TOWARD A NUMERICAL CONCEPTION OF A TECHNOLOGICAL EVALUATOR FOR COMPOSITE STRUCTURAL REPAIR: SHEAR CHARACTERIZATION

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Abstract
An innovative bonded repair evaluation, through the design of a detail-sized evaluator and representative from the industrial application, is proposed thanks to the study of the interface behaviour. This paper deals with a primary major phase which follows three stages: First, non-standard shear tests have been conducted, Secondly, with the geometrical data obtained through the experiments, a 2D model has been designed to be as light as possible and compared to the experimental results. Finally, a failure criterion form has been validated to implement a behaviour law in the future numerical conception of the bonded repair evaluator, in complement of the low-time consuming modelling strategy.

1. Introduction

With the new generation of composite aircrafts, the operators are going to be confronted to a lot of new repair issues. It is now crucial to implement a repair process for large primary composite parts, as trying to promote the bonded assembly, now certified only in case of non-transmission of service and ultimate stresses to the part.
For economic and technical reasons, a primary part cannot always be dismantled and the damaged zone must be repaired on field. The necessity of a multi-level evaluation is the requirement for a repair to be optimal and reliable, in order to go toward the certification thanks to a study done in representative working conditions for the repaired zone.
The work on coupons is necessary and crucial to find information on the bonded interface or the material without adding any other influences. Nevertheless, at the detail scale or for primary structure, couplings and influences must be taken into account. That is why a further work has to be done at an upper scale, to observe and analyse the bonded repair in a situation close to the industrial application.
The goal of this analyse is to engage a study about bonded repair in this kind of situation, focusing on the evaluation of the interface behaviour, with a patch debonding [3]. For this work, a detail-sized evaluator for bonded repair, with the solicitation and the associated kinematics, will be numerically conceived in order to make a comparative study of various repair process. However, to perform such a numerical design, it is necessary to get a very light modelling that will permit to lead hundreds of iterations to obtain the best compromise.
First, to be able to go towards such a multi-level evaluation and have a consistent model, this paper presents the work to get experimental information on the adhesion in a situation where

substrates surfaces are close to the surfaces obtained after repair machining (in terms of surface states or geometry – milling radius etc.).

This paper focuses on a composite single step-lap bonded repair with a variable step length. Tests were chosen to study the parameters locally and with a minimum of couplings. The machining of the coupons to create the steps leads to a non-standard geometry and non-standard tests. A composite/composite bonding is studied, as manufacturer data are not given for the chosen substrates or even the chosen manufacturing process. The mechanism of shear stress is investigated here, even though the phenomenon of peel stress also has been studied.

A first experimental work, which takes over the study of shear stresses, is lead to get values about the bonded joint and the failure of the coupons. Afterwards, a 2D model is designed, with all the parameters experimentally measured taken into account, to be as light in FE as possible. Finally, uncoupled parameters are identified in order to choose an adequate failure criterion form, presented in this paper. This failure criterion will be added to the 2D light modelling which will be in the centre of the numerical conception of the detail-sized evaluator.

2. Experimental study

2.1. Geometry, material and manufacturing process

The necessity to get information on the bonded interface comes from two reasons: the first is that the manufacturer data give those properties in the case of a metal/metal bonding and this paper focuses on a composite/composite bonding. The second reason is that this study deals with a step-lap repair, and its manufacturing process is quite different from a single lap repair, used in normalized standard tests. So, new tests have to be conducted, respecting the repair process. In order to get as many information common to a majority of step length as possible, three step lengths were studied: 12mm, as it is a length proposed for cosmetic repair in the SRM A330, and two lengths of 6mm and 20mm, chosen arbitrarily to surround the "reference" length of 12mm.

The repair involves a unique step-lap repair, machined in the centre of the substrate and designed to be tested in a standard tensile machine INSTRON®. The coupons were made from HEXPLY® M10.1-CHS and the specimen layup consists in 16 plies of 0.32 mm per ply. It gives a nominal thickness of 5.12 mm with the following stacking sequence: $[0/+45/90/-45/-45/90/+45/0]_s$.

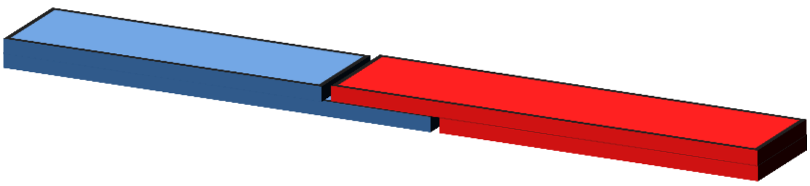

Figure 1: Principle of the step-lap repair

Bonded coupons were machined with a manual mill; half of the plies ±0.05mm were taken out to keep a constant thickness, even in the repaired area, as the epoxy adhesive film is 0.1mm thick. The specimens underwent surface abrasion and surface cleaning with acetone and drying before bonding. The symmetry of the substrate enables the coupons to be cut at the middle and turned over to create the unique step-lap repair.

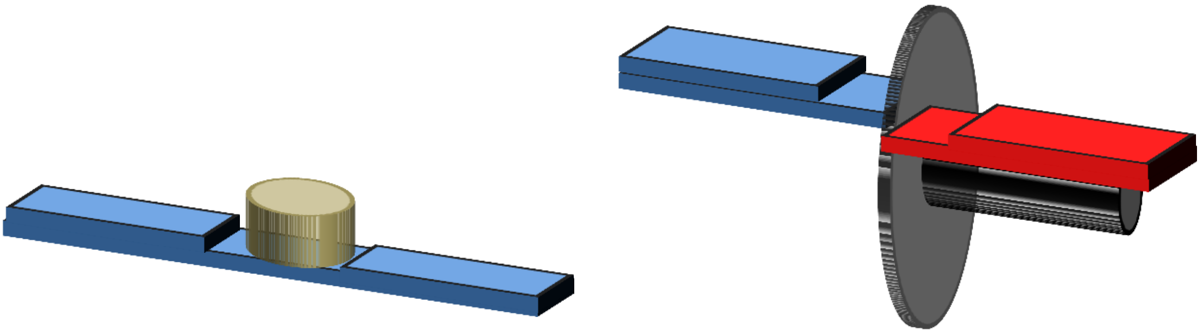

Figure 2: Manufacturing process: manual milling (left), cutting (right)

The bonding of the two parts was performed under heating mats and in a vacuum bag. Both epoxy adhesive film and patch were cured at 120°C during 30 minutes and then cured again at 150°C during two hours. The final dimensions of the coupons are 200mm long and 30 mm wide.

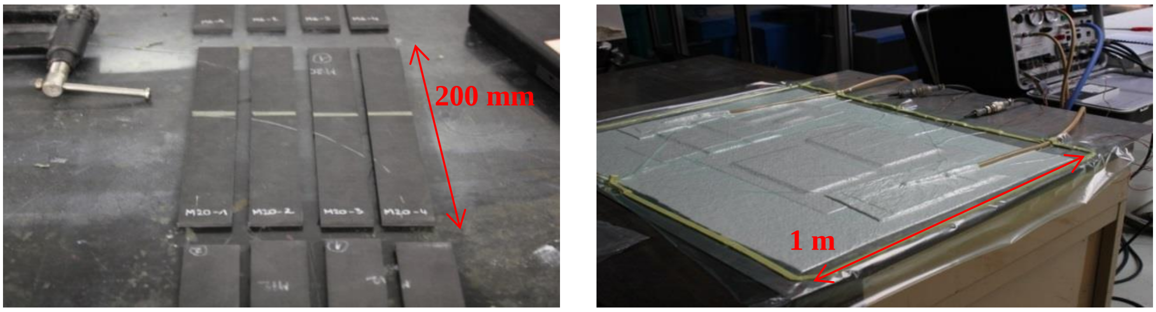

Figure 3: Final coupons (left) and vacuum bag with heating mats to cure the coupons (right)

Traction tests were performed on every manufactured coupon until failure happened thanks to an INSTRON® tensile machine. The Table 1 gives the mean failure force for each step length.

Coupon step length [mm]	Mean failure force [N]
6	4180 (±700)
12	9018 (±730)
20	8681 (±1720)

Table 1: Mean failure force for each step length

It may be observed that the mean failure value has a tendency to be proportional to the length from 6mm to 12mm and that for the step lengths of 12 mm and 20 mm, the mean values are quite similar. It comes corroborate the theory that over a mean value of 12mm for a step length, the transmissible shear load does not increase anymore. The geometrical data linked to those results have been studied to optimize the future numerical model.

2.2. Study of the geometrical data

The main goal of the FE modelling will be to validate a 2D model as light as possible and so it is important to be as accurate as it can be. A study of the geometrical data has been done and the target parameters, such as the step length, will be compared to the measured values. The measurements were made thanks to digital microscopy (with a magnification x30) and were gathered in Table 2, with the target parameters.

	Target parameters [mm]	Measured values [mm]
	6	3.57 (± 0,35)
Step length	12	7.96 (± 0,59)
	20	14.91 (± 0,23)
Bonding play length	1	0.9 (± 0,22)
Composite ply thickness	0.32	0.31 (± 0,01)
Bonded joint thickness	0.1	0.102 (± 0,015)
Width	30	30.18 (± 0,13)

Table 2: Difference between target parameters and measured values

During the digital microscopy, it has been observed that the bonding slipped during the curing, creating gaps, partially filled with epoxy adhesive film or just empty (Fig.4). This information need to be taken into account during the modelling.

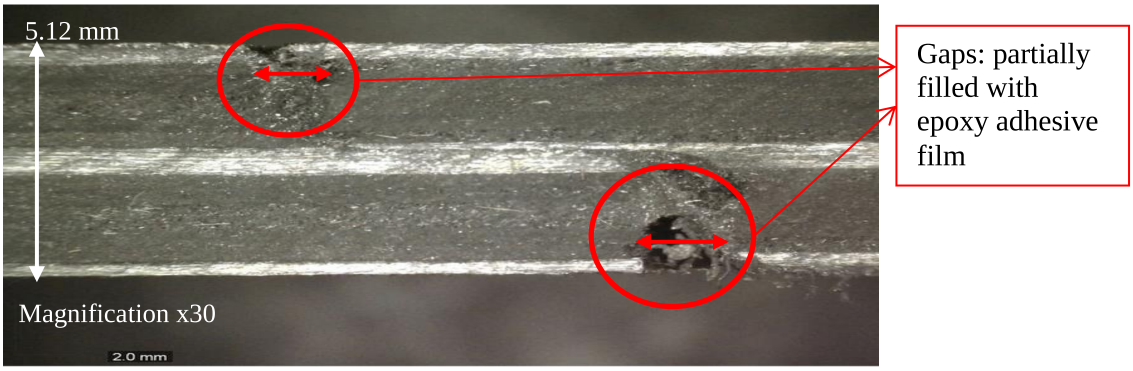

Figure 4: Digital microscopy showing the gaps appeared during the curing

Thanks to the measured geometrical data and all the information obtained with the microscopy, it is now possible to design a 2D model and to compare the numerical results with the experimental shear stresses, obtained in this case by an analytical calculation.

3. Toward a light FE model

3.1. 2D modelling

A further work will be to analyse the numerical response of a detail-sized evaluator, so it is crucial to design a first 2D model as light as possible, in order to develop this strategy. Thanks to the study of the geometrical data, bonding gaps and measured step lengths can be taken into account in order to get numerical failure shear stresses.

To create such a 2D model, Samcef® Finite Element software was used, defining the substrates as 2D shell parts and the epoxy adhesive film as a 3D part. The modelling is divided into three parts: first, two parts representing the substrates of the repair are designed from part to part of a middle plane, which is the bonded joint plane. To combine the three planes all together, the middle plane of the bonded interface is extruded on each side of it (Fig.5).

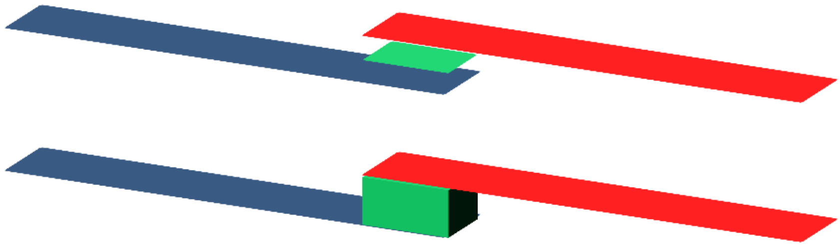

Figure 5: 2D modelling (with blue and red the substrates and green the bonded joint), different planes for each part (up) and the extrusion of the bonded joint (down)

The subtlety of this 2D modelling strategy is that creating different planes moves the neutral fibre of the substrates from the desired position. It is necessary to perform an eccentric design of the 2D parts to recover that desired location, as it can be seen in Figure 6.

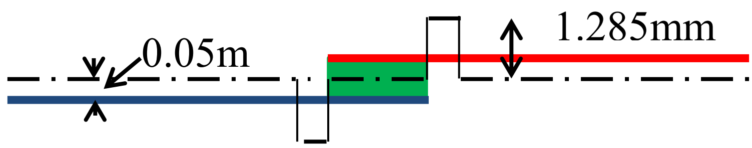

Figure 6: Eccentric design of the neutral fibre

3.2. Results

Shear stress cartography can be obtained for each step length (Fig.7), and it can be observed that a zone faintly loaded appears in the centre of the cartography for each step length. This area seems to increase with the length of the step, but the mean value seems close for every step length.

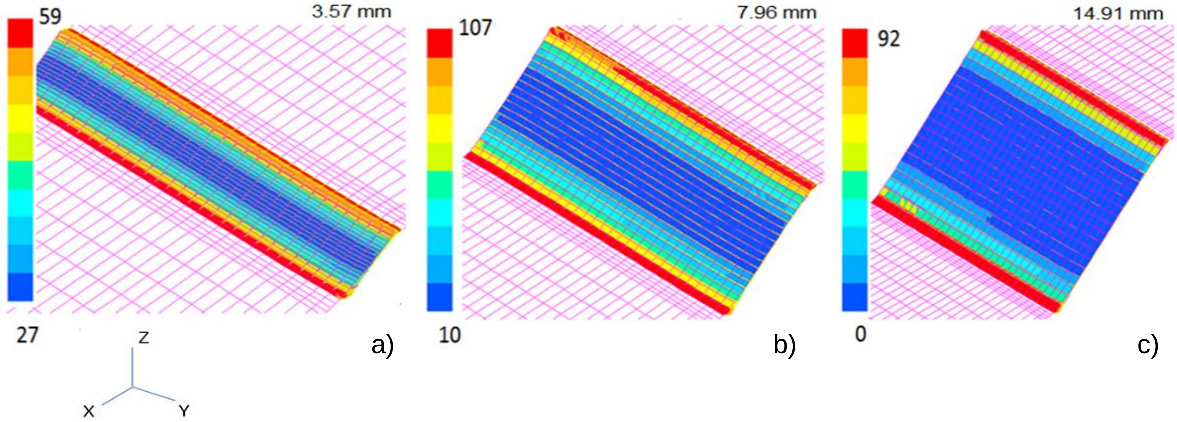

Figure 7: Shear stress cartography at failure of each step length for : a) 3.57 mm b) 7.96 mm and c) 14.91 mm

Table 3 gathers the mean shear stresses found numerically and by analytical calculation of the experimental results. It can be noticed that the results are quite similar, so the light numerical model seems to be consistent.

	Mean Shear Stresses	
Step length [mm]	Numerical model [MPa]	Experimental procedure [MPa]
3.57	39.03	39.01 (± 5.0)
7.96	37.76	37.88 (± 3.9)
14.91	19.41	19.35 (± 3.8)

Table 3: Mean shear stresses of the study

4. Failure criterion and mesh sensitivity

4.1. Failure criterion

In order to be accurate in the study of the bonded interface failure, it would be interesting to validate a failure criterion. This would feed the future work on the numerical conception of a detail-sized evaluator with a behaviour law, and is necessary to perform several iterations with an automatic analysis of each calculation. In the literature, the most popular failure criterion comes from Whitney&Nuismer [1] (1):

(1)
$$\bar{\tau}_{ZX} = \frac{1}{d_0}\int_0^{d_0} \tau_{ZX}\, dx$$

where d_0 is a characteristic length, which is assumed to be the bonded length for a scarf lap repair (close to a step-lap repair).

Number of elements in the length of the step		20	
Step length (mm)	3.97	8.23	15.25
Size of an element	0.2	0.41	0.74
Associated Criterion (MPa)	40.9	41.3	26.6

Table 4: Shear stress with the Whitney&Nuismer failure criterion

With this failure criterion (1), the Table 4 gathers the shear stress calculated thanks to it. It can be noticed that, for a step of 14.91mm (target step of 20mm), the criterion does not apply. Drawing the evolution of the shear stress in the length of the steps (Fig.8) shows that from a certain value (close to 9.5mm), the curve draws a plateau with a shear stress almost no-existent. This plateau needs to be taken into account in the failure criterion form.

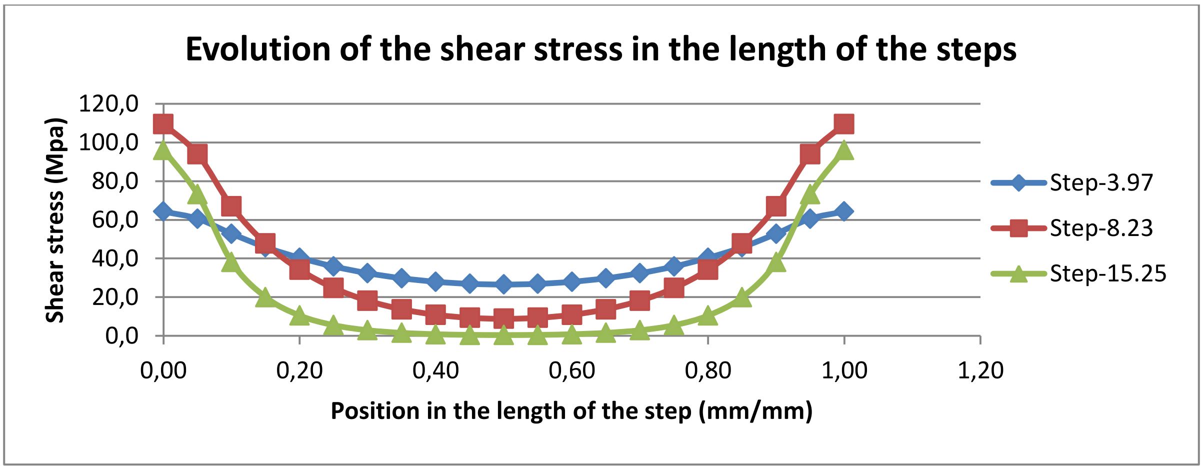

Figure 8: Evolution of the shear stress in the length for each step

The second failure criterion (2) is inspired by the first criterion, except that useful length d_u is defined, not including the faintly loaded zone. The table 5 gathers the new shear stress calculated with the preceding failure criterion. The second failure criterion, written here in a form which is adapted to numerical data (2) can be validated as the shear stress associated is quite similar for every step length.

(2)
$$\bar{\tau}_{ZX} = \frac{1}{d_u}\sum \tau_{ZX\,i} \times l_i$$

where d_u is the useful length, assumed to be equal to the step length if it is less than 9.5mm and 9.5mm otherwise and l_i is the length of an element *i*.

Number of elements in the length of the step		20	
Step length (mm)	3.97	8.23	15.25
Size of an element	0.2	0.41	0.74
Associated Criterion (MPa)	40.9	41.3	41.5

Table 5: Shear stress with the validated failure criterion

4.2. Mesh sensitivity

Now that a failure criterion has been validated, a mesh sensitivity of the 2D model can be done in order to obtain a numerical model as light in elements and CPU time as possible. The goal of this study is to find the most little number of elements necessary to acquire the most consistent shear stress results. The evolution of the shear stress in the width of a target step of 20mm has been traced (Fig.9)

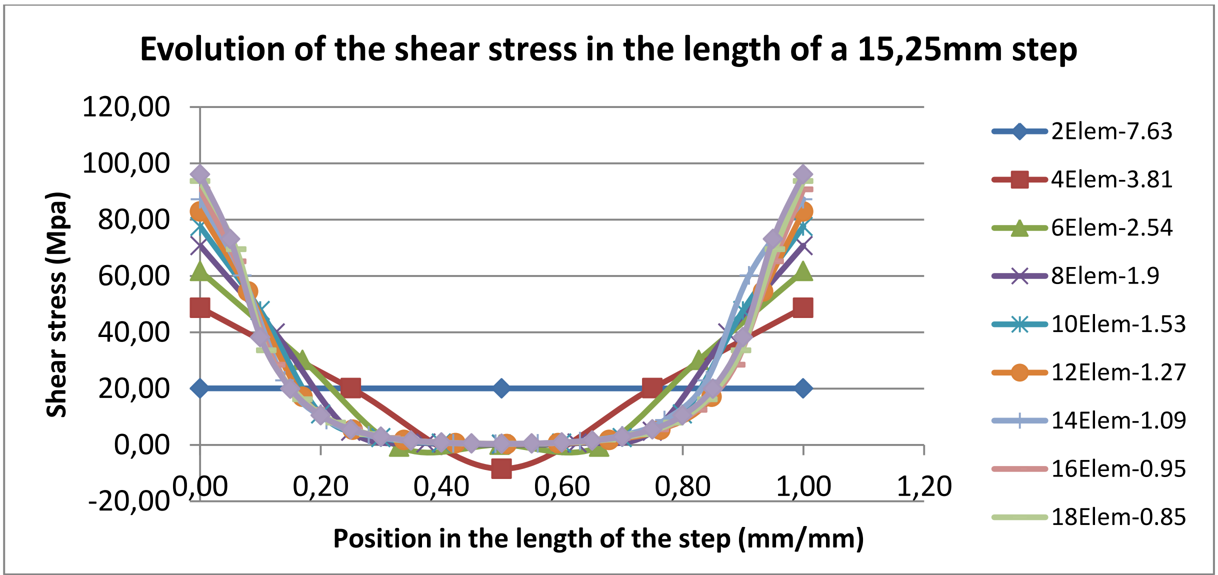

Figure 9: Evolution of the shear stress for 10 different numbers of elements in the width of a step

It can be noticed that from 8 elements, the plateau of non-existent shear stress appears and the table 6 comes corroborate this number of elements with the shear stress calculated from the validated failure criterion. Indeed, from 2 to 6 elements, the values of shear stress do not seem consistent and 8 elements is the best compromise between a light and a relevant model.

Number of elements in the length of the step	2	4	6	8	10	12	14	16	18	20
Size of an element (mm)	7.63	3.81	2.54	1.9	1.53	1.27	1.1	1	0.85	0.76
Criterion (MPa)	32.2	41.5	41.9	41.4	40.7	40.1	39.5	39	38.5	38.1

Table 6: Shear stresses calculated with the validated criterion for each number of elements

5. Conclusion and prospects

Bonded interface shear failure properties have been brought out thanks to non-standard experiments, in complement of the manufacturer data. Coupons have been fabricated and mechanical tests were performed. Experiments show that several values, such as the step lengths, are quite far from the targeted dimensions and those differences need to be taken into account in the numerical modelling. Moreover, the transmissible loading for a step-lap repair seems proportional to the step lengths until a step value of 12mm. Further work is being done to confirm this tendency.

A strategy of mixed modelling 2D/3D has been implemented to represent the bonded interface behaviour, with the necessity to be as light as possible. The results seem consistent with the experimental values, relevant and non-time-consuming.

A failure criterion form has been validated, and mesh sensitivity has been performed. This work was adapted to the conditions of the study, in terms of geometry, manufacturing process etc. It appeared that a number of 8 elements in the length of a step was enough to describe consistent shear behaviour in this step, while limiting the CPU time.

This primary phase, with the complementary peel study, is meant to help the next step of this work: the design of a detailed-sized evaluator [4]. This evaluator will be designed (Fig.10) to study the patch debonding, with combined solicitations and kinematics, chosen in advance and enhanced with a multi-axial testing machine.

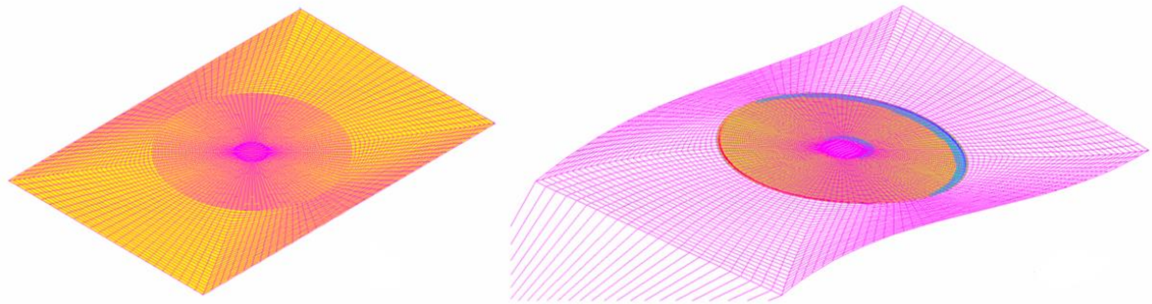

Figure 10: Possible geometry of the technological evaluator

Thanks to this technological evaluator, it will be possible to evaluate different step lengths, to compare several repair processes (for instance abrasive water jet VS manual machining, hard patch VS soft patch etc.), to optimize the patch geometry [2] or to analyse the repair behaviour under cyclic fatigue

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