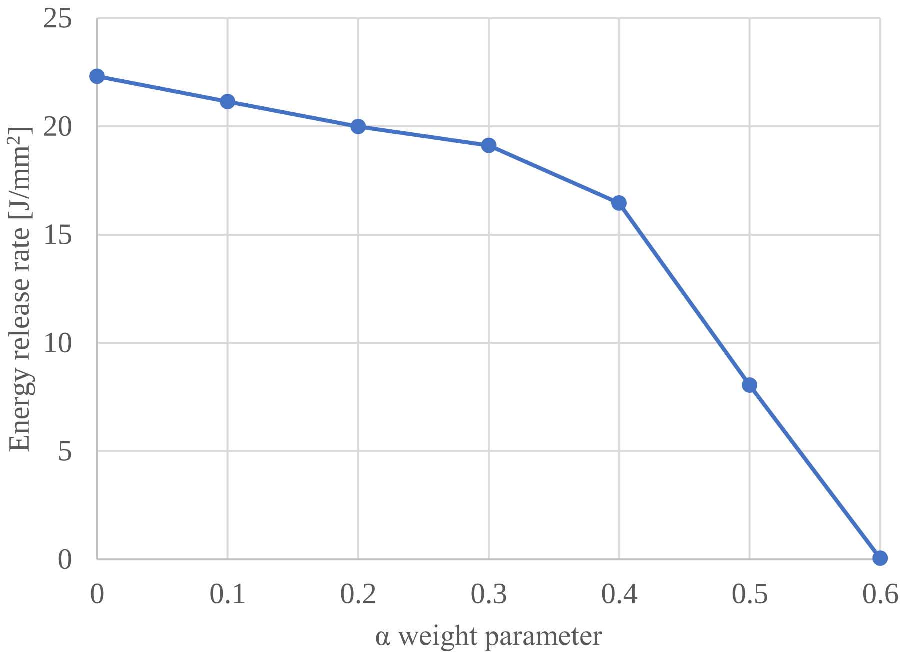

Figure 7: Energy release rate of converged topologies for different contributions, α, of the compliance and energy release rate terms of the objective function

9 CONCLUSIONS

This works proposes a topology optimisation of very large composite structures with kissing bond defects. The methodology, fully explained in Ref. [xxx], brings together capabilities from FNM, LSM and continuum design sensitivity analysis, and integrates them into a codebase suitable for use within a generic FE package through user element functionality.

The explicit boundary tracking in 3D models made possible by the coupling of FNM and LSM allows us to have:

- a clear solid-void interface;
- direct access to boundary nodes;
- improvement of accuracy of computations at the boundary; and
- improved geometry representation.

The proposed topology optimisation method based on the energy release rate and its design sensitivity allows us to:

- improve sensitivity computation – in terms of accuracy and computational cost;
- introduce the effect of defects into the design process; particularly, the effect of kissing bonds. This leads to the ability to generate designs with lower energy release rate.

The proposed workflow and algorithm are implemented in Abaqus and was designed to:

- make use of user element type interfaces;
- handle complex and large models;
- allow for multiscale modelling techniques;
- enable remote visualization and post-processing on high performance computing clusters.

In summary, this works presents a methodology that has the potential to fundamentally change the design of large composite structures.

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