A COMPARISON STUDY ON STRENGTH ANALYSIS OF COMPOSITE REPAIR ADHESIVE ZONE BY ANALYTICAL METHODS AND ABAQUS COHESIVE ZONE MODELLING TECHNIQUES

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ABSTRACT

Prediction of the failure in composite repair is a widely studied subject in the literature due to the increasing importance of analysis over the expensive testing. Interlaminar failure is one of the most common failure modes that occurs in the repair of composite laminates. In early stages, analytical methods were offered to predict the strength of the bonded repair, providing fast and conservative solutions One of the methods is based on shear strain distribution over the bond line of the repair. With the increasing computational capability, several finite element solutions were offered for analyses. Interlaminar failure, delamination in composite structures are commonly performed by the cohesive zone method (CZM). Commercial finite element analysis (FEA) packages are widely used both in industry and academia to predict the failure status in bonding regions. Abaqus finite element program is widely used in the aerospace industry and aerospace researches. In this article, a comparative study is made for failure prediction by analytical method and Abaqus to ascertain the differences that arise. Effect of the bondline thickness was also studied and results were compared for both approaches.

INTRODUCTION

In aerospace industry, the usage of the composite structures is increasing tremendously. Big or small-scale damages on composite structures occur in large number inevitably. To ensure the structural safety, the damages should be repaired.

Efficient and accurate solutions in prediction of the failures in composites are required for safety of the structures, lowering the costs and shortening the time to market.

As well as analytical methods, numerical solutions are offered by many commercial FEA packages to analyze the strength of the adhesive layer of the repair. Abaqus cohesive zone method (CZM) is one of the most powerful tools to predict damage initiation and propagation in adhesive layer. Abaqus has built-in capabilities such as utilizing power law and Benzeggah-Kenane (B-K) criteria [Benzeggagh and Kenane, 1996] in calculation of Gc for mixed mode. Implementation of CZM requires extremely fine mesh in the cohesive zone. To allow the coarser mesh, the length of the cohesive zone can be increased artificially by reducing the

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interfacial strength [Turon, 2007]. Song et al [Song 2008] propose parameter selection guidelines for CZM analyses suggesting that the cohesive zone element parameters and mesh densities should be determined by performing single mode simulations of simple specimens of the same material.

Most scolars use implicit methods to analyze bonded joints having severe convergence problems. High efficiency and acceptable accuracy of 3D models was demonstrated by Ye et. Al [Ye 2018].

The objective of this paper is to present a comprehensive study to reveal the level of advantages and disadvantages of both methods. Analytical methods provide fast and conservative solutions whereas Abaqus requires more resources for modeling and analyses. However, Abaqus could provide more realistic solutions which could help to reduce the weight.

METHODOLOGY

Analytical Solution

Analytical method used in this article was proposed by Ahn [Ahn, 2000] for uniform double lap repairs. Investigations are based on uniform double lap shear repaired tensile test specimens as shown in Figure 1. The method provided good agreement with the test results [Ahn, 2000].

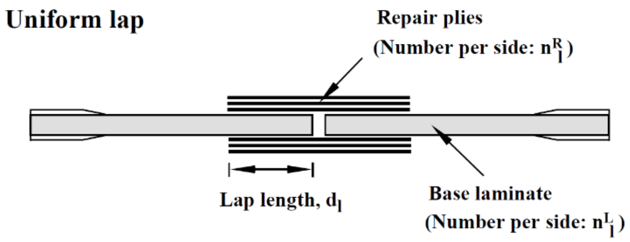

Figure 1*:* Uniform Double Lap Repair Tensile Test Specimen [Ahn, 2000]

The method assumes that the repaired laminate fails due to shear failure of the adhesive layers treated as an “interlayer” and aims to find shear strain distribution over the lap length. The interlayer exhibits elastic-perfectly plastic behavior. The shear strains at the elastic limit and at plastic failure are γ_{ef} and γ_{pf}, respectively.

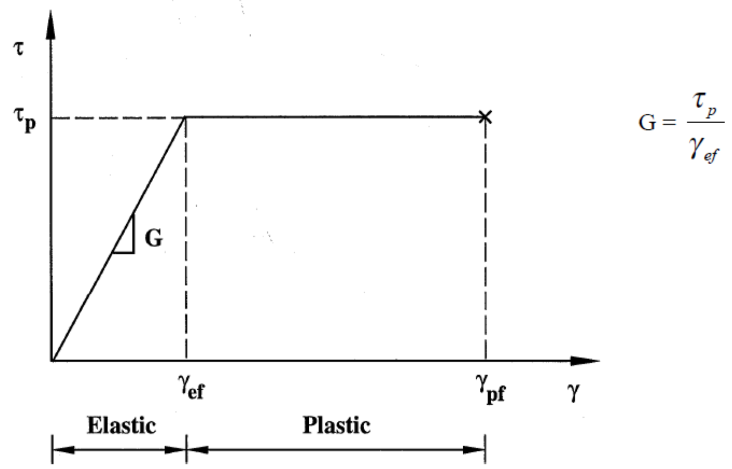

Figure 2*:* Elastic – Perfectly Plastic Behaviour of Interlayer [Ahn, 2000]

Force equilibrium for infinite small part of the repair region (see Figure 3) can be written as follows.

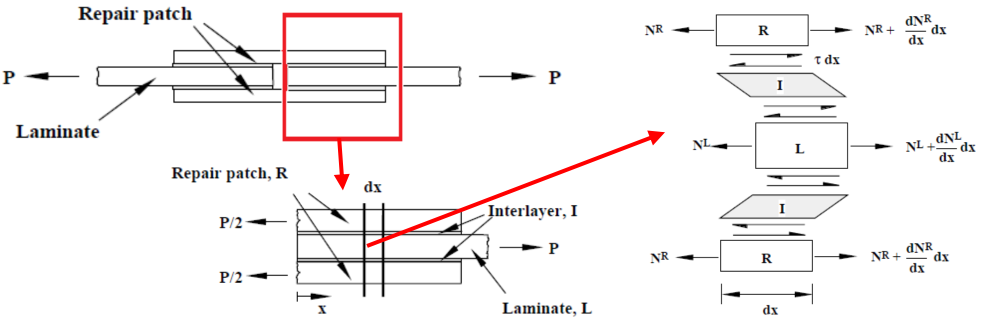

Figure 3*:* Uniform Double Lap Repair, Force Equilibrium [Ahn, 2000]

$$\frac{dN^L}{dx} - 2\tau = 0 \qquad \text{Laminate}$$

$$\frac{dN^R}{dx} + \tau = 0 \qquad \text{Repair Patch} \qquad (1)$$

Figure 4 presents the deformed shape of the infinite small part of the repaired region. Between repair patch and the interlayer, deformed shape of the repair patch and the length due to shear deformation at the end of the part is added which is shown with red line. Similarly, yellow line is drawn for the laminate interface of the interlayer. Then by equating the length of these two lines the geometric compatibility equation (2) is obtained.

$$(\varepsilon_x^L + 1)dx + \gamma h_i = (\varepsilon_x^R + 1)dx + (\gamma + \frac{d\gamma}{dx}dx)h_i \qquad (2)$$

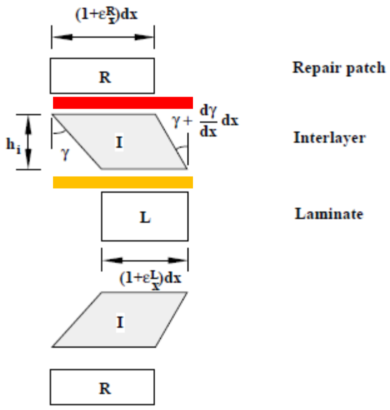

Figure 4*:* Uniform Double Lap Repair, Geometric Compatibility [Ahn, 2000]

By rearranging and combining the equations (1) and (2), the differential equation (3) for shear strain distribution over the adhesive layer length in x-direction can be obtained.

$$\frac{d^2\gamma}{dx^2} = \frac{1}{h_i}\left(2\alpha_{11}^L + \alpha_{11}^R\right) \qquad (3)$$

where the solutions are:
For the elastic region:

$$\gamma = psinh(\lambda x) + qcosh(\lambda x) \qquad (4)$$

For the plastic region:

$$\gamma_p = \frac{\lambda^2 \gamma_{ef}}{2} x^2 + rx + s \qquad (5)$$

There are four possible scenarios for the behavior of the interlayer:

1. The entire interlayer is linearly elastic
2. A perfectly plastic region near the x = 0
3. A perfectly plastic region near the x = dl
4. A perfectly plastic region near both the x = 0 and x = dl

At the locations where the elastic and plastic regions meet the shear strains in the elastic and plastic regions are equal (with the value γ_{ef}) and are continuous. The locations xp1 and xp2 are unknown and must be determined from the solutions of the equations.

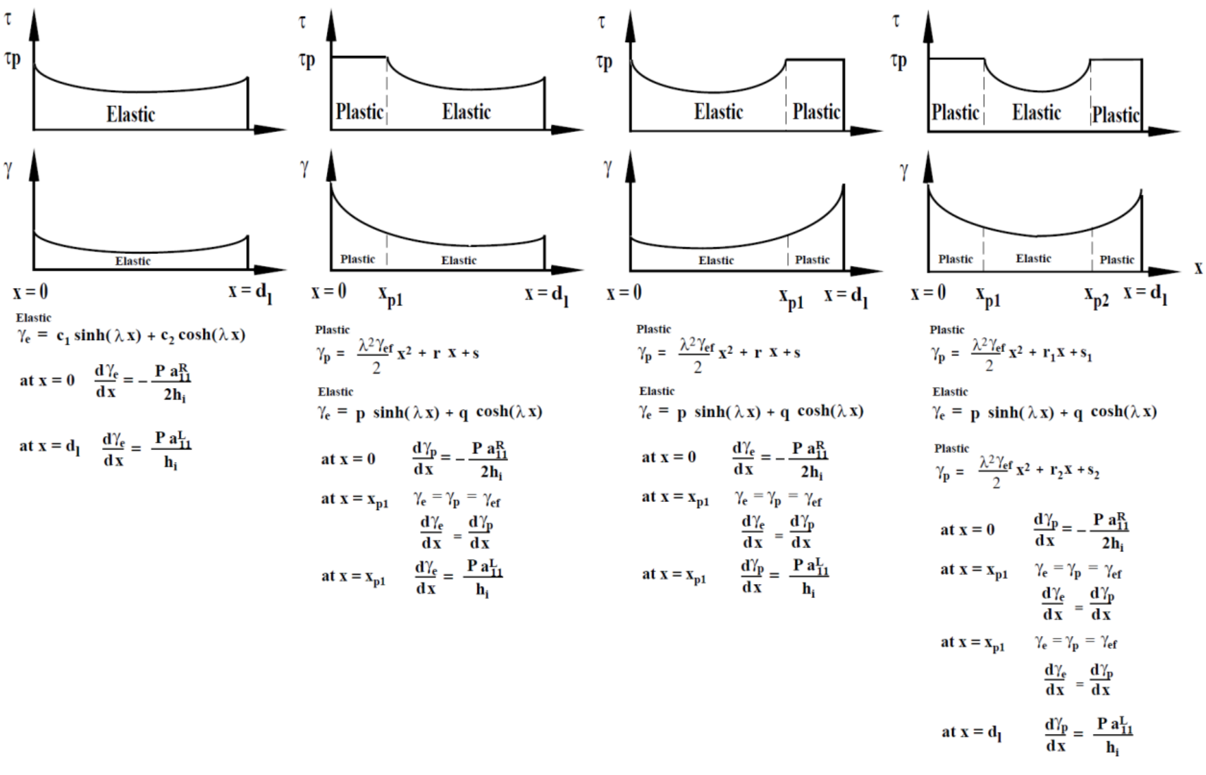

Figure 5: Uniform Double Lap Repair, Boundary Conditions and Continuity Conditions [Ahn, 2000]

The algorithm of the solution is also provided by Ahn [Ahn, 2000].

- A load P is applied such that under this load the entire interlayer is in the elastic region. The shear strain as a function of location x is calculated by the equation above.
- The load is gradually increased, and at each load the shear strain is calculated.
- The procedure is repeated until the shear strain reaches the elastic limit γef either near the x=0 or near x = d1 end of the interlayer.
- The applied load is gradually increased, and at each load the shear strain as a function of x is calculated by the equation given either for the plastic region is near x = 0 or for the plastic region is near x = dl.

- The procedure is repeated until the shear strain is at or above the elastic limit at both the x = 0 and x = dl ends of the interlayer.
- The applied load is gradually increased, and at each load the shear strain as a function of location x is calculated by applying the boundary conditions.
- At each load in steps 2. and 3. the shear strain is compared to the plastic failure strain γpf.
- The load P at which the shear strain γp, at any point in the interlayer, reaches the plastic failure strain γpf, is taken to be the failure load (P = F).

In the present study, an Excel sheet with a VBA code was implemented to determine the elastic plastic strain transition points, the strain distribution curves along bond line (see Figure 6) by finding the coefficients of the strain distribution curves in all elastic and plastic regions and finally the failure load.

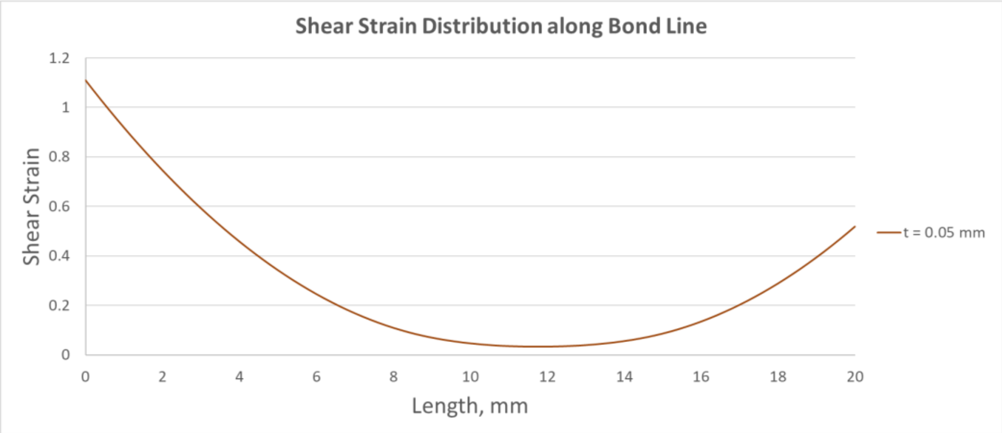

Figure 6*:* Analytical Shear Strain Distribution

The shear strains at x=0mm are higher than the ones at x=20mm. This is an expected consequence of the difference of x-direction stiffness. As the laminate is more stiff then the repair patch, higher shear strain is at x=0mm. If the repair patch would be more stiff then higher shear strain would be observed at x=20mm.

FEM CZM solution

Another method that is presented in this article is cohesive zone method for FE. A commercial solver Abaqus V14 is utilized. Dynamic implicit solver with quasi static application is used.

The models have been created for uniform double lap shear repair specimen having same dimensions except the thickness of the interlayer and material properties. Abaqus 6.14 is used as solver. Solid elements - C3D8R are used in this study to model the composite laminates and cohesive elements - COH3D8 is used for interlayer [Abaqus 6.13 Documentation]. In order to determine the mesh size of the cohesive layer a convergence study was performed for double cantilever beam – Mode I [Davila, 2008].

The uniform double lap shear repair is symmetrical model - Figure 7. Therefore 1/8th model was used with symmetrical boundary conditions - Figure 8. AS4/8552 UD for parent laminate and g0904/Epocast52AB for repair patch with quasi isotropic layup. Adhesive material is Epocast52AB as repair patch is wet lay up on the pre-cured parent laminate. There is a 5mm space between two parent laminates to simulate the damage. Two repair patches connects the parent laminates from top and bottom side symmetrically in order to eliminate secondary bending moment effects.

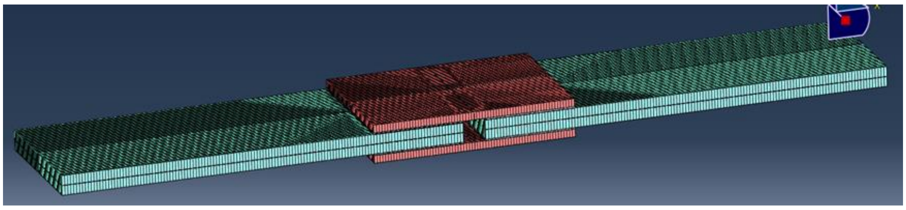

Figure 7: Abaqus Uniform Repair Modell

Model is loaded under tension. To simulate the tests only gage length of the specimen is modeled. The end of the specimen is connected to reference point by kinematic coupling and 0.4mm of tensional displacement was applied.

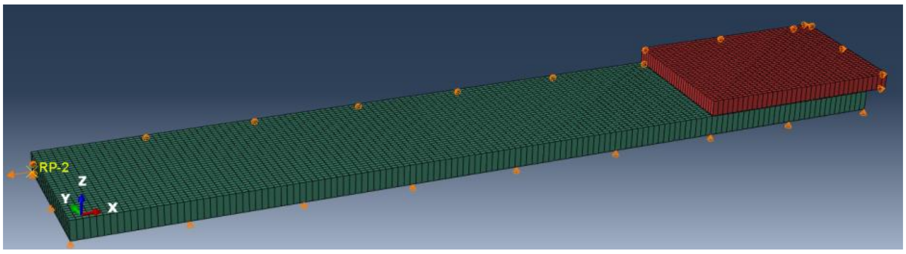

Figure 8*:* Abaqus Uniform Repair Model Symmetry Boundary Conditions

Simiar to analytical method, the results reveal that, the shear strains at x=0mm are higher than the ones at x=20mm as expected Figure 9. This shows both model behavour is the same. Note that x=0mm is at the damage side of the parent laminate and x=20mm is at the repair patch end on the parent laminate.

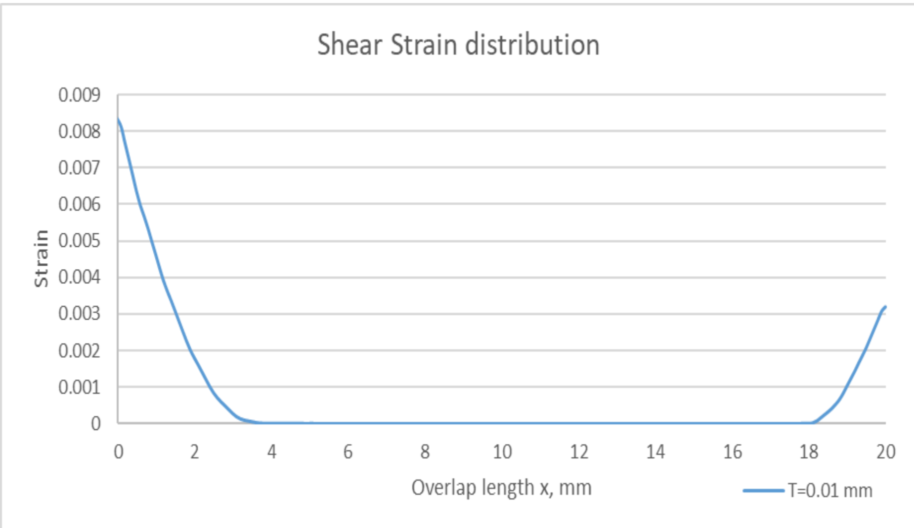

Figure 9*:* Strength vs Adhesive Layer Thickness According to Analytical Solution

The shear strain is higher at x=0mm. Therefore, damage starts at x=0mm .The evolution of the crack is presented in Figure 10. First the damage level of the cohesive element increases at x=0mm in parallel to strain distribution. Then, damage starts at the corners, where edge effects are significant. Failure starts also at x=20m. After little increase of the load final intact region remain in the middle closer to the x=20mm. Then total failure occurs.

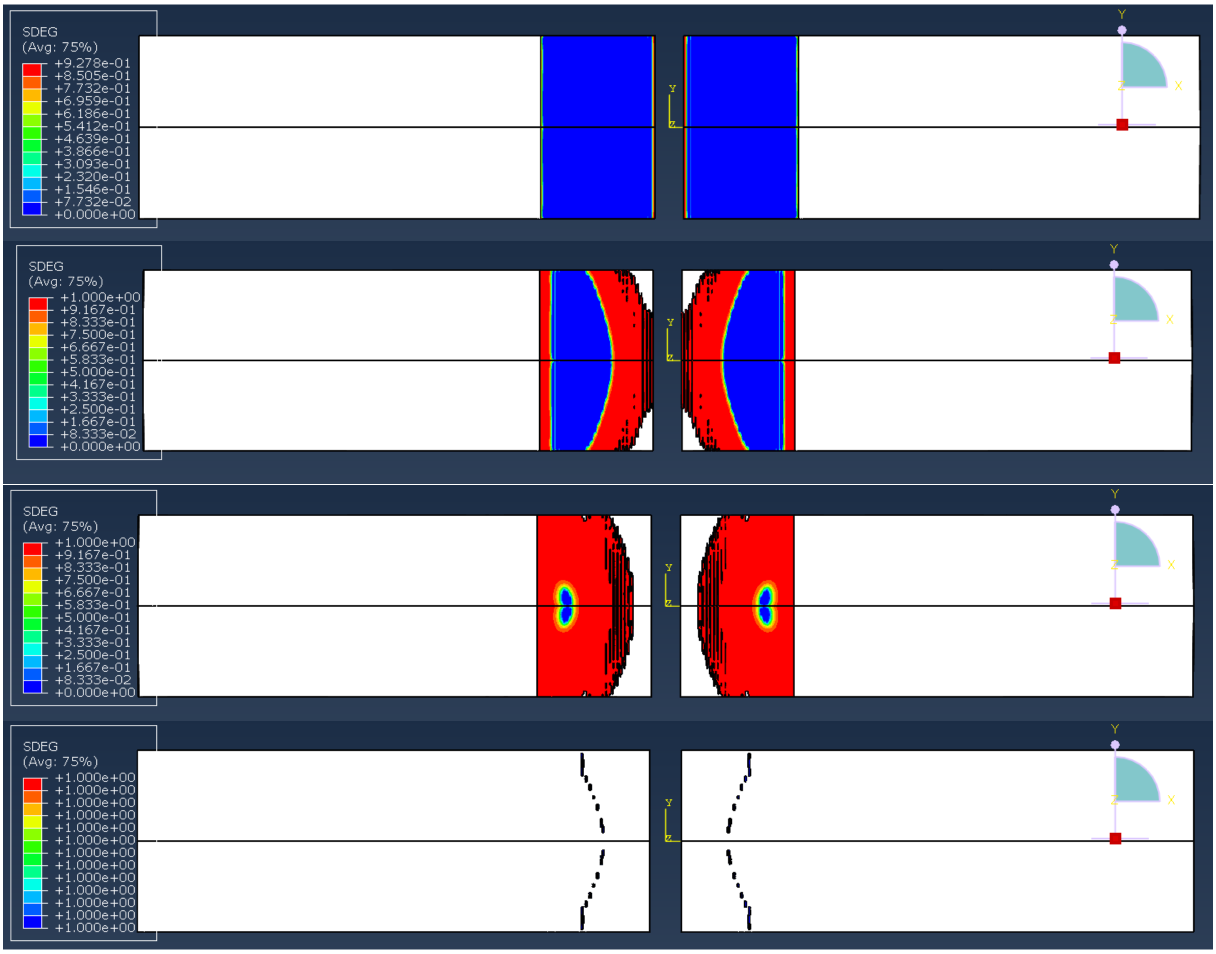

Figure 10: Abaqus Uniform Repair Model Cohesive Damage at Failure

A test campaign was setup for this double lap shear case. Parent laminate is prepreg material and cured in autoclave. The repair patch was wet laid up on the parent material no additional adhesive material was used. Universal tensile test machine was used to perform the test at RT/AR conditions. The load displacement diagrams of the test and FEM was compared in Figure 11. FEM results are in good agreement with the test results.

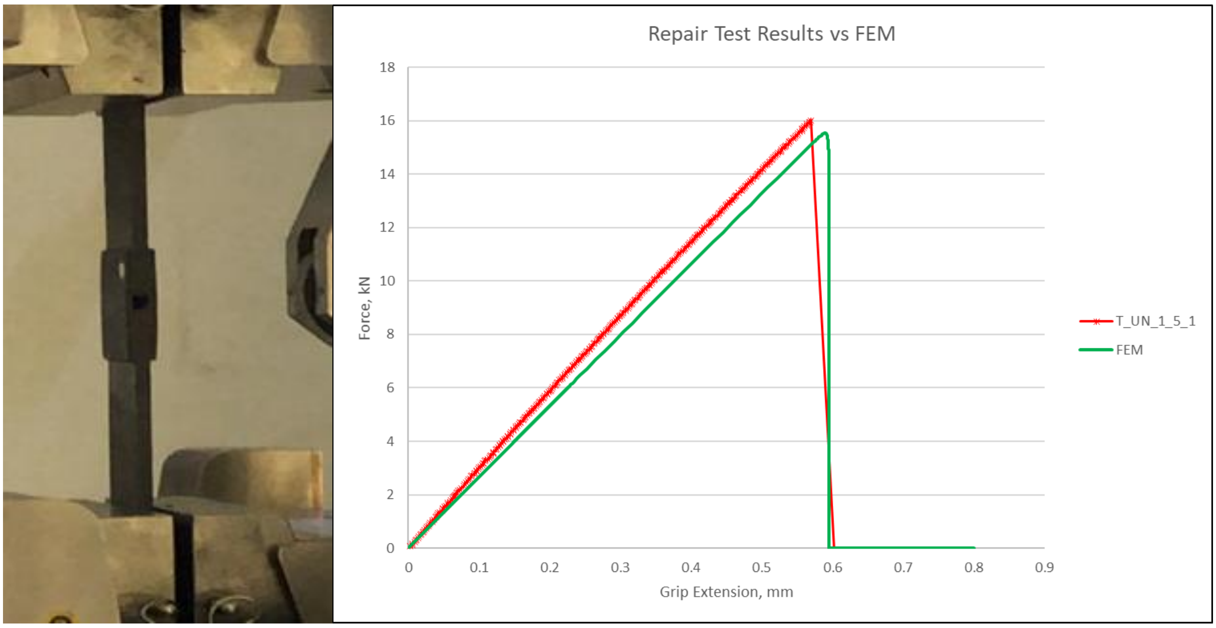

Figure 11: Abaqus Uniform Repair Model Load-Displacement Diagram vs Test Results

The failure loads calculated with Abaqus and Hand calculation are at the same order of magnitude but exact values.

The effect of the adhesive layer thickness
There are several parameters affecting the strength of the repair. The thickness of the adhesive layer affects the strength significantly. The comparison of the studies for adhesive layer thickness effect on strength of repair from FE CZM and analytical method is presented in terms of failure load.

Shear strain distribution along the bond line at failure load obtained by analytical solutions is provided in Figure 12. For lower thickness, just before failure, strain increase more steep at the edges and very low value at the middle with respect to x-direction. As the thickness increases the strain distribution becomes more evenly distributed. This requires much force to make the strain reach to failure value. This explains why the failure load increase with the thickness in analytical methods.

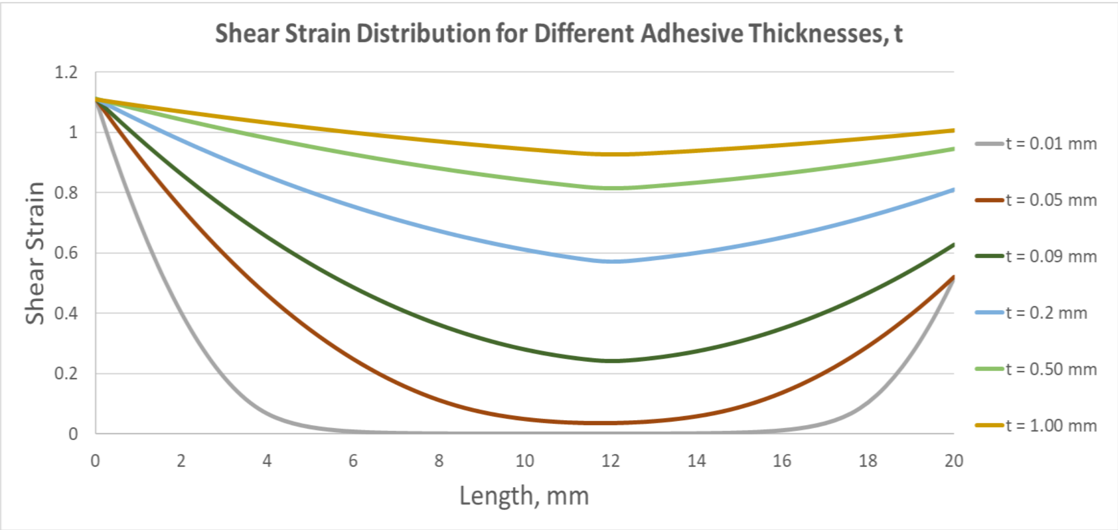

Figure 12: Analytical Shear Strain Results

The change in strength values of bonded repair with the thickness of the adhesive layer obtained from analytical solutions is provided in Figure 13.

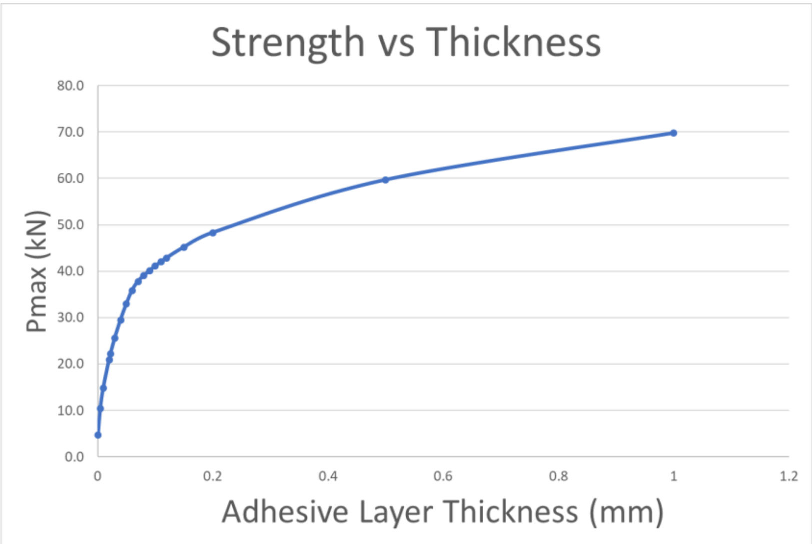

Figure 13: Strength vs Adhesive Layer Thickness According to Analytical Solution

FEM analysis was repeated for different adhesive layer thickness see Figure 14. All the other parameters are the same.

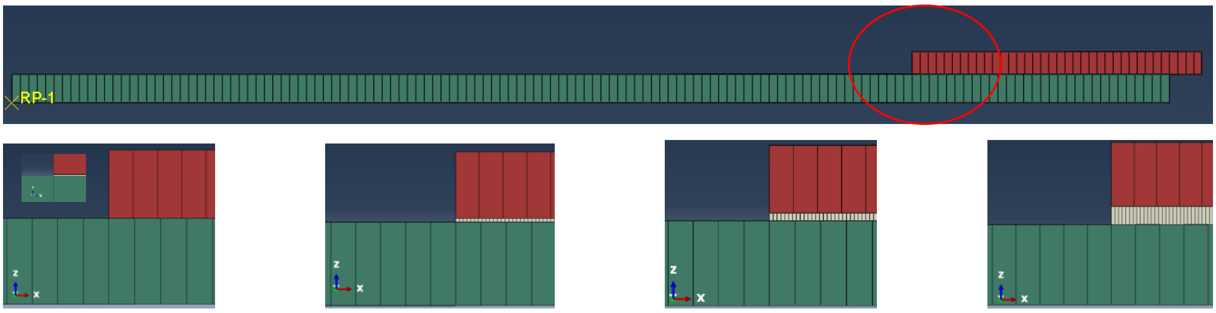

Figure 14: Strength vs Adhesive Layer Thickness According to FEM Solution

Similar to analytical solution, FE results shows that the strength increases with the thickness up to certain value. At 1.00mm thickness, strength slightly decreases with respect to the previous value.

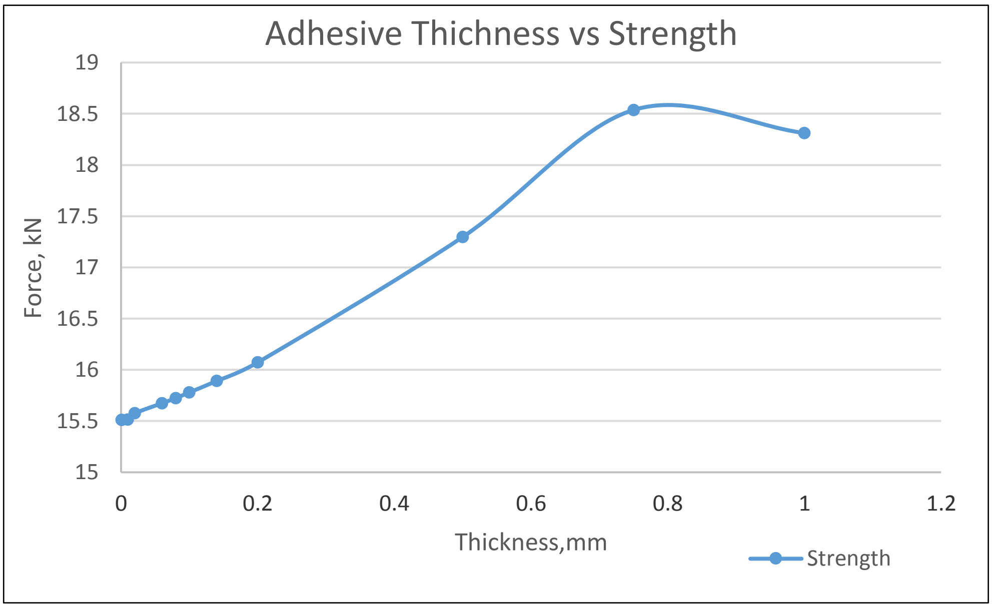

Figure 15: Strength vs Adhesive Layer Thickness According to FEM Solution

The failure load increase with the thickness for methods and converge to certain value asymptotically. This value is much higher in analytical methods than the FE method. The range of the strength variation in FEM is less than the analytical method.

Concluding remarks

There are many studies for bonded repair analysis in literature. This study aims to provide a comparison between FE and analytical methods to reveal advantages and disadvantages of the methods over each other. Analytical method is much faster and sensitive to adhesive layer thickness. On the other hand, FE method requires high computational cost. Material properties used in analytical method is slightly different than the FEM. For analytical method elastic strain limit and plastic strain at failure values are required. In FEM case G_{IC} and G_{IIC} values with mixed mode ratio parameters.

The effect of the thickness of adhesive layer on the strength of the repair is investigated and comparisons between the results obtained by Abaqus and analytical methods is performed. Strength increases as thickness increases for both methods. However, some experimental results in literature show the opposite. The following theories were proposed to explain this phenomenon. [Arenas, 2010]. According to Crocombe: [Crocombe, 1989] the plastic spreading of the adhesive along the overlap occurs more rapidly in thicker adhesive. [Adams and Peppiat,

1974] claimed that joint strength decrease with adhesive thickness due to thicker boundaries contains more defects such as voids and microcracks.
Consequently, both method predicts the failure loads in an acceptable range but increasing the thickness of the adhesive without changing any material properties might give misleading results especially in analytical method presented in this paper.

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