Impact of material degradations on load transfer and assembly behavior. Application to reinforced holes in composite assembly.

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Abstract
Materials Non-linearity influences are estimate by qualitative analysis on assembly. A composite model with damage is used, based on a classic thermodynamical formalism, and identified by experimental datas. The interest of hole reinforcement method for bolted joints is discussed, for two different cases, by analyzing the load transfer on the bearing surface and the global behavior.

1 Introduction
Despite having low efficiency, fasteners joints are widely used in aeronautic structures. The ease of assembly, inspection and maintenance are the main reason of this result [1]. The recent massive introduction of composite materials – which not have a particularly high bearing strength [2] - for structural parts brings a new challenge for assembly design.
In order to avoid the relative composite bearing weakness, hole reinforcement methods have been suggested. The principle consists in the modification of the load transfer around the hole by the introduction of a metallic bushing. As a result, it could be expected to reduce the stress concentration factor, and in this way to reach to a better assembly efficiency.
Several processes of reinforcement are possible. For instance, inserts can be bonded [1]-[3], expanded, or even bonded and expanded [4].
To confirm the relevance of this approach, and to compare assembly method, an accurate prediction of the load transfer in the structure (particularly in the vicinity of the hole) is a necessity.
However, it is well known that damage phenomena are complex and various, especially in bolted composite joints [5]. Moreover damage mechanisms may have an important impact on the load transfer (re)distribution into the structure. Thus, the present paper proposes to quantify their influence on the load transfer and stress redistribution, for several holes reinforcement assembly types.

2 Problem descriptions
We consider an elementary assembly as described on Figure 1. D is the composite hole diameter and w the specimen width. The composite part is fixed at one end, and loaded with a pin through the hole. We can note that with this configuration the composite material is not confined around the hole. Considering that most of composite parts used in aeronautic

application are close to quasi-isotropic lay-up, the stratification used in this study is $[90/45/0/-45]_{2S}$. However, the model proposed below could be employed for others lay-ups.

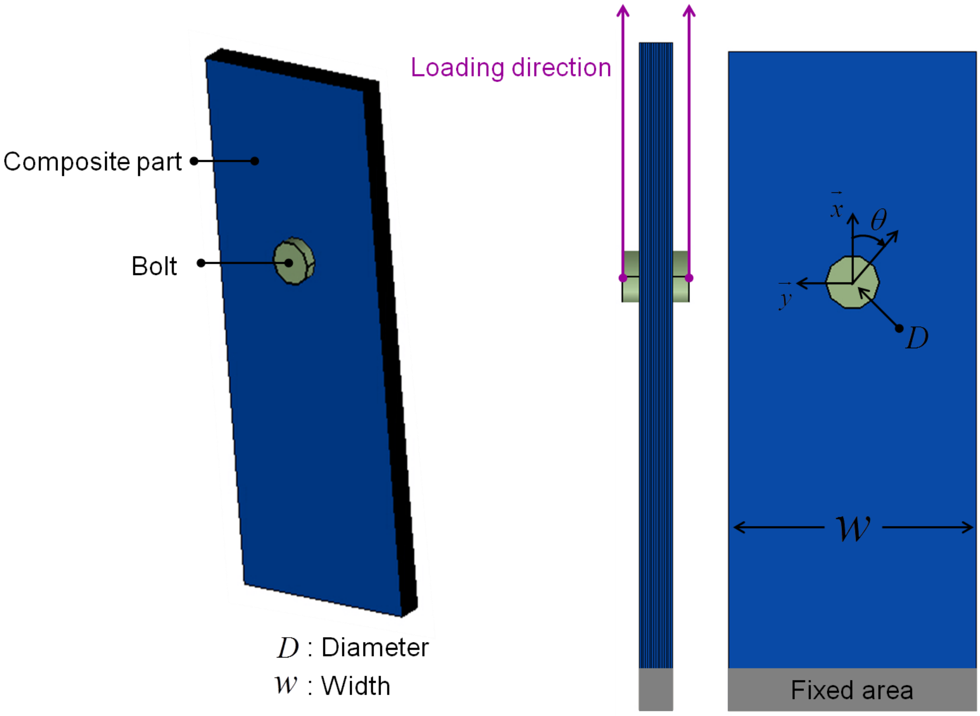


Figure 1. Assembly description

In this paper, the hole reinforcement for such assembly is realized by a A286 stainless steel bushing. The two different configurations discussed in this paper are adjusted and interference fit bushing reinforcement.

In order to analyze the load transfer around the hole, we can define three surfaces on the composite part, the net-section surface S_n, the bearing surface S^+ and the low surface S^- (Figure 2).

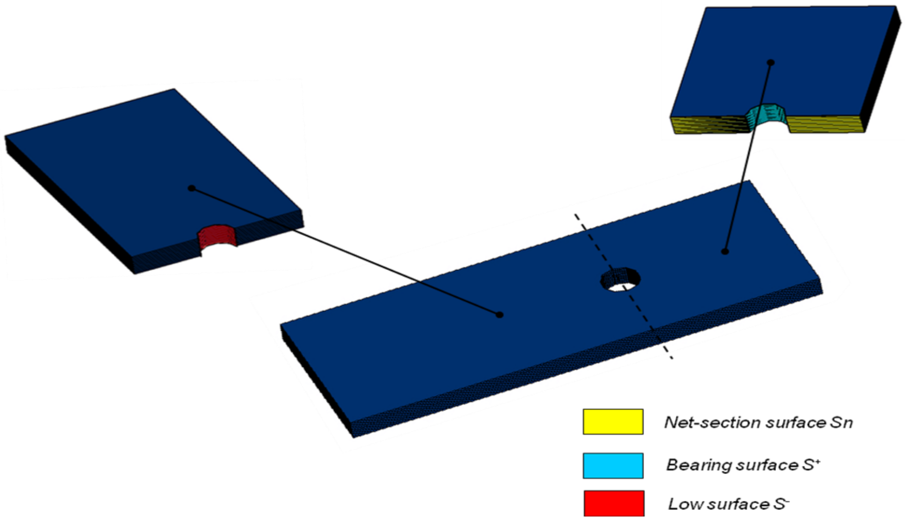


Figure 2. Definition of load transfer surfaces

$\vec{F} = F\vec{x}$ being the loading transmitted by the fastener, we can introduce three load transfer parameters:

$$\begin{aligned} F_n &= \Lambda_n \left|F\right| \\ F^+ &= \Lambda^+ \left|F\right| \\ F^- &= \Lambda^- \left|F\right| \end{aligned} \tag{1}$$

Where F_n, F^+ and F^- are forces transferred by S_n, S^+ and S^-. Λ_n, Λ^+ and Λ^- are associated load transfer parameters. The position on the hole is located by the angle θ defined on Figure 1. In this paper, we focus the discussion on the load transferred by the bearing surface S^+.

According to the equation (1), Λ^+ can be calculated by:

$$\Lambda^+ = \frac{1}{F} \iint_{S^+} \left(\sigma_{xx} \cos(\theta) - \sigma_{xy} \sin(\theta)\right) dS \tag{2}$$

Where σ_{ij} are the stress tensor components in the coordinate system defined on Figure 1.

We also introduce following parameters:

$$\lambda^+(\theta) = \frac{\sigma_{xx} \cos(\theta) - \sigma_{xy} \sin(\theta)}{F} \tag{3}$$

$$\lambda_h^+(\theta) = \int_{\frac{-h}{2}}^{\frac{h}{2}} \lambda^+ dz \tag{4}$$

Where h is the composite thickness.

3 Composite material model

A composite 3D damage model was developed, based on a thermodynamical approach **[6]**, and was identified on T700GC/M21 CFRP composite.

It includes:

- Non-linear elastic behavior in fiber direction (tension and compression)
- Progressive damage in fiber direction for compression loading
- Elastic-plastic behavior due to matrix degradation in shear and transverse directions
- Progressive delamination with inter-laminar cohesive elements

The non-linear elastic behavior in fiber direction was found in **[7]**. Damage law in compression loading was based on experimental and numerical work found in literature **[7]-[8]**.

Damage and plastic evolution laws in shear and transverse directions were identified on tensile test on $[+45\ /\ -45]_{ns}$ and $[90]_n$ laminates. The extension to out-of-plane direction needed for the 3D model is based on an isotropic transverse assumption. Comparison between experimental and model results on shear behavior is represented on Figure 3.

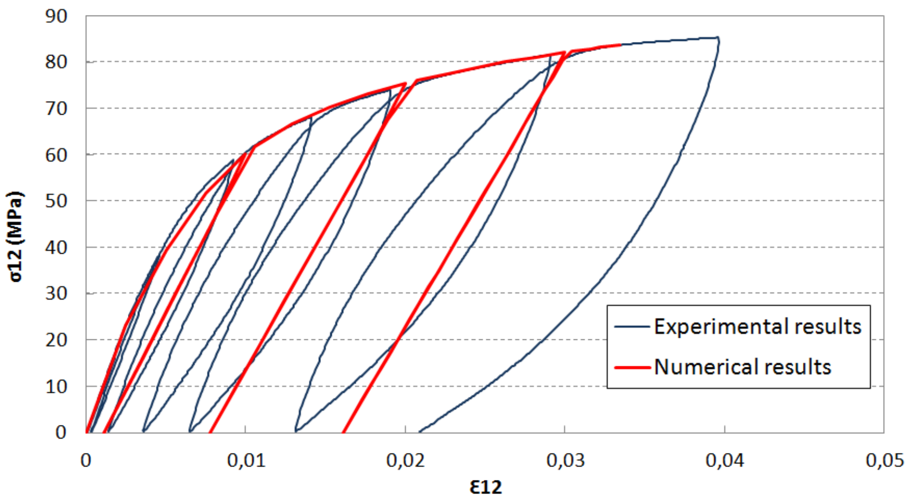


Figure 3. Comparison between model and experimental test on shear behavior

4 Finite elements models description

ABAQUS software was used to model the assembly. To be coherent with composite behavior law, each ply, with local orientation, is modeled. The pin is assumed to be rigid. As demonstrated in **[9]** this assumption can be justified for qualitative analysis.

The behavior model was implemented using a UMAT subroutine.

Delamination initiation value are coming from experimental test data **[10]**. The Benzeggagh-Kenane model **[11]** is used to described the energy release rates in mixed modes failure (mode I and II). Cohesive elements are used to include the inter-laminar model in FEM.

To avoid numerical localization due to softening behavior and reduce mesh dependency, a delay effect is introduced in the damage evolution laws.

Cohesive elements are used to model inter-laminar behavior.

The behavior of A286 stainless steel is represented by an elasto-plastic law identified with the help of a tensile test. Assembly dimensions for each configuration are detailed in Table 1.

Assembly	Composite hole diameter (mm)	Internal bushing diameter (mm)	External bushing diameter (mm)
No bushing	6.5		
Adjusted bushing	9	6.5	9
Interference fit bushing	9	6.5	9.02

Table 1. Assembly description

The interference level for the interference fit bushing is 0.01 mm, which represent a radial preload of about 70 MPa.

The geometric $\frac{D}{w}$ ratio chosen for assembly (0.25) will lead to a bearing failure mode.

5 Results and analysis

The bearing damage sequence is relatively complex, because of the large variety of damage mode involved **[5]**, **[12]**. Figure 4 represents experimental results obtain with a fit interference bushing. The curve is characterized by non-linearity and sudden loss of load.

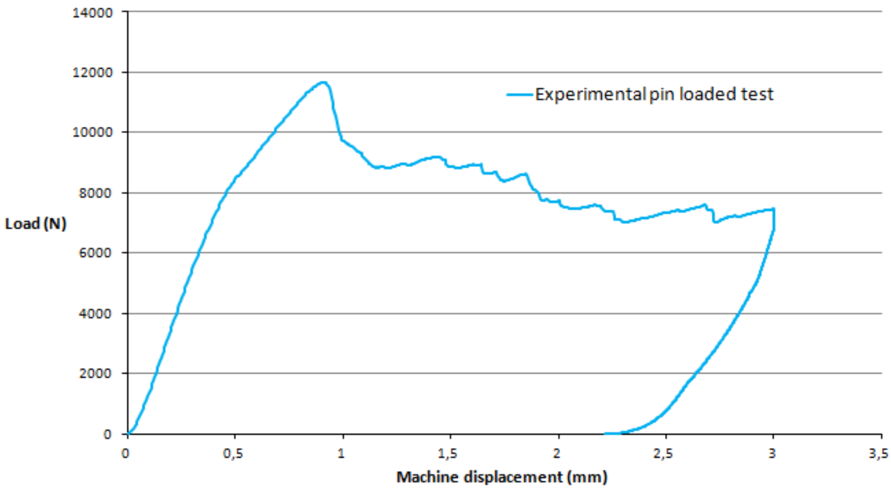


Figure 4. Experimental pin loaded test on reinforced hole assembly (fit interference bushing)

The first interest here is to represent the load/displacement behavior, and to analyze the damage scenario predicted by the model. Figure 5 represents the model response with the damage scenario. The elastic model response is plotted as a comparison.

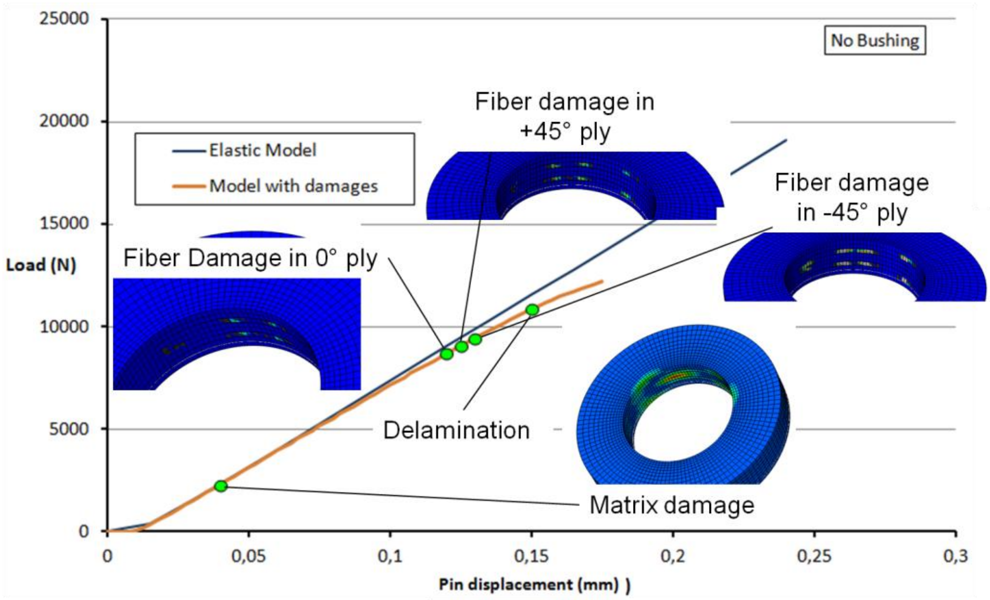


Figure 5. Damage prediction scenario and model response (fit interference bushing)

Damages first occur in the matrix, at 2200N. Thus, appears fibers degradation, in the 0° plies (8700N), the +45° plies (9000N) and finaly in the -45° plies (9500 N). Delamination occurs beyond (11000N). The degradation scenario is globally consistent with literature. The general aspect given by the model is quite good. The progressive loss of rigidity is observed and the maximal load reached is in a quite good agreement with experimental test. But the main topic here is to extract qualitative information to evaluate degradation influence. The failure load is assumed to be done by the model divergence. Work in progress should determine if this divergence have physical or numerical origin. To go further, the damage model should be improved and stiffness evolution compare with experimental test.
We now compare the three types of assembly (Figure 6).

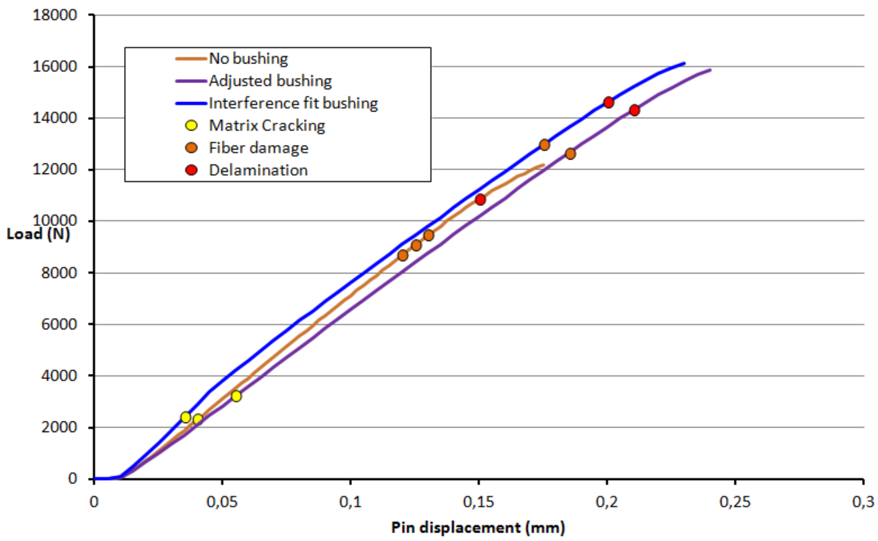


Figure 6. Macroscopic behavior of assemblies

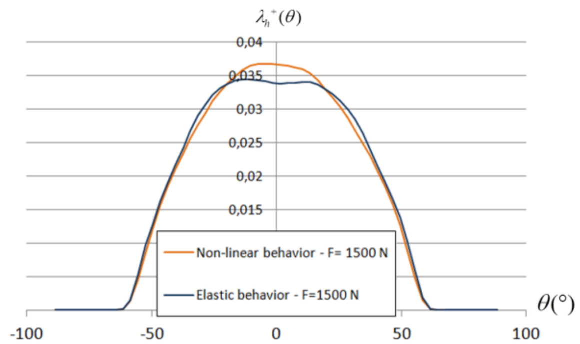
We can see that the same scenario is followed by each type of assembly. The difference lies in the level of initiation, and the gap between the different damage steps. We can also notice that the fiber degradation occurs almost in the three direction (-45°/0°/+45°) at the same time approximately when the hole is bushing reinforced.

Qualitatively speaking, rigidity of assemblies is coherent: the adjusted bushing assembly has a slightly lowest rigidity than the no bushing assembly. Actually, the assembly behavior could be compared with a no-bushing assembly, with a 9 mm pin (and as a consequence, a smaller net-section surface), in term of behavior. At the opposite, the interference fit assembly has the higher rigidity rate, due to the bushing rigidity (higher than composite rigidity) and the bushing/composite interdependence. We can also note a first decrease of rigidity (at about 3000 N), which is causes by the loss of the bushing/composite contact on S^-.

Of course, these are qualitative observations and analyses, and have to be confirming by experimental tests.

In order to have a greater understanding of the macroscopic behavior, we are interested in load transfer mechanism, and influence of materials degradation.

The load transfer parameter λ_h^+ is plotted on Figure 7 and 8.



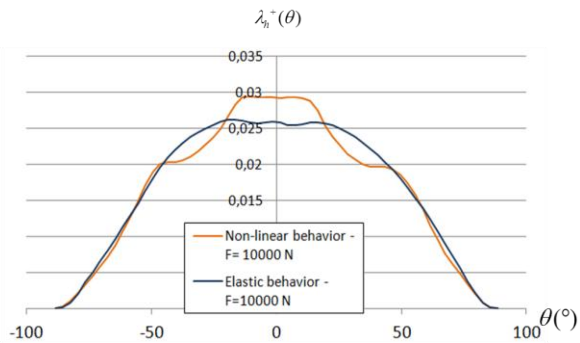


Figure 7. Model influence on λ_h^+ distribution (no bushing assembly)

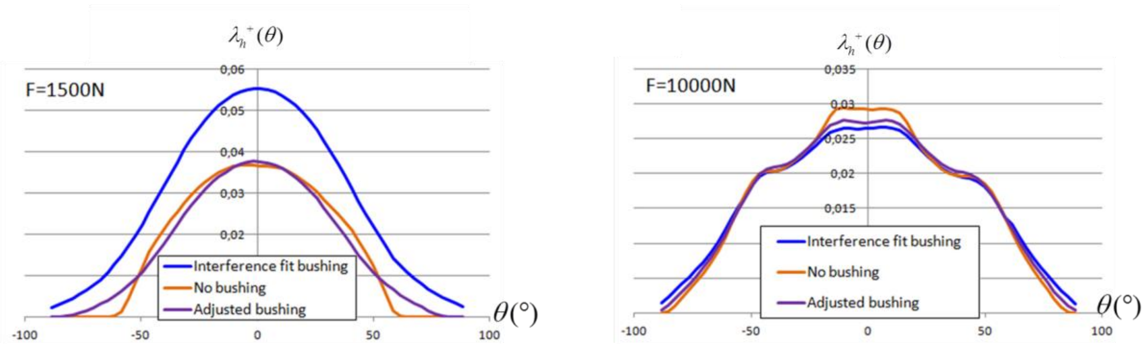


Figure 8. Assembly influence on λ_h^+ distribution (damage model)

The λ_h^+ distribution variation of the elastic model is limited (Figure 7). The pin contact being more important, the effective angle of load transfer becomes greater. But the general aspect is the same along the loading. In the non-linear case, damages influence the distribution of the load transfer. Influence of the 0° direction is becoming weaker during the loading: The 0° fibers direction degradation lead to adjacent plies redistribution.

Figure 8 shows the variation of load transfer distribution for the three assembly types. Qualitatively speaking, the introduction of a bushing reinforcement induces a greater load transfer distribution. In interference fit bushing assembly, the distribution is disadvantageous for low loading (because of the interference residual stress), but a better redistribution is noted for a more significant load. This is a consequence of a greater surface participation.

The general behavior of load redistribution can be illustrated by plotting the σ_{xx} contribution of plies as a function of the angle direction (on S^+) and the loading (cf. Figure 9). Only the four internal plies of the half stratification are represented. To illustrate these phenomena, the no bushing assembly instance is represented.

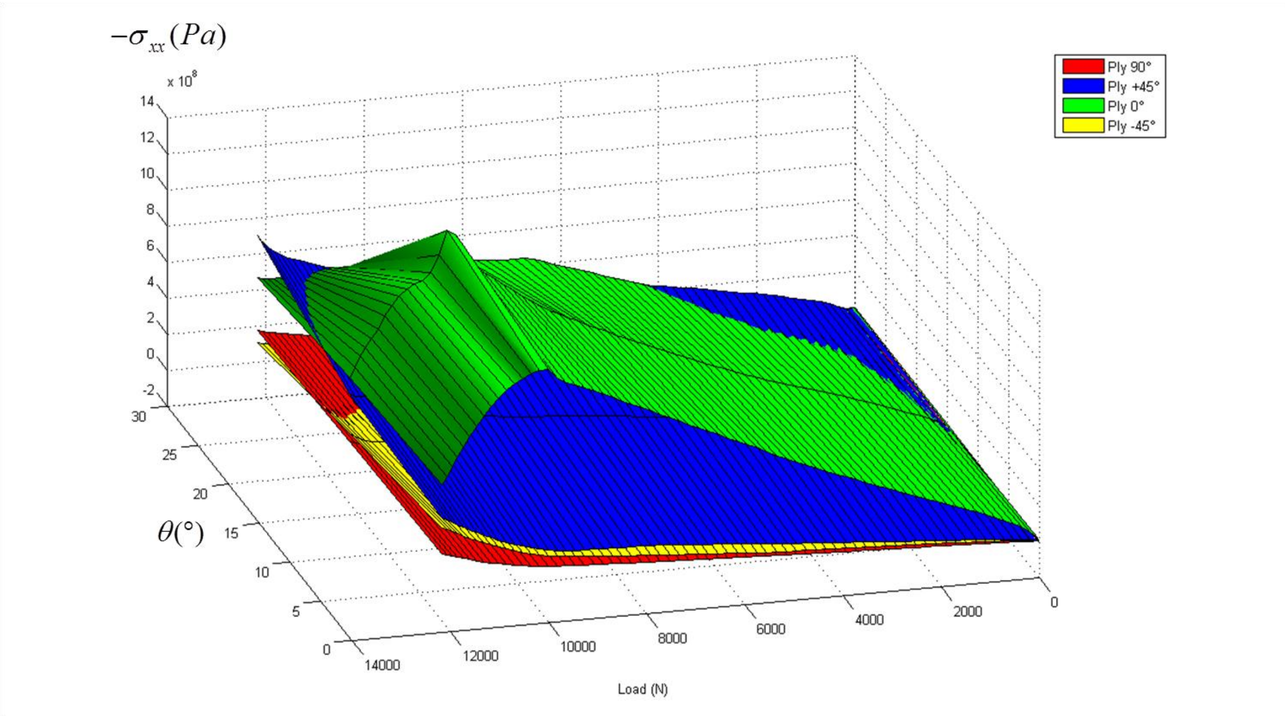


Figure 9. Macroscopic behavior of the no bushing assembly

We can see the degradation influence on the load transfer between 0° and +45° plies. Same behavior have been noted on hole reinforcement assembly, with a better distribution of the load transfer.

6 Conclusion

The goal of this paper was to estimate qualitative influence of non-linearity (linked to damage in our case) on an pin loaded reinforced hole behavior.

Material non-linearity has important impact on the global behavior of pin loaded hole, and could be necessary to estimate hole reinforcement assembly type efficiency, analyze load mechanism or design assemblies. However, to have a real interest, it must be able to corroborate experimental tendency, in term of general behavior, damage scenario and ultimate load. So in the one hand improvement can be made on damage law prediction by including links between damages modes.

In the other hand a way in progress to compare model and experimental damage scenario consist on measuring load transfer change using digital image correlation.

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