

Global/Local Fracture Mechanics Analyses of advanced Aerospace Structures

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Summary

In this paper a Hierarchical approach for the analysis of advanced aerospace structures is presented. The proposed Global/Local model uses two kind of numerical methods for the different steps of analysis. In particular the first step of the Hierarchical procedure is performed by the Finite Element code Patran/NastranTM, while the local analysis is performed by using a Boundary Element code based on the multidomain anisotropic technique. The accuracy and the effectiveness of the model have been demonstrated analysing classical stress concentration problems. Then the procedure has been used to analyze more complex structure among which a riveted patch repair, applied on a cracked panel, is presented in the present paper.

Introduction

The use of composite materials in the field of aeronautical and aerospace structures is increasing more and more, due to their inherent feature, which make them very suitable in the framework of reliable lightweight and high strength/stiffness structures. In spite of these advantages, extreme caution must be devoted to the employment of composite materials in highly loaded sections and to the evaluation of the reliability of the allowed new configurations. The behaviour of these structures, in particular where various discontinuities such as cutouts, holes or cracks are present, results very complex and therefore accurate and efficient numerical analysis strategies are needed to caught the structural behaviour close to the discontinuities. In order to reduce the computational effort required to achieve reliable solutions, the Global/Local approach has been proposed. This hierarchical technique is based on the concept that a structure is globally analysed by using a coarse mesh with the aim to obtain appropriate boundary condition to impose in a restricted region where a much more refined mesh is applied. The pioneering work about this subject was published by Mote [1]. Later many strategies have been proposed for implementing Global/Local techniques (see [2, and 3]). In this paper the Global analyses are performed by using a finite elements code, while a Boundary Element code for anisotropic media, based on a multidomain technique (see [4, 6]), is used to analyse the refined local models. The displacement field, deriving from the coarser model is used as boundary conditions to perform the subsequent level of the analysis. When the local region includes one or more bolted joints the pin loading are preliminary calculated during the Global analysis and then transferred,

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coupled with the displacement field, as boundary conditions for the local ones. To show the effectiveness and the accuracy of the proposed Global/Local approach the analysis of a riveted patch repair, applied on a cracked panel, is presented.

Procedure of the Global/Local approach

The overall solution strategy adopted in this paper is based on an inheritance concept. The behaviour shown by the more refined model strongly depend upon the data inherited by the hierarchically precedent analysis, performed on the coarser model. To perform an accurate Global/Local analysis three key points are fundamental: (i) an adequate characterization of the coarser model, it means that particular attention must be paid in the choose of the simplified structural schema, which will govern the behaviour of the more refined region; (ii) the hierarchical interface problem, in fact the inherited data could not exactly match with the more refined mesh of the successive model and so the use of an interpolation region becomes mandatory; (iii) an accurate local analysis must be carried out paying particular attention to mesh refinement close to the strain and stress concentration areas.

The core of the approach is the Patran/BEM interface code which automatically creates the local region and its mesh. The Global analyses are performed by Patran/NastranTM finite elements code, using 3D shell elements to model the skin and 1D bar elements to model the stringers and the fasteners. At this level of analysis neither of cracks and holes is considered avoiding the time consuming and the difficulties related to the finite element modelling of these stress concentration sources. Thus, in the Global analysis it assumes that if the crack/hole is small enough with respect to the structure dimensions it will not be modelled. Accordingly, cause the crack/hole have to be recognized by the Global/Local interface code to obtain an automatic local model generation, some technique have to be developed to achieve this goal. The cracks are located directly on the coarser model as BAR elements having as material and property name 'CRACK', no more that a flag. It is worth noting that the 'BAR CRACK elements' are not taken into account in the FE Global analysis, but they are only dummy elements used by the interface code. As well as the 'BAR CRACK elements', the 1D BAR elements that model the pins are used by the interface code to create the holes in the Local region and to transfer the pin loading computed during the Global analysis. Note that radial stress distribution varying as a cosine function and applied over half the hole has been assumed (see [5]). It is to specify that in the local analyses laminates are modelled as equivalent anisotropic media and that only the in plane behaviour of the plate is analysed.

Local analysis

As mentioned above, the local analyses are performed by using a BEM code based on a multidomain anisotropic technique. So, in this section, it will briefly

review the boundary element formulation developed for two-dimensional elastic domains Ω with boundary $\partial\Omega$ lying in the x_1x_2 planes, under the hypothesis of linear elasticity and generalized plain strain field. The elastic state of the body is described in terms of mechanical displacements \mathbf{u} , strains $\boldsymbol{\varepsilon}$ and stresses $\boldsymbol{\sigma}$. It is worthwhile to note that ε_{33} is trivially zero due to the previous assumptions but it is kept in the formulation to maintain a compact and efficient matrix notation. Applying the reciprocity theorem and considering a particular displacement field corresponding to a concentrated force acting in an infinite domain and applied at the point P_0 the well known Somigliana identity for elasticity in matrix form can be obtained

$$\mathbf{c}^* \mathbf{u}(P_0) + \int_{\partial\Omega} (\mathbf{t}^* \mathbf{u} - \mathbf{u}^* \mathbf{t}) d\partial\Omega = \int_{\Omega} \mathbf{u}^* \mathbf{f} d\Omega \quad (1)$$

where the matrix \mathbf{c}^* can be calculated according to [6], \mathbf{t} and \mathbf{f} are the boundary tractions and the body forces, respectively, while \mathbf{u}^* and \mathbf{t}^* represent the kernel fundamental solutions that can be deduced by a modified Lekhnitskii's approach (see [8]). The boundary integral formulation has been numerically implemented by using the BEM (see [4]). A linear algebraic system is obtained and it could be written as

$$\mathbf{H}\Delta + \mathbf{G}\mathbf{P} = 0 \quad (2)$$

where \mathbf{H} and \mathbf{G} are the square influence matrix that coupled with the boundary conditions provides the solution of the problem for a single domain in terms of displacements and tractions nodal values Δ and \mathbf{P} , respectively. When the investigated domain is made up of piece-wise different materials or when cracks and/or inclusions are present, the problem can be solved by using a multidomain approach (see [4, 6]).

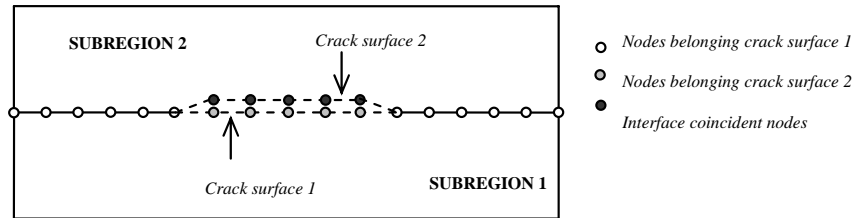


Figure 1: Multidomain crack modelling strategies

It is worth to note that when the multidomain technique is used to model a crack, the original cracked domain must be divided into two subregions in such a way that the common interface between two different subdomains must contain the crack surfaces, see figure 1.

Application

In order to access the efficiency and the accuracy of the proposed model the analysis of a riveted patch repair applied on a cracked fuselage panel is presented. The geometry and the material properties have been taken from [10]. The configuration analysed undergoes a bi-axial stress, $\sigma_x = \sigma_y = 100$ MPa, and due to symmetry only one quarter of the structure is considered as shown in figure 2. In the Global model the fasteners that connect the doubler to the skin are simply modelled as single bar element having the same geometry and the same material properties of the rivets while the holes degenerate into nodes (see [9]). In order to access the reliability of the above mentioned pin model, the configuration 2 described in table 1 has been analysed and the pin loading compared with those presented in [10]. The Global analysis of configuration 2, whose computational times are equal to about 40 seconds, is based on 25867 four nodes quadrilateral elements and 8 bar elements with a total number of nodes of 21307. The comparison with the pin loading computed by the FEM analysis in [10] shows a maximum percentage error of 4.7% in correspondence of the fifth rivet. It is worth to note that no modelling difficulties are associated with the construction of the global model since a simple automatic IsoMesh has been used for the analysis.

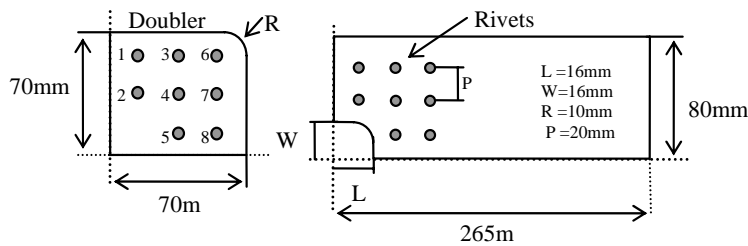


Figure 2: Geometry and Loading configuration

Configuration 1, described in table 1, has been analysed to find the most loaded hole and the displacement field to use as boundary condition for the local analysis performed on a restricted region surrounding the above mentioned rivet hole. The Global model and the run times for the Global analysis are the same as for configuration 2. The most loaded hole is the sixth. The maximum pin load acts in fact on the hole 6 and have a magnitude of 543 N with components $F_x = -384$ N and $F_y = -384$ N.

With the aim to compare the results to those obtained in [10] two different Local analyses have been performed. The first concerns a restricted region surrounding the most loaded hole in which no crack is considered. This analysis allows to choose the crack initiation site corresponding to the point in which the maximum principal stress acts. The second Local analysis is performed on the same region

<i>Configuration</i>	<i>Skin thickness (mm)</i>	<i>Doubler thickness (mm)</i>	<i>Rivet diameter (mm)</i>	<i>Rivet shear stiffness (N/mm)</i>
1	1.2	1.4	4	2.9×10^4
2	1.4	1.6	4	3.1×10^4

Table 1: Characteristics of the two configuration analysed

but a crack of length 1 mm, emanating from the point of the hole in which maximum principal stress acts, has been considered. The local model related to the local region without crack consists of 120 constant boundary elements and only few seconds are needed for the analysis. In figure 3a the maximum principal stresses are shown with the most stressed crack initiation site located at point A. The second Local analysis is performed on a cracked region surrounding the sixth hole. The crack emanates from point A of figure 3a and has a length of 1 mm. The boundary mesh consists of 310 constant elements. In this case the run time is of about 25 seconds. Figure 3b shows the crack opening displacements from which the SIFs are calculated. Only KI has been calculated since the loading condition on the crack tip is pure Mode I. The crack is in fact oriented perpendicular to the maximum circumferential stresses. The SIF obtained by the G/L analysis is $KI=330 \text{ MPa mm}^{1/2}$. Comparing the above result with the SIF obtained by Armentani [10] FEM non-linear iterative contact analysis the percentage error found is 1.5%.

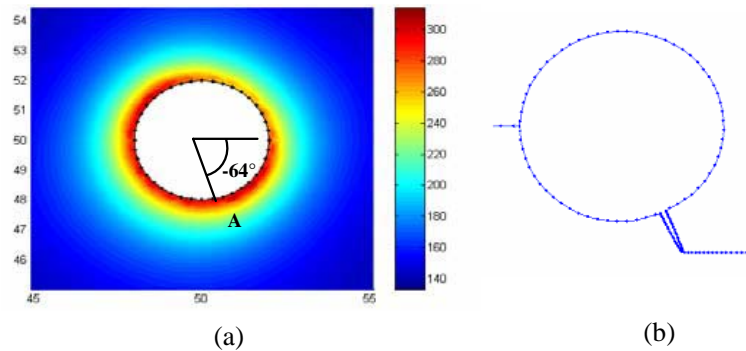


Figure 3: (a) Maximum principal stress (MPa) at hole six. (b) Crack opening displacement

Conclusion.

In this paper a Global/Local analysis strategy for obtaining the fracture mechanics behaviour of complex aerospace structures is presented. The two different steps of the analysis are performed by using two different numerical methods. In particular, the coarser Global models are studied by using the finite element code Patran/NastranTM, while a boundary element code for isotropic and anisotropic me-

dia, based on a multidomain technique, is used to analyse the refined local models. An efficient Patran/BEM interface code is implemented in order to automate the entire procedure. It in fact allows the automatic detection of the cracks and/or holes in a structure and the creation of the boundary mesh. Great computational efficiency and a substantial reduction of the modelling time have been achieved

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