DOI: 10.13009/EUCASS2023-422
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

A Global-Local defect and damage initiation model for launcher composite structures pre-sizing

Alexy TAILLEUR[1†], Kévin MATHIS[2], Ange ROGANI[3], Pablo NAVARRO[1], Steven MARGUET[1] and Jean-François FERRERO[1]

[1] *Université de Toulouse, Institut Clément Ader, UMR CNRS 5312, Toulouse, France*

[2] *CNES Direction Des Lanceurs, Paris, France*

[3] *CT Ingenierie, Toulouse, France*

alexy.tailleur@univ-tlse3.fr – kevin.mathis@cnes.fr – ange.rogani@ctingenierie.com – pablo.navarro@univ-tlse3.fr steven.marguet@univ-tlse3.fr – jean-francois.ferrero@univ-tlse3.fr

[†] Corresponding Author

Abstract

This paper deals with the development of a numerical approach to study damage initiation in flawed launcher laminated composite structures during pre-sizing phase. It is realised through a novel 2D-3D top-down submodelling method adapted to large and complex composite structures. The aim of this numerical strategy is to address defects and damage as early as possible in the development stages of launcher composite structure. A new displacement interpolation based on a fourth order polynomial has been proposed and Kirchhoff-Love theory has been used in addition. Very accurate stress fields are obtained in the local area compared to a refined global model.

1. Introduction

The proportion of composites in Ariane launchers is constantly increasing at each new iteration. Conventional sizing methods of space structures are not suitable for taking into account defects/damage in these structures at the beginning of their development. Indeed, numerical simulations of large damaged composite structures involve high computational costs and are therefore not convenient to rapid pre-sizing loops. Global-local approaches have been developed as a reliable and efficient tool to study the onset and the propagation of damage.

1.1 COLIBRI dimensioning tool

COLIBRI is a platform developed and used by CNES for the design and dimensioning of composite structures for space launch vehicles [16]. This tool sets the critical load threshold before any damage occurs and take into account manufacturing and operational defects via knockdown factors to ensure damage tolerance. More complex methods exist but they come at the end of the development phase, once the architecture is fixed. Therefore, the chosen structure is optimal to meet the specifications but is not necessarily the most efficient to withstand the presence of defects or damage. It is therefore necessary to deal with defects and damage as early as possible in the development phases of the structure.
The composite structures optimised in COLIBRI present large dimensions. In addition, previous studies conducted by CNES and CTI have shown that 3D modelling of the structure, using cohesive elements, is essential to represent damage such as delamination. Due to high computational costs, performing damage calculations on these whole structures is not a feasible solution at the pre-dimensioning stage. In addition, damage initiation and propagation are generally local phenomena that are triggered in stress concentration zones with pre-existing defects such as manufacturing or assembly imperfections, service damage or inadequate maintenance [19].
This dilemma between calculation times adapted to pre-dimensioning and an accurate representation of defects and damage within a composite structure can be addressed by means of submodelling.

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1.2 Global-local approach

1.2.1 Global-local methods overview

Widely developed over the last two decades, there are now several categories of global-local approaches. The method most commonly used in industry and commercial software is a top-down loose coupling approach. As shown in Fig.1, it is a two-stage process. First, a simulation is performed on a complete structure with a coarse mesh ("global model"). Then, a new simulation with a refined mesh is carried out on the specific areas to be studied ("local models"). These are two separate models. This is why they are referred to as loose coupling.

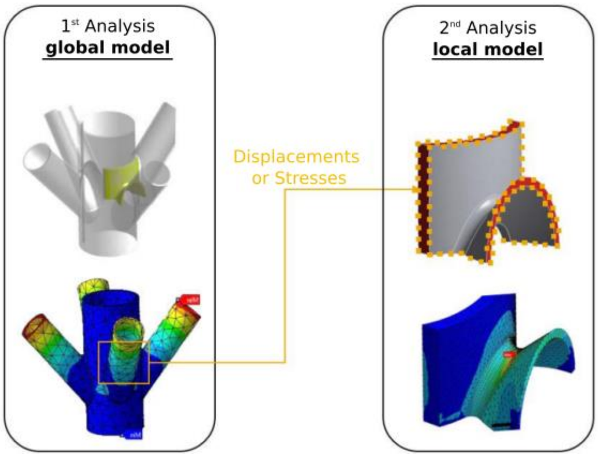

Figure 1: Illustration of top-down approach

Mechanical quantities are extracted from the global solution and are used as boundary conditions of the local model. Displacements [8, 9, 22] are generally preferred to stresses [15, 30] as prescribed quantities at the boundaries of the local domain because of their higher convergence rate.
Despite its advantages, the top-down approach is limited to cases where the overall response of the structure is not likely to be significantly influenced by the local behaviour. On the other hand, bi-directional submodelling [2, 12, 14, 19, 37] is extremely well suited to damage propagation. Indeed, local information are transferred back to the global model and the global-local process becomes iterative.

1.2.2 Local boundary conditions

After the global static analysis, translations and rotations are known at the global nodes (Fig. 2). These data need to be transferred to the local domain interface. The local model has a more refined mesh than the global model. Consequently, intermediate values of displacement along the boundary must be determined. Initially, displacement interpolation was performed using linear shape functions. Later, authors proposed the use of Lagrange interpolation [35] or cubic splines [9].

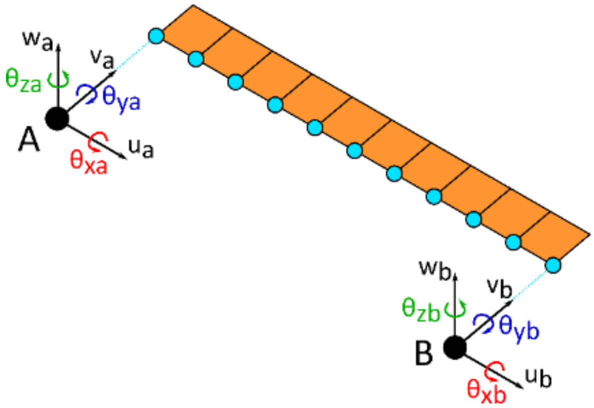

Figure 2: Nodal displacements after global static analysis

Secondly, the placement of the local model boundary is another key point in the success of the global-local approach. As shown by Mao [22], applying displacements at the interface introduces adverse effects in the accuracy of the

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solution of the local static problem. They proposed a widely adopted method which involves the use of a transition zone placed around the critical zone, as shown in Fig. 3.

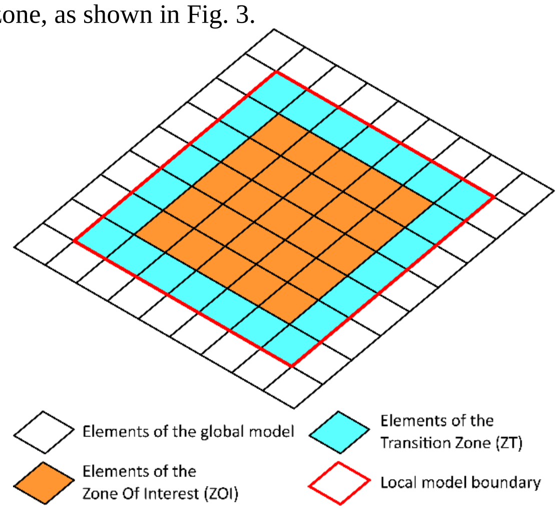

Figure 3: Local model with transition zone

The suggested size of the transition area is equivalent to a coarse mesh element. As a result, the local model does not correspond exactly to the area of interest, the size of model is increased. [33] studied the effect of interpolation functions on the fidelity of the results obtained for local simulation. Shape functions introduce singularities in the stress field, whereas a cubic spline interpolation generates results in agreement with the exact values. Furthermore, the use of cubic splines would allow to have local boundaries closer to the critical zone. On the contrary, using shape functions would require enlarging the local domain to reduce the impact of singularities at the boundaries.

1.3 Damage modelling

1.3.1 Delamination modelling

Delamination is one of the three main failure mechanisms in laminated composites. This separation of adjacent plies usually occurs in preferred areas and leads to significant decreases in the material strengths.
Delamination in composites is often modelled using Virtual Crack Closure Technique (VCCT) or by cohesive interface elements. VCCT is based on linear fracture mechanics and assumes that the energy released during delamination propagation is equal to the work required to close the crack [17, 18, 31]. The main drawback of this technique is that the crack initiation zone must be known in advance, which can be difficult for large complex structures. Cohesive Zone Modelling (CZM), proposed by [4, 20] is another main approach to represent delamination onset and propagation. The behaviour of the cohesive interface is defined by a traction-separation law relating interfacial stresses and displacement jumps at the interface of potential crack. Different forms of cohesive law have been studied in the literature; bilinear, exponential, trapezoidal,...[1, 6, 13]. Both methodologies (VCCT and CZM) have already been studied in the scope of submodelling to represent delamination onset and propagation [2, 5, 17, 34].

1.3.2 Porosity modelling

Voids can be located within a ply (intra-ply voids), as well as in the interface between two plies (inter-ply voids). The presence of voids degrades the mechanical properties dominated by the matrix and the interface [23, 24]. Micro-models are the main category of void modelling [3, 10, 36]. This is mainly because the behaviour of the porous materials is impacted by the location of voids in the laminate but also by their size, shape or distribution [26, 27].
From the point of view of pre-dimensioning, it is not possible to go down to such a small scale and to represent the voids in the material so finely. [20] uses CZM to simulate the presence of inter-ply voids. Finally, knock-down factors can be used [25] as well as empirical laws to determine the material strength reduction [7, 11, 21, 32].

1.3.3 Matrix cracking modelling

Matrix cracking is one of the first damage modes in composite laminates subjected to mechanical and/or thermal loads. A first way to represent intra-laminar cracking is based on continuous damage mechanics (CDM). Developed over the last two decades, eXtend Finite Element Model (XFEM) allows the modelling of crack initiation and propagation without prior knowledge of the crack path or the need to update the mesh. It has been successfully used in the case of

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the global-local approach [26, 29]. XFEM can be coupled with CZM, and matrix cracking can also be simulated using cohesive elements [6, 28].

1.4 Objectives

The objectives of the present work is to develop a numerical strategy to take into account the presence of defects and damage in laminated composite structures during pre-sizing stage. The proposed approach allows to go from large dimensional structures represented with 2D shell elements to 3D local areas where defects such as porosity, matrix cracking and delamination have been inserted. Sometimes hard to detect, those damage can lead to a decrease in mechanical properties and a loss of strength. Furthermore, when the structure is loaded, and especially in a reuse scenario, this damage can propagate and lead to final failure with dramatic consequences. For all these reasons, it is important to understand and characterise the behaviour of damaged composite structures:

- At the design level, to improve the performance of structures, challenge mass and cost by accepting to live with damage while avoiding loss of integrity
- At the backup level to be able to confidently predict the propagation of damage and characterise the shape and size of fragments after an accidental event or after neutralisation of the launcher.

This work is a first part in the development of the global/local strategy for modelling damage initiation and propagation in launcher composite structures during pre-sizing phase. The methodology developed focuses therefore on the initiation of damage in the presence of defects.

Most of the works develop their approach via the commercial software Abaqus or use the submodelling module directly implemented in this same software. Here, everything is realized through the numerical solver Nastran only. The automation process is carried out by means of routines written in Python.

2. Developed approach

2.1 Unidirectional submodelling

The aim of the proposed approach is to detect the onset of damage in laminated composite structures which may have manufacturing or operational defects. Hence the one-way loose coupling global-local methodology is suitable for this problem. As shown in Fig. 4, two distinct simulations are performed, one after the other. The information flows from the "global" model to the distinct "local" model.

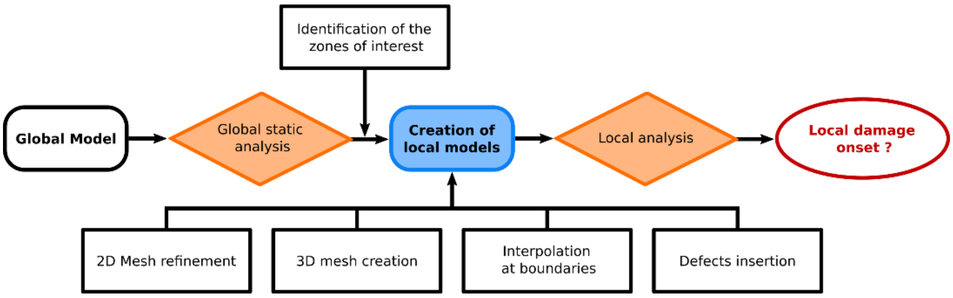

Figure 4: Flowchart of the unidirectional loose coupling procedure

2.2 Loca model's boundary conditions

A key to submodelling is the transfer of information between global and local scales. In the proposed approach, the displacements have been chosen to serve as boundary conditions for the refined local calculations. The displacements are only known at the nodes of the original mesh. Two steps are then necessary to constrain all the boundaries of the local domain. First, the displacements must be interpolated at the nodes present in the plane on the local mesh boundary. This corresponds to step 1 in Fig. 5. In this way, the intermediate values of the displacement between two adjacent nodes of the global mesh (between A and B in the example) are obtained. Because of the three-dimensionality of the local model, a second step is necessary to determine the displacements in the thickness of the boundaries. It is represented in step 2 of Fig. 5.

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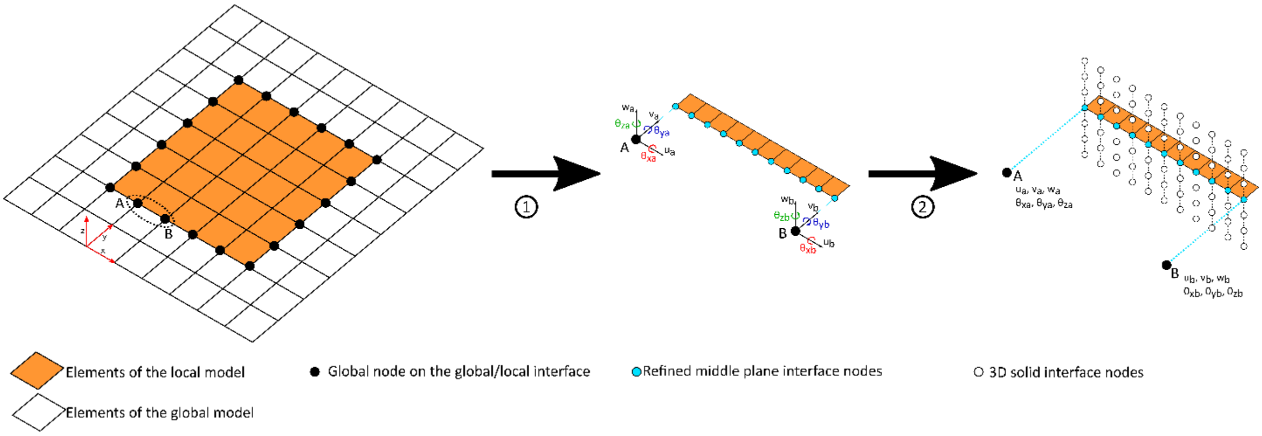

Figure 5: Boundary conditions interpolation steps

For the first part of the displacement interpolation, the displacements u and v (in the (x,y) plane) have been linearly interpolated. The interpolation proposed here for out-of-plane displacements w is carried out global element by global element. After the first global simulation, 12 data items are available in each global element: 4 displacements w, 4 rotations around the x axis and 4 rotations around the y axis. A polynomial of order 4 is therefore required to determine w(x,y). As the 4th-order basis is composed of 20 coefficients, truncation was chosen in accordance with the literature:

$$\boldsymbol{w(x,y) = A_1x^3y + A_2xy^3 + B_1x^3 + B_2y^3 + B_3x^2y + B_4xy^2 + C_1x^2 + C_2y^2 + C_3xy + D_1x + D_2y + E} \quad \textbf{(1)}$$

According to Kirchhoff-Love theory, the rotations θx and θy are defined by Eq. (2) and Eq. (3) respectively.

$$\frac{\partial w(x,y)}{\partial y} = \theta_x \quad \textbf{(2)}$$

$$\frac{\partial w(x,y)}{\partial x} = -\theta_y \quad \textbf{(3)}$$

In order to determine the performance of the polynomial interpolation, multiple simulations were conducted in presence of transition zone. All type of loadings are schematized in Fig. 6.

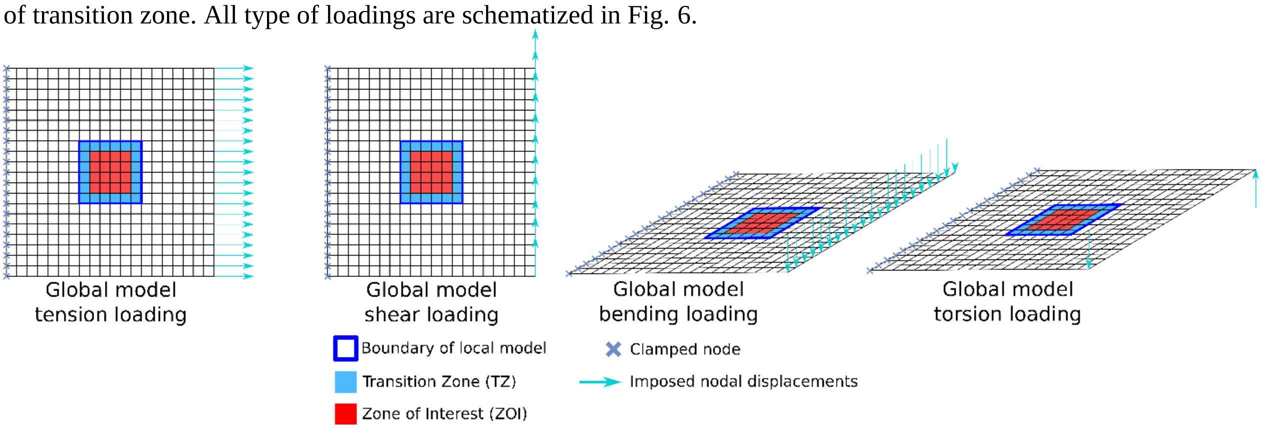

Figure 6: Schematisation of the different modelled loading modes

For each type of solicitations, three models were carried out:

- coarse global model,
- fine global model,
- local model with a mesh size as fine as the fine global model.

The design of experiments was conducted on a 200mmx200mm composite plate meshed with shell elements. The analyses have been done on an unidirectional laminate first and then on the following stacking sequence: [45/90/-45/0/0/0/-45/90/45]. The ply thicknesses were all equal to 0,1mm. The material properties are available in the Tab. 1.

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Table 1: Material properties used for analysis

Material Properties	**E_{11} (MPa)**	**E_{22} (MPa)**	**G_{12} (MPa)**	**G_{23} (MPa)**	**G_{13} (MPa)**	**ν_{12}**
Values	160360	9942	6131	6131	3829	0.33

The elements of the global coarse model have a size of 10mmx10mm. The size of the elements of the fine global model and of the local model is 1mmx1mm. Hence, it corresponds to a factor 10 refinement. The results in the area of interest of the local model were then compared with those of the fine global model. As shown in the Tab. 2, the use of this polynomial allows a very satisfying correlation under all types of solicitation for stress values.

Table 2: Percent error between the stress results from fine global model and the local model

2D interpolation	**$\|\Delta\sigma_x\|$**	**$\|\Delta\sigma_y\|$**	**$\|\Delta\sigma_{xy}\|$**
Tensile	<0.1%	<0.1%	<0.2%
Shear	<3%	<5%	<0.2%
Bending	<0.1%	<1%	<1%
Torsion	<1%	<1%	<0.2%

For instance, the calculated σx stress field in the zone of interest of ply 1 for the bending load case is shown in Fig. 7.

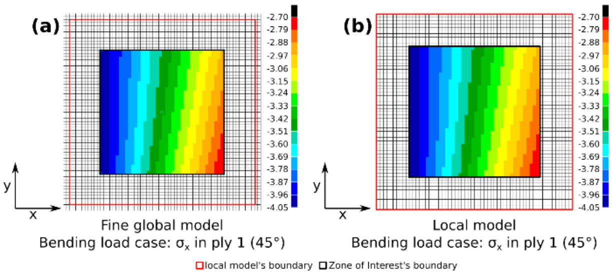

Figure 7: σx in ply 1 for bending load case

2.3 3D Local Model

The proposed approach allows to go from a global model meshed with 2D shell elements to a local model meshed with 3D solid shell Nastran elements. The model will be used in fast optimisation loops during the pre-dimensioning phase of composite structures. Thus, to keep it efficient and to reduce the computational cost, only one 3D element is used in the thickness of a ply. The displacements interpolated at the boundary via the Eq. (1), Eq. (2) and Eq. (3) must then be transformed in pure translational displacement degrees of freedom at each boundary nodes. For this purpose, the Kirchhoff Love displacement field defined by Eq. (4) will be used

$$\begin{aligned} u(x,y,z) &= u_0 + z\theta_y \\ v(x,y,z) &= v_0 - z\theta_x \\ w(x,y,z) &= w_0 \end{aligned} \qquad (4)$$

For this first verification, the plate tested has orthotropic properties and the following stacking sequence: $[0]_5$. As with the validation of the fourth-order polynomial for the interpolation of the displacement field w, four stresses were tested on the composite plate: tension, shear, bending and torsion. The results presented correspond to the comparison of minimum and maximum strains in ply 5 (0°). As Tab. 3 shows, the use of this displacement field gives a very satisfactory correlation under all types of loading for the deformation field and therefore the stresses.

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Table 3: Percent error between the strain results from 3D fine global model and 3D local model

3D interpolation	$\|\Delta\varepsilon_x\|$	$\|\Delta\varepsilon_y\|$	$\|\Delta\varepsilon_{xy}\|$	$\|\Delta\varepsilon_I\|$	$\|\Delta\varepsilon_{II}\|$	$\|\Delta\varepsilon_{III}\|$
Traction	0%	<1%	X	0%	<0.3%	<1%
Cisaillement	<1%	<0.8%	0%	<0.3%	<0.3%	<0.3%
Flexion	0%	<0.5%	<3%	0%	<0.4%	<0.3%
Torsion	<0.4%	<0.6%	<0.2%	<0.2%	0%	<0.2%

2.4 Local Damage Introduction

Defects and damage such as porosity, matrix cracking and delamination are inserted into the local model. The onset and progress of delamination will be represented using cohesive elements placed at the interface between plies. These are linear 3D elements with zero thickness. Thus, the solver will necessarily be set in SOL 400 "implicit non-linear".
In order to limit the size of the local model, cohesive elements are not inserted between all plies but only at the interfaces where delamination is likely to occur, i.e. between plies of different orientations. Being the most present in the literature, the bilinear cohesive law will been used in the first instance.
Currently, porosity and matrix cracking will be modelled via damage variable which will tackle the material properties. Indeed, using cohesive elements to represent matrix cracking could lead to high computational costs and is not in line with the pre-sizing approach

3 Conclusion

In this paper, a 2D-3D loose coupling submodelling approach adapted to the pre-dimensioning of large composite structures has been formulated. This method is fully compatible with the Nastran solver and allows the local insertion of defects such as porosity, matrix cracking and delamination.
A new displacement interpolation based on a fourth order polynomial has been proposed. Although this interpolation does not eliminate the need for a transition zone, the very good correlation between the stress fields obtained via the refined global model and the local 2D model demonstrates the effectiveness of the interpolation formulated. The interpolation of the 3D displacement at the local zone boundary using the Kirchhoff-Love displacement field still needs to be verified in the presence of cohesive elements before validating the full unidirectional approach. However, the results obtained without cohesive elements demonstrate an excellent correlation between a global 3D simulation and the global 2D / local 3D process.
Regarding the insertion of defects and the damage onset, the choice was made to use CZM to represent delamination. A reduction in material allowances will initially be used to model elements damaged by porosity and matrix cracking. Finally, when this approach is fully completed and validated, the next step will be to develop the feedback loop from the local model to the global model. The experimental campaign has just begun. It will be used to calibrate and validate the insertion of defects into the local model.

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