REPAIR DESIGN IN COMPOSITE STRUCTURES

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ABSTRACT

Use of composite materials for primary aircraft structures has increased for the past few years along with the need to repair those structures in case of damage. This study focuses on modeling bonded scarf/step monolithic repairs under tensile load. A numerical study using ABAQUS software has been conducted to study the effect of an over-ply on those repairs. Different parameters were taken into account: over-length of the over-ply, addition of a filler ply, orientation of the over-ply. The effect of these parameters on peel and shear stress distribution in the bondline is studied. The addition of an over-ply allows reducing bondline stresses near the free edge of the adhesive.

1 INTRODUCTION

As the use of composite materials in primary aircraft components increases, interest in repair methods has grown. Indeed, composite materials have high strength, high stiffness, long fatigue life, and light weight but they are sensitive to impact which can cause delamination, matrix cracks, fiber failure and material crushing. These damages can induce severe reductions in strength and stiffness that may lead to structural failure. Therefore, it is crucial to have effective repair methods to restore the damaged component to a usable condition. Bonded patch joining is often used because it allows high strength recovery and does not affect much the aerodynamic performance of airplane components [1]. The effects of adhesive thickness, scarf angle and patch plies sequence have been studied in the literature for repairs and bonded joints under tensile load. Increasing the adhesive thickness tends to decrease the strength and stiffness of bonded joints [2] and scarf/scarf repairs [3] under tensile load. From[3, 4], scarf/scarf repairs have been found more effective for low scarf angles. Finally it has been shown in [5] that the patch ply sequence has to be the same as the parent material because it allows avoiding stress concentrations caused by the difference of stiffness between the plies of the patch and the parent (for scarf/scarf repairs).

Despite the above progress in understanding of bonded repairs, in order to efficiently predict the failure and optimize the design of repairs, there is still a need for accurate numerical analyses. Different approaches have thus been developed to describe the adhesive and, more generally, repairs behaviour under tensile load [6, 7]. Shih-pin [8] uses an elastic-plastic model with shear failure criterion to describe the adhesive film behaviour. This kind of numerical approach is interesting because it only requires the determination of the shear elastic-plastic properties of the adhesive film whereas other approaches require, in addition, critical strain energy release rates and crack path.

This paper aims at presenting a parametric study of the utilization of an over-ply on monolithic repairs. It is well known that peel and shear stresses develop in the bondline depending on the shape of the repair (scarf/step, scarf/scarf, step/step repairs) [7] and that using an over-ply can protect the repaired part from environmental damage or external impact. The point of interest here is to investigate if using an over-ply influences the mechanical properties and failure of the repairs. Gunnion *et al.* [9] showed on scarf/scarf repairs that the addition of an over-ply not only induce a drop in peel and shear stresses in the bondline but also cause a delay in crack initiation at the scarf edge. It was also shown in [9] that different lay-ups for the over-ply and the increase of the number of over-laminating plies provided no significant differences in reducing peel and shear stresses in the bondline. Breitzman *et al.* [10] showed, on scarf/scarf

repairs, that the over-ply has only an effect on stress distribution in the plies and in the adhesive area which are near it. Pinto *et al.* [11] showed on scarf/scarf repairs that a strength recovery of 70% can be reached with over-plies on both side of the repair (but this is rarely a feasible option) and a strength recovery of 50% was reached with only one over-ply for the lowest scarf angle and the longest over-ply. Adding an over-ply on only one side of the repair induces a slight deflection of the laminate that may cause failure according to Pinto *et al*. [11]. Yoo *et al*. [12] showed experimentally that having an over-ply does not have significant effect on the strength of the repaired section.
Here we perform a parametric study of the scarf-step repairs using the finite-element software ABAQUS. First, the parametric model is described and then the results of parametric study are presented. In particular, the effects of an over-ply, of a filler ply and of the over-ply orientation on 8-ply and 16-ply repairs are discussed.

2 PARAMETRIC MODEL

2.1 Geometry

The longitudinal cross-section of a scarf/step repair of a quasi-isotropic laminate is modeled in 2D in the (x, z) plane. The scarf angle is 3°. In order to simplify the analyses, only half of the repair is modeled. Using the geometric partitioning method, one then defines the parent plies, the patch plies, the adhesive, the over-ply and the filler ply (depending on the configurations). With the aim of being close to actual repair configurations, the adhesive is modeled between the over-ply and the parent part of the repair. The over-ply was added only on the upper surface of the repair. Tables 1 and 2 summarise the different configurations that have been considered in the study of the effects of an over-ply on the mechanical properties of the repair for 8-ply and 16-ply laminates, respectively. The over-ply over-lap length (L_{OL}) was taken equal to either 6.37 mm or 12.7 mm. The parameters that have been investigated are the length of the over-lap (L_{OL}), the addition of a filler ply and the orientation of the over-ply. The over-lap (L_{OL}) is defined as the length between the end of the patch and the end of the over-ply. Geometries and dimensions are shown in Figure 1.

8-ply repair	Description		
Parent stacking sequence	[((+45/-45)(0/90)(-45/+45)(90/0))$_S$]		
Patch stacking sequence	Without filler ply [((+45/-45)(0/90)(-45/+45)(90/0))$_S$]		With **(+45/-45)** filler ply [((+45/-45)(0/90)(-45/+45)(90/0))/(90/0)(-45/+45)(0/90)(+45/-45)**(+45/-45)**]
Orientation of the over-ply	(+45/-45)	(0/90)	(+45/-45)

Table 1. Description of the configurations for the 8-ply repairs.

16-ply repair	Description		
Parent stacking sequence	[((+45/-45)(0/90)(-45/+45)(90/0))$_{2S}$]		
Patch stacking sequence	Without filler ply [((+45/-45)(0/90)(-45/+45)(90/0))$_{2S}$]		With **(+45/-45)** filler ply [((+45/-45)(0/90)(-45/+45)(90/0))$_2$/((90/0)(-45/+45)(0/90)(+45/-45)**(+45/-45)**]
Orientation of the over-ply	(+45/-45)	(0/90)	(+45/-45)

Table 2. Description of the configurations for the 16-ply repairs.

2.2 *Material properties*

The ply material is a 0.19 mm thick plain weave (PW) carbon fiber reinforced out-of-autoclave prepreg from Cycom (5320 EO) and the adhesive is a 0.25 mm-thick CYTEC FM300-2M epoxy film. The properties of these materials, at room temperature, are provided in Tables 3 and 4. Each ply in the model has its own stiffness matrix calculated from the elastic properties in Table 3 [7]. Stiffness matrices were supposed to be equal for both (0/90) and (90/0) plies and for both (+45/-45) and (-45/+45) plies. The over-ply is made with the same material as the parent and the patch. The orientation of the over-ply is (+45/-45) except in section 3.3 where the orientation of the over-ply is (0/90). The orientation of the filler-ply is (+45/-45) in all configurations.

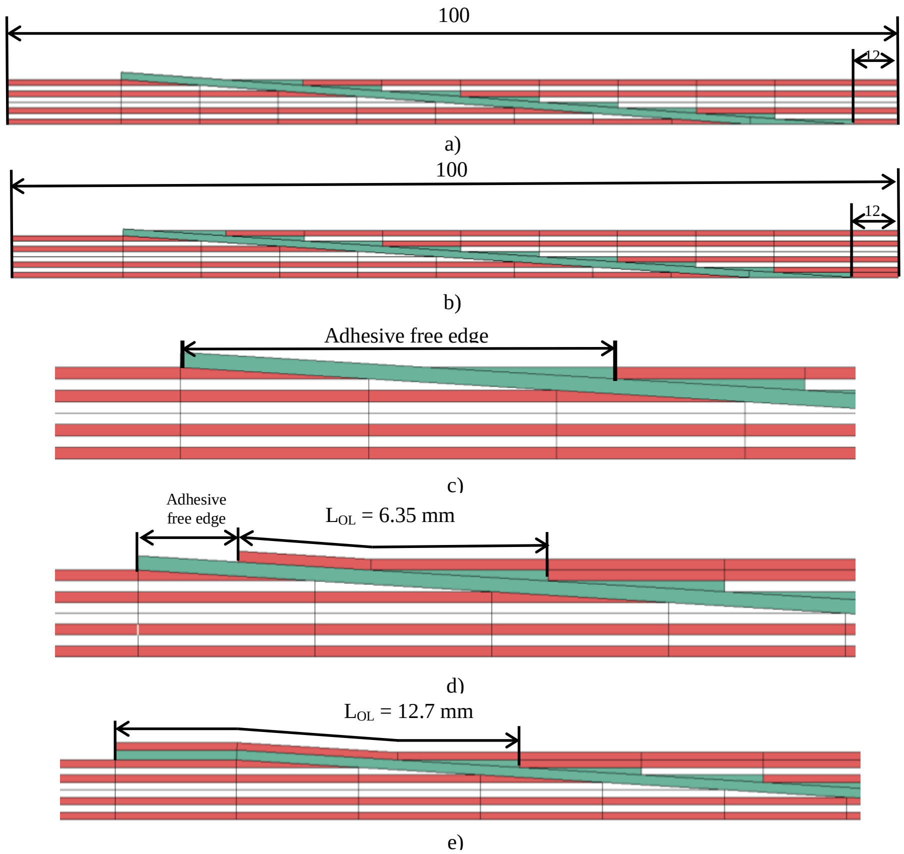

Figure 1. Descriptions of the configurations (dimensions are given in mm, not to scale). a) Baseline 8-ply repair (no over-ply and no filler ply). b) 8-ply repair with filler ply and no over-ply. c) Adhesive free edge definition. d) 8-ply repair with L_{OL} = 6.35 mm. e) 8-ply repair with L_{OL} = 12.7 mm.

Property	Unit	PW Material
$E_1 = E_2$	[GPa]	64.8
E_3	[GPa]	10.0
G_{12}	[GPa]	4.93
ν_{12}	-	0.047

Table 3. Elastic properties of the PW composite material at room temperature.

Property	Unit	Adhesive material
G	[MPa]	866.64
τ^{ult}	[MPa]	51.9
γ^{ult}	[%]	12
ν	-	0.3

Table 4. Mechanical properties of the FM300-2M adhesive film at room temperature.

2.3 Boundary conditions

To simulate a tensile test, the right side of the model (patch side) was restrained with symmetric boundary conditions and a linear displacement along the x-axis was imposed on the left side (parent side) of the model. The boundary conditions and the applied displacement are illustrated in Figure 2.

2.4 Mesh

Each ply and the adhesive layer were discretized using two and four elements through the thickness, respectively, as shown in Figure 3. The analysis used ABAQUS/STANDARD to study the stresses distribution along the bondline in the middle of the adhesive film.

Figure 2. Boundary conditions and applied displacement (figure is not to scale).

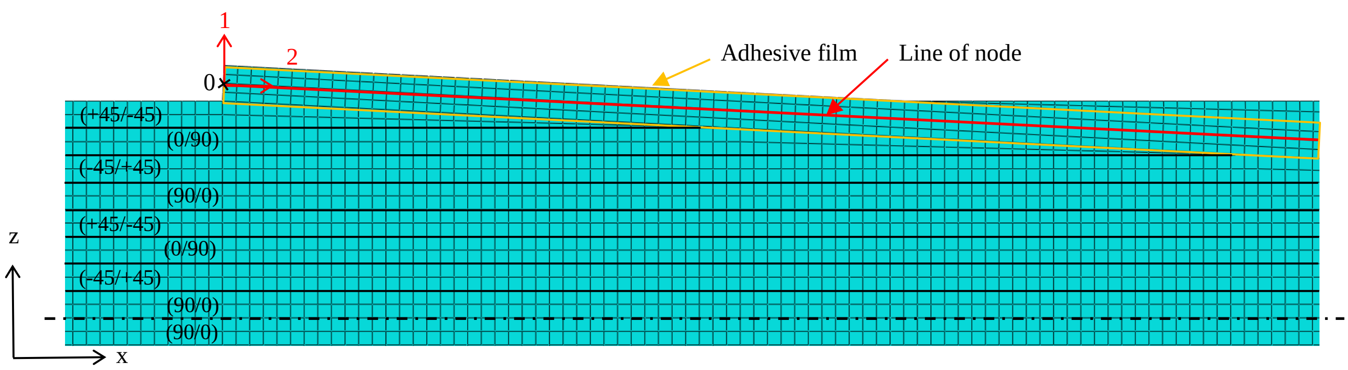

Figure 3. Mesh representation and line of node.

2.5 Analysis methodology

Stresses distribution is studied in the bondline along the same node line for all configurations. This node line is in the middle of the adhesive. A local coordinate system (see Figure 3) allows the definition of the peel stress (σ2) as the stress normal to the bondline direction (2-direction) and the definition of shear stress (τ_{12}) as the stress in the (1-2) plane. In order to have a direct comparison of the relative magnitude of the stresses, they have been normalized to the far field applied stress (σ_x) then multiplied by 1000 for convenience as follow:

$$\frac{\sigma_2}{\sigma_x} \times 1000$$
$$\frac{\tau_{12}}{\sigma_x} \times 1000 \tag{1}$$

The distance along the bondline has been normalized. The origin point is taken at the same location for all configurations as shown in Figure 3.

3 PARAMETRIC STUDY RESULTS

3.1 Effect of an over-ply on 8-ply and 16-ply composite repairs

The effect of an over-ply was investigated for 8-ply and 16-ply scarf/step monolithic composite repairs. Figure 4 hows the normalized peel and shear stress distribution along the bondline for 16-ply repairs with a (+45/-45) over-ply of different lengths (L_{OL} = 6.35 mm and L_{OL} = 12.7 mm). The results for a 16-ply repair with no over-ply is added for comparison. Having a 6.35 mm-over-length over-ply creates a supplementary peak in the shear and peel stress distribution along the bondline compared to a repair with no over-ply. These peaks are mitigated when the over-length is 12.7 mm because the over-ply fully recovers the free edge of the adhesive.

The results obtained for the 8-ply scarf/step monolithic composite repairs are not shown. It was observed that stresses in the bondline are larger for 8-ply repairs than for 16-ply repairs. However, the effect of adding an over-ply is the same.

Adding an over-ply to reduce stress peaks in the bondline is relevant when the over-length is long enough to allow the over-ply to fully recover the free edge of the adhesive. This over-length depends on the thickness of the plies used for the patch and for the parent as well as on the thickness of the adhesive.

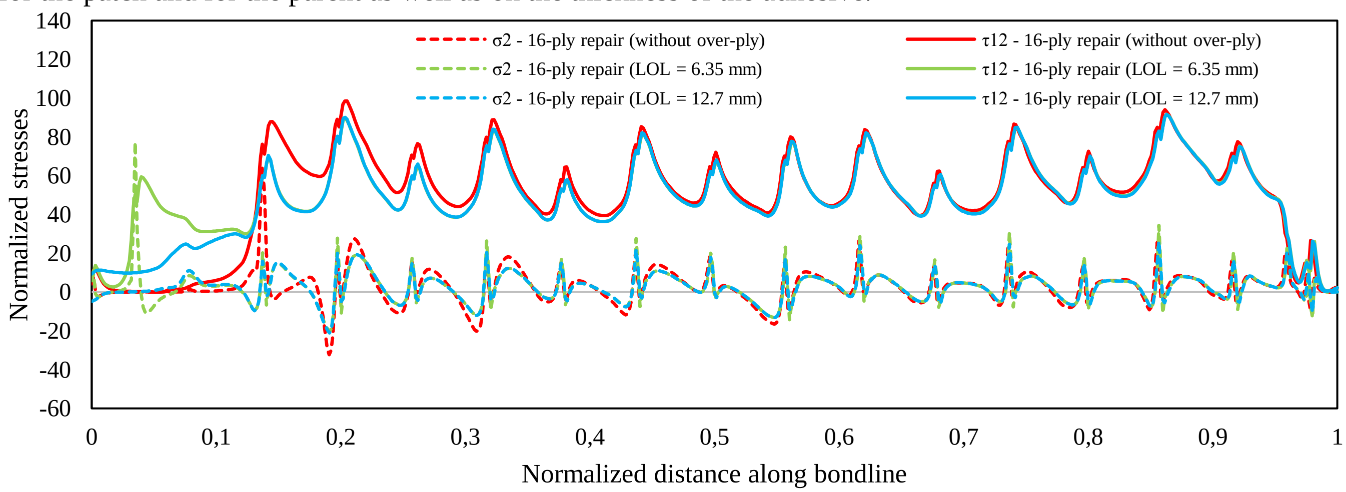

Figure 4. Effect of an over-ply on the peel and shear stress distribution for a 16-ply composite repair.

3.2 *Effect of a filler ply on 8-ply and 16-ply repairs*

Most articles [1, 3] study repairs for which the patch structure strictly matches the parent structure (same material and lay up). The objective of the work presented in this section is to investigate what happens when a filler ply is added. Figure 5 and 6 present respectively the normalized shear and peel stress distribution along the bondline for 8-ply repairs: i) with a (+45/-45) filler ply and an over-ply (L_{OL} = 12.7 mm) and ii) with a (+45/-45) filler ply but no over-ply. Theses figures also present normalized shear and peel stress distribution along the bondline for the baseline 8-ply repair (no filler ply and no over-ply) for comparison.

As the figures show, adding a filler ply creates a supplementary peak in both shear and peel stresses near the free edge of the adhesive. However, the overall shear and peel stresses level is reduced when a filler ply is used, especially around the (+45/-45) ply of the patch located at 0.3 on the normalized distance along bondline. As can be observed in the figures, the effect of the over-ply on the repair with the filler ply is the same as for repairs with no filler ply. Compared to the baseline configuration, the repair with a filler ply and an over-ply (L_{OL}=12.7 mm) presents a decrease of 44% for the highest shear stress peak and of 89% for the highest peel stress peak ((+45/-45) ply).

Repairs with a filler ply and an over-ply that fully recovers the free edge of the adhesive are interesting because they allow for a larger reduction in stress peaks in the bondline than in repairs with no filler ply. This can be explained by the fact that with the addition of a filler ply, each ply of a given orientation in the patch is closer to the corresponding ply in the parent. This can reduce stress concentrations that cause peaks in the bondline. Although not shown, the same trend is observed for 16-ply repairs.

3.3 *Effect of the over-ply orientation on 8-ply and 16-ply repairs*

The effect of changing the over-ply orientation from (+45/-45) to (0/90) on bondline stresses for 8-ply and 16-ply repairs has been investigated. Figures 7 and 8 show the normalized shear and peel stress distributions along the bondline obtained for the 8-ply repairs only. For both over-ply orientations, the over-lap length is the same and equal to 12.7 mm. Theses figures present also the normalized shear and peel stress distributions along the bondline for a 8-ply repair with no filler ply (baseline repair) for comparison.

As can be observed in Figure 7, no changes are noticed for peel stresses between the (0/90) over-ply and the (+45/45) over-ply. The peel stress peak decreases by almost 91 % for both cases. However, as shown in Figure 8, the effect of a (0/90) over-ply on the shear stress distribution is more pronounced than with a (+45/-45) over-ply. The main shear stress peak decreases by almost 52% with a (0/90) over-ply whereas a (+45/-45) over-ply allows a reduction of 38%. The repair with a (0/90) over-ply shows lower shear stresses on average than the repair with a (+45/-45) over-ply. This can be explained by the fact that a (0/90) ply is stiffer than a (+45/-45) ply and allows for a reduced stress transfer in the adhesive. The same trend is observed for 16-ply repairs.

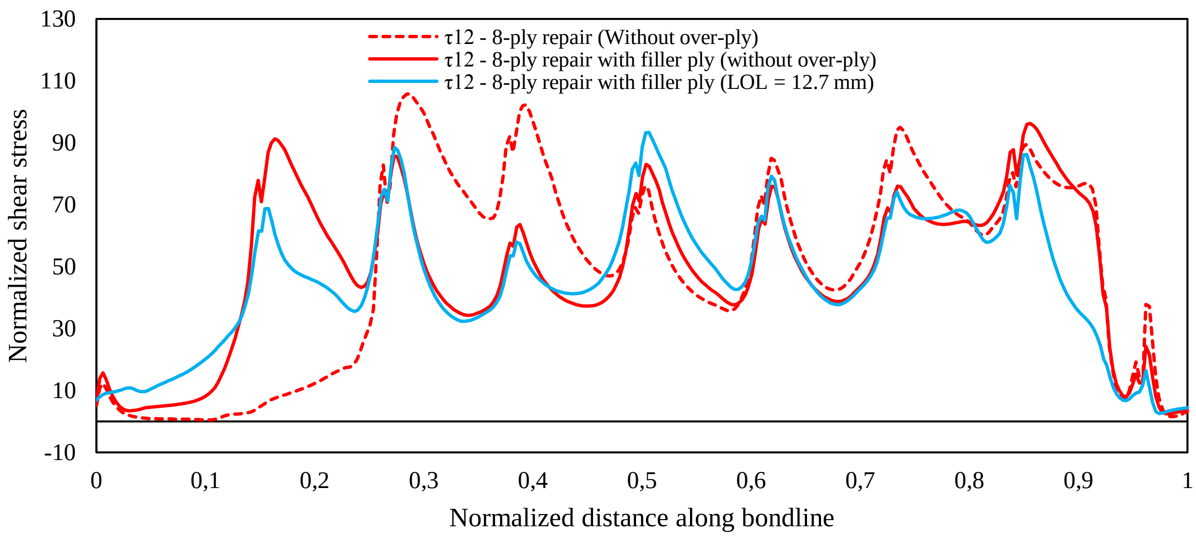

Figure 5. Effect of a filler ply on the shear stress distribution for a 8-ply composite repair.

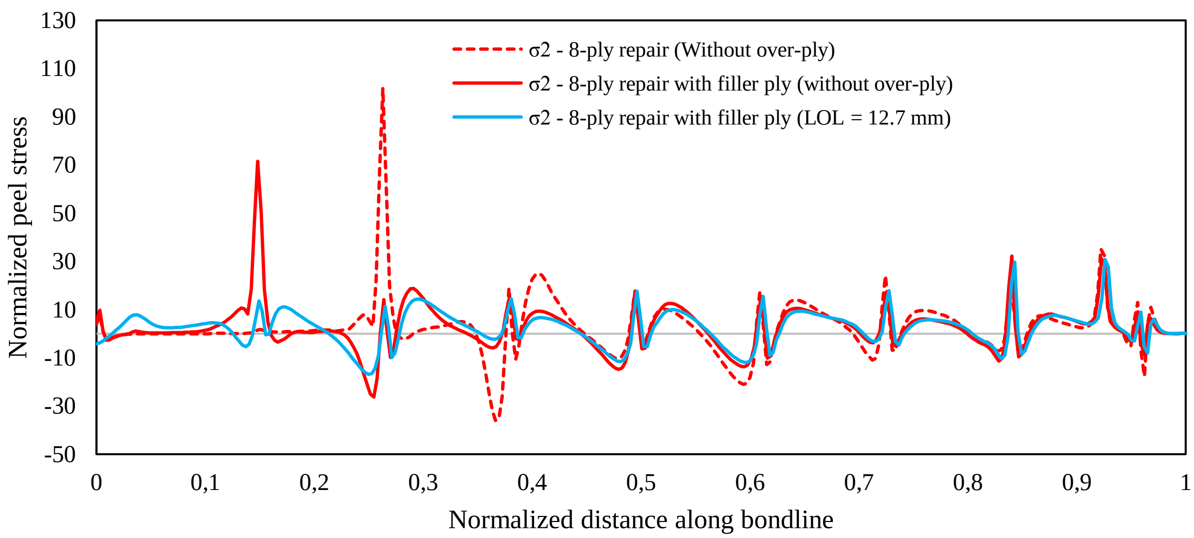

Figure 6. Effect of a filler ply on the peel stress distribution for a 8-ply composite repair.

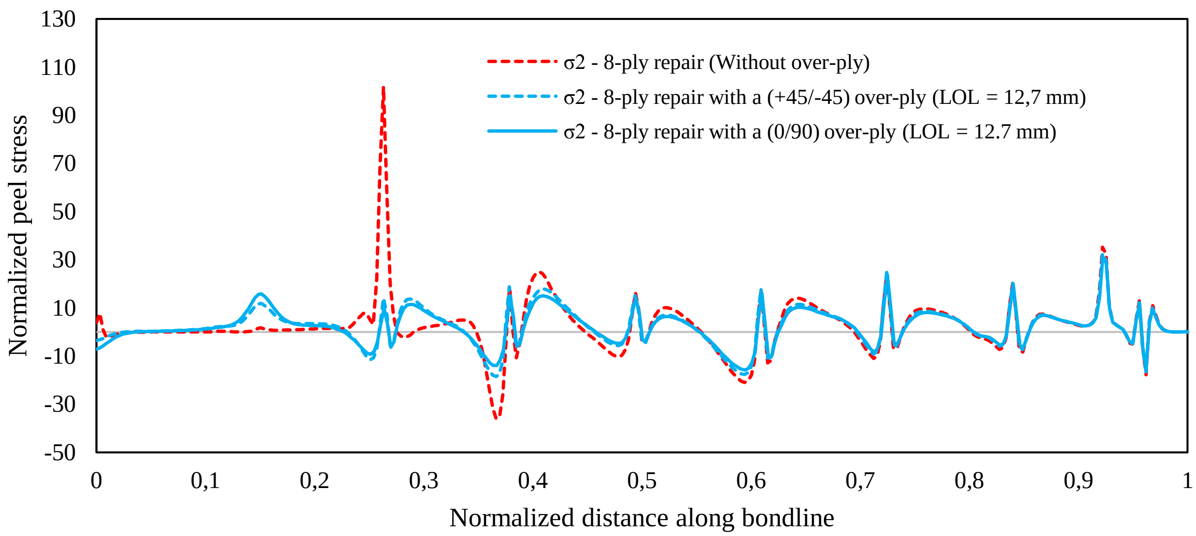

Figure 7. Effect of the over-ply orientation on the peel stress distribution of a 8-ply repair.

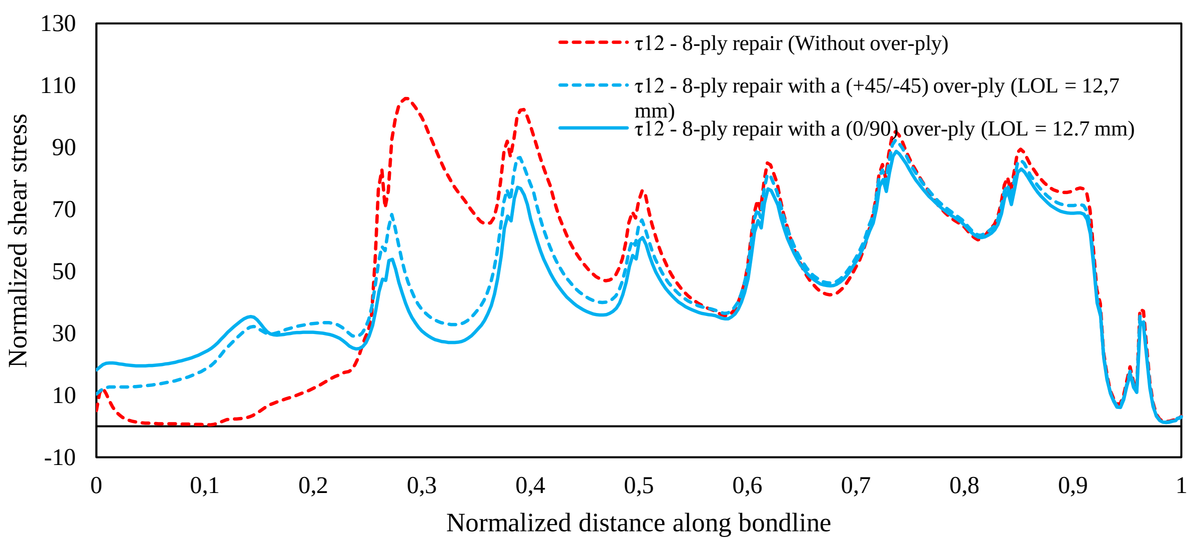

Figure 8. Effect of the over-ply orientation on the shear stress distribution of a 8-ply repair.

4 CONCLUSION AND FUTURE WORK

This paper presented a numerical parametric study on the effects of different parameters on scarf/step bonded repairs with 3°- scarf angle. Different configurations were investigated. The parent laminate had either 8 plies or 16 plies. The over-ply was either a (+45/-45) or a (0/90) ply. In addition, the use of a (+45/-45) filler ply was investigated. The main conclusions are that:

- Adding an over-ply has a positive effect on the stresses distribution in the adhesive only if the over-ply recovers the free edge of the adhesive. This depends on the thickness of the plies of the patch and of the parent and on the thickness of the adhesive.
- When a filler ply is added in the patch, shear stresses in the bondline decrease.
- Changing the orientation of the over-ply allows decreasing shear stresses.

Future work will consist in running numerical analyses to predict failure of the repair and conducting experiments on the effect of an over-ply in order to compare and validate the numerical study.

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