Composites Science and Technology 115 (2015) 43–51

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

On the use of global–local kinematic coupling approaches for delamination growth simulation in stiffened composite panels

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ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form 8 April 2015
Accepted 11 April 2015
Available online 17 April 2015

Keywords:
B. Delamination
C. Finite element analysis (FEA)
C. Multiscale modeling
C. Stress transfer
VCCT

ABSTRACT

This paper investigates kinematic coupling approaches for FE simulation of the mechanical behavior of complex composite structures.

Two coupling methods belonging to the family of kinematic coupling approaches, namely the point-wise kinematic coupling and the weighted residual kinematic coupling are analyzed and assessed with respect to their application to non-linear structural FE analyses.

The investigated kinematical coupling approaches have been implemented in the in B2000++ FEM code developed by SMR® and used to couple global–local domains characterized by different mesh refinements.

A stiffened composite panel with an artificial bay delamination under compressive load has been adopted as numerical benchmark. Results in terms of stress distributions at domains interfaces, obtained with several FE models characterized by different coupling approaches and different mesh refinements, have been compared with the results obtained adopting a reference test-case model with mesh continuity and merged modes. Furthermore, the influence of the coupling approach on the delamination growth simulation has been assessed. Finally considerations about the computational effectiveness of the coupling approaches with respect to the reference test-case are introduced.

1. Introduction

The use of composite materials is continuously increasing for aerospace applications due to their promising specific strength and stiffness. However, the complexity of composites damage phenomenology involving different failure modes, interacting each other, is seriously limiting the effectiveness of designing with these outstanding materials. One of the most common and critical failure modes is the delamination, which can have relevant effects on the reduction of the residual global strength of a composite laminate. Indeed, a delaminated composite panel under compression may experience delamination growth induced by local and global instabilities leading to the anticipated compressive failure.

Finite element procedures for the simulation of the delamination growth induced by local and global instabilities are generally based on fracture mechanics concepts and involve the evaluation of the Strain Energy Release Rates (ERR) at the delamination front [1]. Some numerical procedures use the total value of the ERR [2] without accounting for fracture modes separation while other techniques such as the Virtual Crack Closure Technique (VCCT) [3] allow to distinguish between the three basic fracture modes ERR contributions (G_I, G_{II} and G_{III}). The growth initiation is, generally, identified based on a growth criterion [4] (basically derived by fracture tests data and by the fracture toughness of the material G_{IC}, G_{IIC} and G_{IIIC}). When the criterion is met along the delamination front, the delamination front is modified thus simulating the delamination opening. An example of linear delamination growth criterion presented in Eq. (1) [5]:

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} + \frac{G_{III}}{G_{IIIC}} = 1 \quad (1)$$

The ERR is a function of both the forces at the crack tip and the Crack Opening Displacements (COD). Hence, numerical tools for the prediction of delamination onset and propagation require a very fine three-dimensional FE model to accurately predict these quantities. On the other hand, a fine 3D discretization of complex structures is sometimes not feasible due to the increase of

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http://dx.doi.org/10.1016/j.compscitech.2015.04.010
0266-3538/

calculation time. Therefore, with the aim of extending the field of applicability of such numerical tools to geometrically complex structures, global/local approaches are introduced [6–8].

In a global/local approach a very large number of elements is employed only in some critical areas of the investigated domain, also called local domains, where the solution is expected to show significant variations in small spatial and/or temporal intervals, while a coarser mesh is employed in the rest of the structure, also called global domain.

The most common solution is to use transition elements to connect the refined local domain to the coarser global domain. An interesting example of transition element was developed by Davila and Johnson [9] to predict the compression strength of dropped-ply graphite–epoxy laminated plates. Each transition element was used to connect a shell element to a stack of brick elements in order to capture the fully three-dimensional response in the vicinity of the dropped ply. Numerical results were in good agreement with the experimental measurements.

Cho and Kim [10] investigated the bifurcation buckling problem of a delaminated composite laminated by means of transition elements. In order to save computer resources without losing accuracy, layerwise elements were used in the local delaminated region. These elements were able to accurately describe the geometric deformations of the delaminated zone, being still computationally less expensive than three dimensional elements. In the rest of the laminate, where the deformation shapes are more regular if compared to the delaminated region, the first order shear elements were used. The transition element was then used to connect the global zone and the local delaminated one. The predicted buckling load was found in good agreement with the one obtained with a fully layerwise model. In [11] this transition element was demonstrated to be effective for the simulation of the post-buckling behavior of delaminated composites under compressive loads. However, the use of transition elements implies a relevant expertise in the formulation of the transition mesh because the presence of distorted elements can invalidate the solution in the transition regions. In order to effectively study local phenomena, more affordable tools can be used in FE codes to couple finite element models with different mesh densities and/or different element types. Such coupling methods allow carrying out very efficient and reliable global/local analyses on large structural components [12].

Alesi et al. [13] studied the behavior of skin/stringer interfaces in stiffened panels by a Multipoint Constraint (MPC) based method implemented in the ABAQUS® code [14]. Since the stress state at the skin/stringer interface is fully three-dimensional, brick solid elements were employed to model this critical local area; while a coarser two-dimensional mesh was used in the rest of the panel. The two different modeled areas were connected together via the MPC elements implemented in ABAQUS®. Krueger and O'Brien [15] and Krueger and Minguet [16] investigated the delamination propagation and the skin/stringer debonding respectively by shell-to-solid coupling elements implemented in ABAQUS®. Pietropaoli and Riccio [17] used the multipoint constraint approach implemented in ANSYS® code [18] in order to couple a coarser shell domain of a stiffened composite panel to a more detailed brick model representing a delaminated domain to test the effectiveness of a new tool for the inter-laminar and intra-laminar damage onset and evolution.

The purpose of this paper is to investigate the behavior of a delaminated stiffened composite panel under compressive load and to test the effectiveness of two coupling methods implemented in B2000++ code developed by SMR®. The coupling methods belong to the kinematic coupling approaches family and are:

- The point-wise kinematic coupling.
- The weighted residual kinematic coupling.

In order to fully understand the peculiarity of these kinematic coupling approaches. Let's consider two subdomains Ω_1 and Ω_2 connected with a common interface Γ, as shown in Fig. 1.

The deformation field is indicated as $x(X)$, where X are the coordinates of the reference configuration. The subdomains Ω_1 and Ω_2 are discretized such that the deformation fields, x_1^e and x_2^e, are C^0-continuous across boundaries.

The residual $r(X)$ on X in Γ is equal to:

$$r(X) = x_1^e(X) - x_2^e(X) = u_1^e(X) - u_2^e(X) \tag{2}$$

The conditions to be imposed on Eq. (2) result in a different coupling approach:

- In the point-wise coupling the residual is set to 0.
- In the weighted residual coupling the residual is minimized: r is integrated over Γ with a weight function and the minimum of the integral is obtained by setting the derivatives to 0 (zero).

The couplings have been tested over a 3-dimensional finite element model representative of a stiffened composite panel with a defect located in the central bay and subjected to a compressive load; the couplings have been employed to connect the region of the defect (local domain), discretized with 3D elements, and the rest of the panel (global domain), discretized with shell elements. In Section 2 the test case is described while in Section 3 the two different kinematic coupling approaches are compared.

2. Test case and FE model description

The numerical tests have been performed on the carbon-fiber reinforced panel, stiffened by three I-section stringers [19,20], schematically introduced in Fig. 2. An artificial circular delamination was located at the center of the bay and placed between the fifth and the sixth ply along the thickness of the skin. The stacking sequence of the skin was $(+45°/-45°/0°/90°)_{4s}$, while the stringers were made of 4 laminates stacked according to the sequence $(-4$ $5°/+45°/0°)_{2s}$. According to Fig. 2, the material 0° direction, which is also the loading direction, is parallel to the y axis.

The mechanical properties of the adopted material system (T800/924) are summarized in Table 1 [21]. The experimental test has been performed under displacement control: the edge BC of the panel (see Fig. 2) has been clamped, while on the opposite edge (OA) a uniform displacement along the y-axis has been applied. The rotation on the edge OA has been constrained and the lateral edges (OC and AB) have been left "free".

The area surrounding the delamination, which is of interest due to the high deformations and stress arising during the loading process, has been modeled by two layers of solid elements, while all the other regions have been modeled by shell elements. Global–local elements have been used to couple the two differently modeled regions. Contact elements have been also placed on the initial

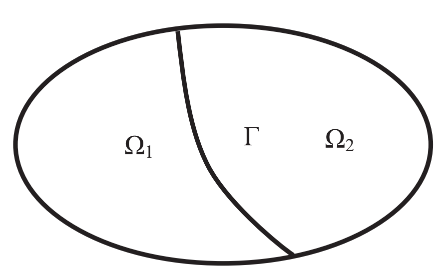

Fig. 1. Subdomains Ω_1 and Ω_2 connected with the common interface Γ.