TOOL FOR DESIGN AND SIMULATION OF JOINT

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ABSTRACT

In the current paper, a brief description of the PhD work is reported. The methodologies for design and simulation of joint are described. In particularity, attention is focalized on bolted joints because they are the most interesting for railways applications considering their mechanical behavior and their cost. The aim of these methodologies is to find an efficient/alternative manner to simulate multi-material joints. At the end, the goal of the PhD works is to develop a selection tool to help design engineers to select the right joining technology for different applications in multi-material railway vehicle structures (composite-aluminium alloy, composite-steel, composite-sandwich…).

1. INTRODUCTION

Composite materials can be efficiently used in the next generation of transport structures. Materials, such as reinforced plastic or sandwich panels are lightweight, durable and easy to use. However there are a lot of complexities associated with their design and manufacturing; these ones today limit the adoption of composites by the transport sector. In design area, the problems are generally due to the difficulties that one has to ride over to understand the behaviour of composites materials. In fact, it's common opinion that researchers have to do a lot of efforts to develop better prediction methodologies for non linear behaviour, damage mechanism, failure modes. It's also important to develop better tools for the specification and the simulation of joints. In fact, for economic reason generally trains are hybrid (they are realized using composites and metallic parts): on account of this design multi-material joints is very hard because there aren't standard methods that one can use.

To have good results (according with experimental ones), we need to use 3D FE models and we need to take into account the effective behaviour of the material. To do this, LaRC criteria [1,2] are used and a numerical implementation of damage is considered [3,4]. However, in industrial field, the use of these methodologies is not easy. In fact the numerical calculation of structural components are realised using 2D model (using shell elements, see Fig.1) and so it is necessary to find the way to translate the results of 3D models in 2D industrial applications. It could be possible to obtain it in two ways: using sub modelling technologies or using the global approach to the study of the joint. The first way consist in execute the analysis using 2D models and, after that, study regions corresponding to joints using 3D models. The second way is to use non-local approach: in this case, the parameters of the characteristic curve are found doing a numerical simulation of the experimental test necessary to find them. The non-local method is described in Camanho and Lambert [5].

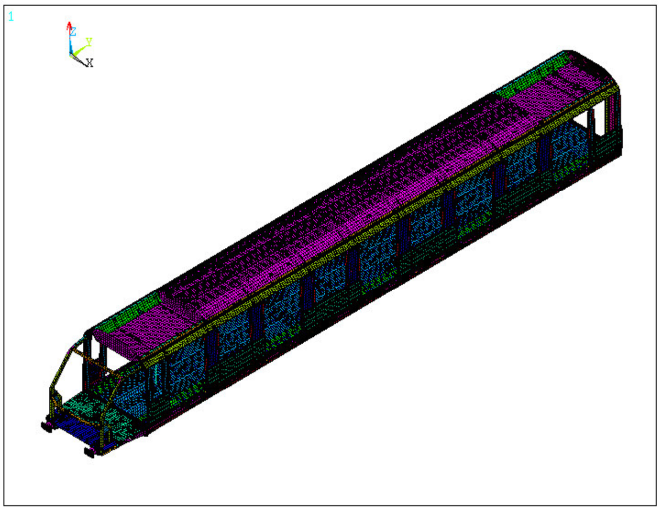

Fig. 1: FE model of railways structure

2. STATE OF ART

2.1 Modeling materials

In railways application, the most useful composite material is GFRP. In fact, the cost of other kind of fibers, like carbon fiber, it's too expensive and so their use is not justifiable. The resins will be used are mainly epoxy, vinylester and phenolique. However the chose of the resins is generally based on legislative reasons.

The complexities in modeling composites are essentially due to failure of unidirectional and laminated composites (these depend on in situ stress), material non linearity, residual stress due to manufacturing operation, size effects, free edge effects, environmental effects and durability, delamination growth and finite element implementation.

A good prediction of the failure of joint depends of the goodness of composite materials modeling. In particular, composites show several failure mechanism as matrix crack, fiber fracture, delamination, fiber kinking; all these mechanism are difficult to consider and implement in composites simulation. To consider the several damage mechanism of the material, LaRC criteria are used. These ones, presented in Davila *et al*. [2] represent a set of six phenomenological failure criteria for fiber reinforced composite laminates. These criteria can predict matrix and fiber failure accurately considering failure matrix under compression, fiber kinking and *in-situ* strengths [1].

2.2 FEM implementation

The complexes damage mechanism in composites naturally result in additional complications of numerical model. The presence of two components and the anisotropy in stiffness and strengths are responsible of the onset of different damage mechanism: interlaminar and intralaminar damage. Interlaminar damage correspond to interfacial separation of the plies and it is generally known as delamination. It is due to defects of manufacturing, fatigue, impact. Intralaminar damage mechanism correspond rather to fibers and matrix cracking.

Interlaminar damage

Interlaminar damage can be studied numerically in two different ways: using VCCT or cohesive elements. Virtual Crack Closure Technique has been used to predict delamination growth in composite materials. This technique is based on the assumption that the energy U dissipated when a crack extend of Δa is equal to the work W necessary to close the crack to the original length. Considering, for example, 4-nodes plane elements as in Fig. 2 SERR value can be written as :

$$G_I = -\frac{1}{2\Delta a} Z_i \Delta w_{i-1} \quad (1)$$

$$G_{II} = -\frac{1}{2\Delta a} X_i \Delta u_{i-1} \quad (2)$$

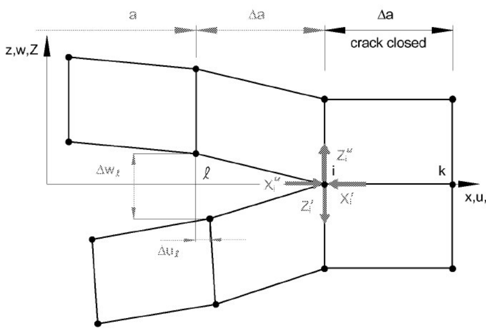

Fig 2: VCCT using 4-node plane elements

This approach allows to obtain the energy release rate components in a very fast way but, only if sufficiently refined mesh is used and when elements at the crack tip have the same dimension in the crack growth direction. However the most important limitation of VCCT is that one have to define an initial delamination. For certain cases this is difficult to know a priori.

One approach that can be used to overcome these limitations is the use of cohesive elements. The definition of a cohesive zone model is based on two main constituents: kinematics of the interfacial surface and constitutive model. The use of cohesive zone method can be used efficiently in the simulation of the onset and propagation of delamination in composites as shown in literature [6,7].

A constitutive relationship between the cohesive traction σ_i and the displacement jump Δ_i is required for modelling the behaviour of the material. A lot of constitutive laws $\sigma_i = \Gamma(\Delta_i)$ have been proposed: linear elastic-perfectly plastic, linear elastic-linear softening, linear elastic-progressive softening, linear elastic-regressive softening. However, independently of the cohesive model used, the energy dissipated at the crack propagation must be equal to the fracture toughness and so, the following relationship

$$\int_0^{\Delta_{if}} \sigma_i \, d\Delta_i = G_c \qquad (3)$$

must be satisfied. In simulation of composites a linear softening behaviour is usually implemented.

Intralaminar damage

Intralaminar damage mechanism occur at different orientations corresponding to fracture planes. The intralaminar damage mechanism are usually represented as a band of localised deformation using constitutive model based on Continuum Damage Mechanics. An accurate Continuum Damage Model should respect two conditions: 1) it

should be based on damage activation functions able to represent the different damage mechanism; 2) its implementation should be independent of the mesh (mesh-independent).
There are several failure criteria that can be used to the purpose and these ones are implemented in commercial software (as Abaqus). However, few criteria can represent the whole complexity of damage mechanism. As shown in Maimí *et al* [3,4], LaRC04 failure criteria can be used to define the damage activation function F_M. In this manner, it's possible to formulate a Continuum Damage Model to predict the propagation of several damage mechanism occurring at intralaminar level. Each damage activation can predict the onset and the type of damage using the following equations:

$$F_M := \phi_M(\sigma^t) - r_M^t \leq 0 \qquad (4)$$

where r_M^t are the internal variables ($r_M^t = 1$ for $t = 0$), $\phi_M(\sigma^t)$ are the LaRC04 criteria and M is an index that accounts for several damage mechanism. When the relationship (4) is satisfied, the associated damage variable d_M is different then zero and so the ply compliance tensor is affected by the presence of damage.
Further to the damage activation functions and damaged compliance tensor, it is necessary to define the evolution laws for damage variables d_M. The damage evolution laws need to assure that computed energy dissipated is independent to the refinement of the mesh. A complete definition of the model and the numerical algorithm is described in Maimí *et al* [3,4].

3. NON-LOCAL METHOD

We have reminded, in previous sections, that FE models used in industrial applications use generally shell, and this essentially for simplicity and for rapidity of the calculation. To study the behaviour of the joint, it needs to understand how to simulate the joints; for that purpose, it can be possible to use two approaches: using the substructuring methodology or apply a global method applied to 2D FE model.
In Camanho et Lambert [5], we can find a design methodology for fastened joints in laminated composites materials (Fig 3-5 are taken from the same article).
In this paper, a methodology to study bolted (or riveting) joint is described. The use of non local method is very important for industrial applications because it allows to obtain design charts for the joints in very fast way (2D analysis - shell elements). The calculation of elastic limit and the ultimate failure of the joint is defined as well as you define the characteristic curve for the joint, as that one reported in Fig. 3.

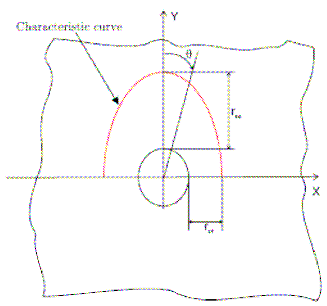

Fig 3 : charcteristic curve

To use a non-local method, we need to define two characteristic distances: the parameter that define the characteristic curve in compression r_{0c} and in tension r_{0t} . The parameter r_{0t} can be calculated experimentally or using a closed form solution. Its definition is not problematic because when you know the characteristic of strength and stiffness of the composite lamina, it is completely defined.

The measurement of the characteristic distance in compression r_{0c} should be ideally performed in bearing test. From the bearing stress-bearing strain curve, it's possible to evaluate the ultimate bearing strain that is the first non linearity on the curve. In Fig. 4 is reported an exemple of bearing stress-bearing strain curve for pinned and bolted joint. It can be point out that the value of ultimate bearing strength is about the same.

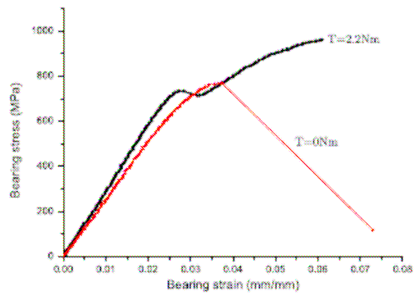

Fig 4 : bearing stress-bearing strain curve

Evaluate the r_{0c} parameters for different lay-up allows to obtain the design charts for each material. In Fig. 5 a design chart is reported. These ones are used to evaluate elastic and failure limit for the joints.

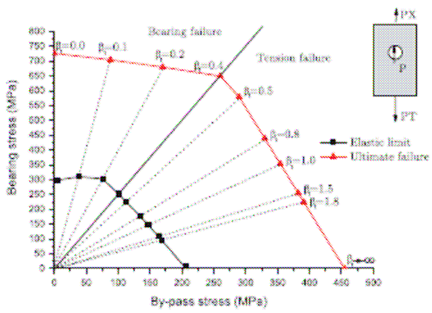

Fig 5 : design chart

Unfortunately, we need to do several tests to extrapolate the measured values to several geometries and different lay-up. Instead of performing physical tests, we can use LaRC criteria and 3D damage model to calculate r_{0c} from the FE model. In this case, we can perform an experimental test numerically.

4. STATE OF WORK AND NEXT STEPS

The several steps of project are summarized in the following:

- Numerical analyses of bolted joints using 2D/3D FEM at Alstom Transport
- Experimental tests at Porto University
- Correlation of numerical and experimental results at Alstom Transport
- Numerical analyses of mock-up at Alstom Transport (2D FEM)
- Realization of mock-up at Alstom Transport

- Test of mock-up at Porto University.

Up to now, numerical models for bolted joints are realised. The next step is performing experimental tests at Porto University to characterize the materials that we have selected for railways application.

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