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Failure onset evaluation of deployable rolled-up composite synthetic aperture radar (DERAC-SAR) antenna via global/local approach

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Abstract

This work focuses on a global/local simulation technique, based on the Carrera Unified Formulation (CUF), developed for failure onset analysis in Deployable Rolled-Up Composite Synthetic Aperture Radar (DERAC-SAR) structures. DERAC-SAR addresses space and weight constraints in satellite systems, featuring a rollable deployment mechanism that induces complex three-dimensional (3D) stress fields near fixed boundaries. Accurately capturing these stress fields typically requires computationally intensive 3D models, but this study proposes a multi-step approach to balance accuracy and efficiency. First, a global analysis using 2D elements is performed with Abaqus to evaluate stress and nodal displacements. These displacements then serve as boundary conditions for a refined local analysis using higher-order models in critical regions. The local domains are modelled using CUF, which supports higher-order plate elements and incorporates geometric nonlinear effects, including large displacements and rotations. The nonlinear equations are solved in a total Lagrangian framework using a Newton-Raphson linearization scheme with displacement-control constraints. This method mitigates computational demands while maintaining accuracy, enabling precise prediction of 3D failures in critical areas during the deploying process.

Keywords: Carrera Unified Formulation; global/local; deployable structures; synthetic aperture radar; 3D stress fields.

Nomenclature

F_τ	Cross-section kinematic expansion
N_i	Shape functions
$\mathbf{u}$	Three-dimensional displacement field
$\mathbf{q}_{\tau i}$	Nodal unknowns

Acronyms/Abbreviations

CUF	Carrera Unified Formulation
DERAC	Deployable Rolled-Up Composite Antenna
DOF	Degree of Freedom
FEM	Finite Element Method
HSC	High Strain Composite
SAR	Synthetic Aperture Radar

1. Introduction

The Deployable Rolled-Up Composite Synthetic Aperture Radar (DERAC-SAR) antenna is a groundbreaking advancement in space radar technology [1]. Designed specifically for space applications, DERAC-SAR utilizes High Strain Composite (HSC) materials that enable it to be compactly stored during launch; once in orbit, the radar deploys, expanding its surface area. This innovative design maximizes efficiency within the constrained environment of space missions, where weight and space are critical factors. DERAC-SAR retains the key capabilities of Synthetic Aperture Radar, including operation in all weather conditions and darkness, making it an essential tool for continuous space-based observation [2][3].

This SAR technology introduces a sophisticated rollable deployment mechanism, essential for addressing the constraints of space and weight in satellite systems. However, this mechanism generates complex three-dimensional (3D) stress fields near the fixed boundaries of the structure, which pose significant challenges for accurate failure analysis [4]. Capturing these stress fields with precision typically necessitates the use of computationally intensive 3D models, which can be both time-consuming and resource-demanding [5]. To address this challenge, the present work introduces a global/local simulation technique based on the Carrera Unified Formulation (CUF) [6]. This approach aims to balance the accuracy of 3D stress field representation with computational efficiency [7][8]. Initially, a global analysis with a validated commercial software utilizing 2D elements is conducted to assess stress and displacements across the entire structure. The computed displacements are then used as boundary conditions for a detailed local analysis, focusing on critical regions where higher-order models are applied. The CUF methodology

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supports advanced plate elements and accounts for nonlinear effects, including large displacements and rotations, within a total Lagrangian framework. By solving the nonlinear equations with a Newton-Raphson linearization scheme and displacement-control constraints, this approach effectively mitigates the computational effort while ensuring precise predictions of 3D stress during the deployment process. This method provides a practical solution for analysing the complex stress fields associated with the DERAC-SAR, enhancing both the accuracy and efficiency of the failure onset analysis.

The paper is organized as follows: Section 2 provides a description of the methodology used and the test case discussed in this work; Section 3 reports the results of the global-local framework. Finally, Section 4 presents the conclusions of the research.

2. Material and methods

2.1 Overview of the simulation method

This study applies a novel global/local method for analysing failure onset in deployable thin composite structures. The proposed technique addresses the limitations of commercial computational tools, which rely on three-dimensional finite elements to capture local stress fields. The proposed method achieves a significant reduction in computational expense without sacrificing accuracy. This is made possible by the Carrera Unified Formulation, which enables higher-order modelling of plate elements, allowing detailed analysis of critical local regions in complex composite structures.

Due to the boundary condition that maintains the HSC's root rigidly curved and the anisotropic nature of the composite materials used in DERAC-SAR, the stowage process generates intricate three-dimensional stress fields in localized areas of the structure. Accurately capturing these stress fields is crucial to assess issues as failure onset. The global/local approach outlined in this work follows a two-step process. First, a global analysis is conducted using the commercial software Abaqus. Then, the local regions are further examined using refined theories based on the CUF framework. Figure 1 provides a schematic of the procedure.

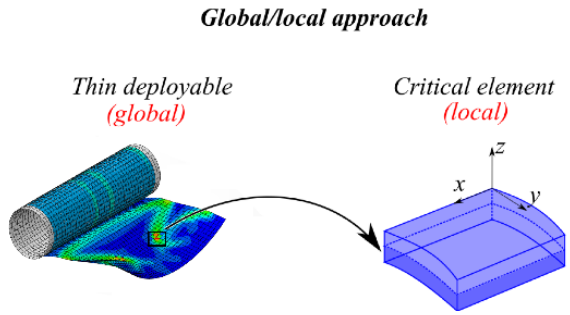


Fig. 1. Scheme of the global-local approach.

CUF has proven to be highly effective and computationally efficient for evaluating complex strain and stress fields in composite structures. This method provides a robust solution for assessing localized structural behaviour while minimizing computational cost. Indeed, the local model is constructed using a higher-order two-dimensional plate theory, based on CUF. In this framework, the three-dimensional local displacement field, $\mathbf{u}(x,y,z)$, is expressed as a one-dimensional expansion function along the thickness (z) and dependent on the primary variables of the mid-surface (x,y), which are evaluated using the finite element method. This relationship can be formalized as follows:

$$\mathbf{u}(x,y,z) = F_\tau(z) N_i(x,y) \mathbf{q}_{\tau i} \tag{1}$$

Here, F_τ denotes the expansion function along the thickness, N_i represents the shape function of the finite element, and $\mathbf{q}_{\tau i}$ is the vector containing the nodal unknowns. The indices τ and i refer to the number of terms in the thickness expansion and the number of finite element nodes, respectively. For example, cubic interpolation functions based on Lagrange polynomials can be employed as F_τ and N_i, as schematically reported in Figure 2, taken from ref. [9].

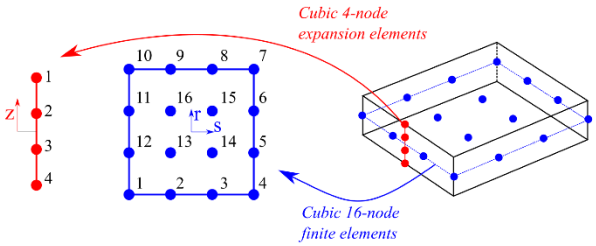


Fig. 2. In-plane and thickness interpolation via CUF [9].

It is important to highlight that the use of Lagrange polynomials results in a displacement-based formulation, meaning that the unknowns in the local model are strictly displacement variables. In commercial software, each node of the global model is typically defined by translational displacements and rotational degrees of freedom (DOFs). The use of Lagrange polynomials in the local model leads to only displacement-based DOFs across the thickness. Thus, a method is required to convert the rotational DOFs of the global model into displacement terms for the local analysis. To address this, a Reissner-Mindlin displacement field is applied in the 2D model to derive the necessary translational displacements at the interface with the CUF local model, see refs. [10][11]. The rotational DOFs are used to compute the displacements at the boundary nodes, providing the boundary conditions needed for the local simulation.

This method offers a refined representation of the displacement field through the thickness of the structure,

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ensuring higher accuracy in capturing local effects in critical regions. By relying on CUF's hierarchical modelling approach, this method enables precise analysis of complex stress and strain behaviours in composite structures, all while maintaining computational efficiency.

2.2 Reference DERAC-SAR

The object under study in the present work is a Deployable Rolled-Up Composite Synthetic Aperture Radar, a compact, deployable structure designed to meet stringent space and weight constraints for satellite missions. The DERAC-SAR consists of a HSC shell that can transition from a tightly coiled state to a fully deployed configuration to function as the substrate of a synthetic aperture radar antenna. The structural characteristics and material properties of this deployable shell play a pivotal role in its performance, both during deployment and while operating in space.

In the present study case, the shell of the DERAC-SAR has a total deployed length of 2.5 and a width of 0.34 m , and its thickness is 0.33 mm. The shell has a radius of curvature of R=0.29 m, which contributes to the coiled configuration when stowed. The deployment mechanism involves rolling the shell over a drum, which is modelled as a rigid body in the simulations, towards the shell's root, which is constrained curved in all of the Degree of Freedom (DoF). A representation of the considered DERAC-SAR is reported in Figure 3.

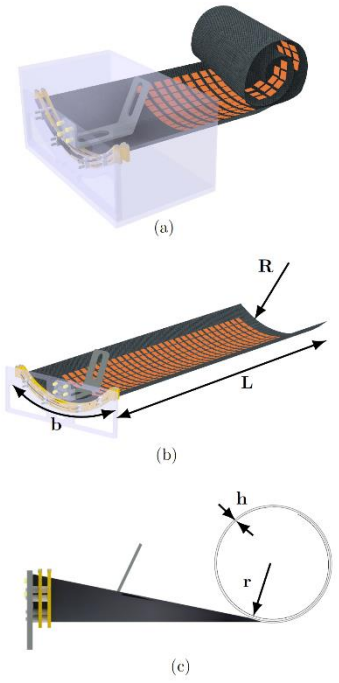


Fig. 3. Representation of the considered DERAC-SAR configuration: (a) partially deployed, (b) fully deployed, (c) coiled.

The composite material used for the DERAC-SAR shell is a low-conductive multi-layer structure designed to withstand the mechanical stresses during the coiling and deployment process. Specifically, the laminate is composed of three plies, arranged in the following configuration:

- The outer layer consists of a sheet of satin weave glass fibre material oriented at 45°, with a thickness of 0.09 mm;
- The middle layer is made of a unidirectional glass fibre ply, oriented at 0°, with a thickness of 0.152 mm;
- The inner layer repeats the configuration of the outermost layer, with the fibres oriented at 45° and a thickness of 0.09 mm.

A scheme of the considered laminate layup is represented in Figure 4.

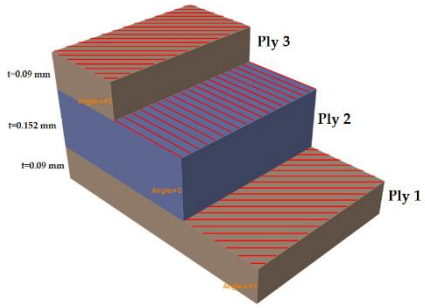


Fig. 4. Scheme of the DERAC-SAR laminate.

The laminate mechanical properties should provide the necessary strength, stiffness, and flexibility. The angular orientation of the fibres in the composite layers is designed to resist both in-plane and out-of-plane stresses, which are significant during the deployment and coiling process. The material choice and the layup configuration also ensure that the radar maintains its structural integrity while undergoing the repetitive stresses associated with space-based operations. The proposed methodology aims to evaluate the structural performance of this system and provide a high-fidelity assessment of critical areas, including their stress distribution, failure indexes and damage onset.

The global structural response of the DERAC-SAR during the stowage process was simulated using a dynamic implicit analysis in three distinct steps:

1. Edge flattening: in the initial step, the free lateral edges of the coiled shell are flattened through the application of controlled rotational displacements. This procedure extends the shell's width, initiating the coiling process.

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2. Contact with deployment drum: in the second step, contact between the shell and a rigid deployment drum was established by imposing a vertical displacement on the drum. This step ensures that the shell conforms to the drum's surface, setting the stage for controlled coiling.
3. Rotational displacement and coiling: finally, a rotational displacement was applied to the deployment drum, causing the shell to coil around it. To prevent high-stress concentrations in the area where the drum is connected to the shell during the coiling process, both the drum and the shell are allowed to move freely in the vertical direction once contact is established at the beginning of step 3.

moving from the flat regions near the drum (A and B) toward the centre of the shell (E and F), and then concentrating near the constraints (G and H).

Table 1. Maximum stress values along and across the fibre direction at different lengths from the fixed root.

	S11 max [Pa]	Pos.	S22 max [Pa]	Pos.
l = 1.97 m	8.64e+6	A	8.64e+6	B
l = 1.41 m	12.86e+6	C	12.86e+6	D
l = 0.53 m	19.85e+6	E	19.85e+6	F
l = 0.19 m	70.87e+6	G	70.87e+6	H

While not reported in Table 1, the maximum compressive stress can be seen to be at a maximum in the coiled region up to l = 0.53 m. After this point, the maximum compressive stress moves into the ploy region. This is notable because the compressive stress is an order of magnitude larger than the tensile stress.

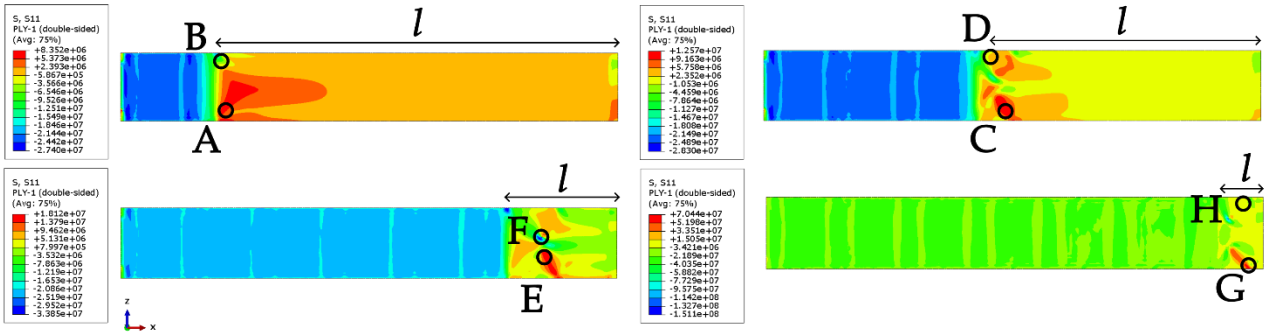


Fig. 5 Stress distribution along the fibre direction (X direction) at different lengths from the fixed root, which is on the right of the plots.

This multi-step simulation approach captures the essential mechanical behaviour of the DERAC-SAR during the coiling process. The results of this simulation provides insight into the complex stress fields that develop in the shell, particularly near the fixed curved boundary condition. In this area, the stress concentrations are most likely to occur due to the transition zone from flat to curved [12].

3. Results

3.1 Global analysis

The results extracted from the global analysis were the stresses along and across the fibre direction (S11 and S22 in Abaqus). The maximum values are reported in Table 1 for different lengths (l) evaluated from the fixed boundary condition to the shell's flat edge. The various lengths were considered to assess the change of the stress field distribution as the coiled shell approached the fixed root. As shown in Fig. 5, the stress development along the fibre direction of the outer ply indicates that by forcing the structure to coil closer to the root, the shell tends to minimise the strain energy stored by concentrating the more costly stretching energy over a smaller area. This area shifts its position (as noted in Table 1) as the length decreases and stress increases,

In Fig. 7, the distinct stress field distribution that develops close to the boundary condition is evident. Such a stress field feature is also commonplace in small tape-spring case studies [13]. In Fig. 6, a physical sample of the coiled DERAC system shows the occurrence of material deformation and damage due to the limited distance available for the shell to transition from flat to transversely curved.

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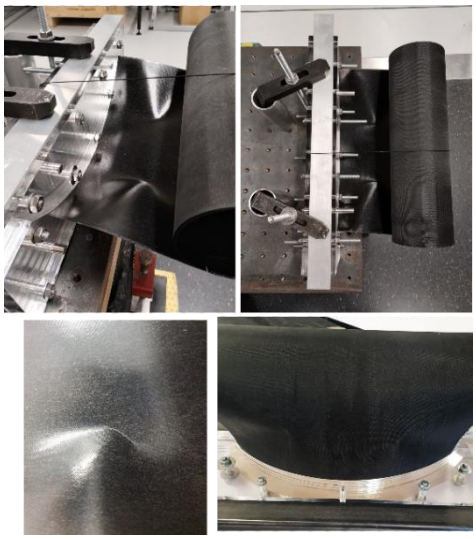


Fig. 6 DERAC coiled configuration with localised region of high stresses that caused material damage.

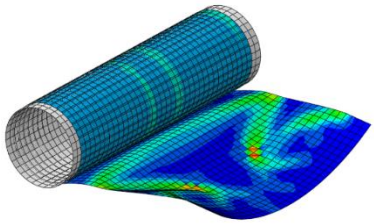


Fig. 7. Shell's coiled configuration where two localized regions of high stress are captured along with a triangular region with lower distribution of the stress.

3.2 Local analysis

It is clear that when the coiled shell is in close proximity to the curved root regions of high stress occur. In practice these regions present as creases making them difficult to accurately characterize using standard shell elements because the magnitude of the stress is sensitive to the mesh density in that region. To obtain a more accurate prediction of the stress in these regions of interest a local analysis is employed. The local analysis has been considered the starting global solution of the intermediate state of deployment of the SAR; an example of Von Mises stress distribution in this case is reported in Figure 8.

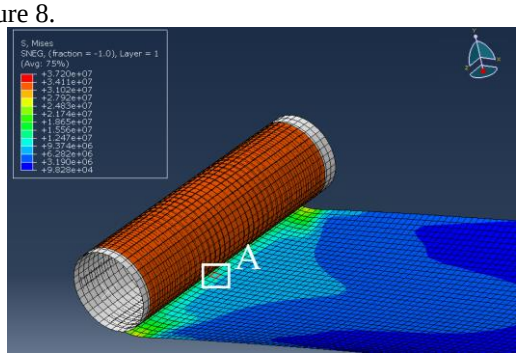


Fig. 8. Von Mises stress distribution, global solution

The local analyses have been performed the element A, highlighted in Figure 8. The in plane stress distributions, together with the stress distribution along the thickness, are reported in Figure 9.

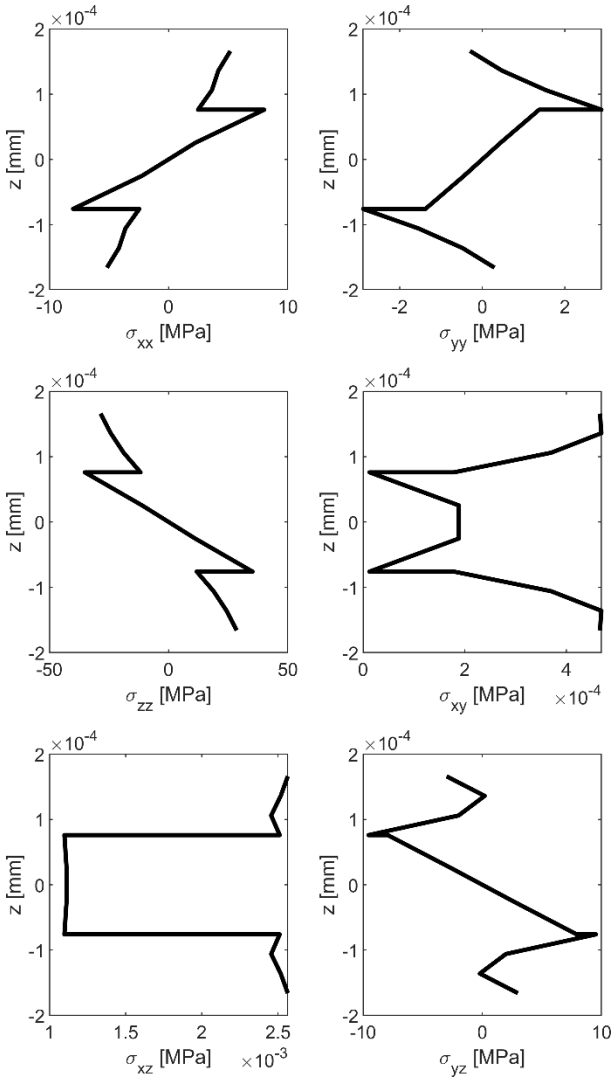


Fig. 9. Local stress distributions (element A).

4. Conclusions

This paper presented a novel global/local simulation technique based on the Carrera Unified Formulation (CUF) for the failure onset analysis of Deployable Rolled-Up Composite Synthetic Aperture Radar (DERAC-SAR) structures. The proposed method addresses the limitations of traditional three-dimensional models, which are computationally demanding for capturing the complex stress fields arising in the critical areas during deployment. By employing a two-step approach, first performing a global analysis using 2D finite elements and then addressing local critical regions with higher-order models based on CUF, the study

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successfully balances computational efficiency with the need for accurate stress predictions.

The results confirm the effectiveness of this approach in capturing the 3D stress distributions, particularly in critical regions where failure is likely to initiate. Comparisons with global Abaqus simulations reveal the accuracy for the in-plane stress predictions; in addition, the significant impact of out-of-plane stress components on failure indices can be included; this is a crucial factor disregarded in conventional 2D analyses. This finding underscores the necessity of incorporating higher-order theories when assessing the structural integrity of complex composite systems like DERAC-SAR. Moreover, the nonlinearities introduced by large displacements and rotations in the local models were handled accurately, further validating the robustness of the global/local CUF-based method. This approach not only reduces computational costs but also enhances predictive capabilities, providing a powerful tool for failure assessment in deployable space structures subjected to geometrically nonlinear deformations.

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