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TENSILE TESTING OF REPAIRED COMPOSITE SPECIMENS WITH DIC MEASUREMENT AND FEM CORRELATION

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ABSTRACT

Repairs of composite structures are widely used in aerospace industry and aerospace researches. There are many analytical and numerical studies in literature. For validation of the analyses, test correlations are mandatory.

Preparing repaired composite test specimens requires specific procedure to represent the repair conditions in actual structures. Abaqus, a widely used commercial finite element package in aerospace industry and aerospace researches, is utilized for numerical analyses. In this article, detailed procedure for preparation of wet layup repaired composite specimens, implementation of DIC system on tensile tests of different types of repaired composite specimens and comparative study of the results with the finite element analysis to validate the outcome of the numerical results is presented.

INTRODUCTION

The fiber reinforced composites became main material choice in aerostructures for their weight efficiency and manufacturing advantages over metallic materials. In parallel, big or small-scale damages on composite structures occur in large numbers inevitably. To ensure the structural safety, the damages should be repaired. Efficient and accurate solutions for repair in composites are required for safety of the structures, lowering the costs and shortening the time to market.

Prediction of the strength and the stiffness of repaired structure is mandatory from safety point of view. As well as analytical methods, numerical solutions are offered by many commercial finite element analysis, FEA, packages to analyze the strength of the repair. Abaqus, one of the most powerful tools for numerical solutions, is used for numerical analyses.

For validation of the analyses, test correlations are mandatory. Repaired composite specimens are prepared for tensile testing using wet layup methodology. One surface of the specimens are painted to form stochastic paint surface for DIC measurements, which is one of the best technique, where the strain varies on the repair patches. Comparison of strain and displacement results from FEM and test results will validate the numerical analysis in terms of stiffness.

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The objective of this paper is to present a comprehensive study to reveal the advantages and disadvantages of DIC measurement techniques on repaired composite specimen testing. Stiffness comparison via DIC measurement provide a validation to material properties, boundary conditions and element types. On the other hand, calculation prediction of failure modes and loads requires different methods in FEM such as cohesive zone method for delamination or debonding and progressive failure analysis for intra laminar failure modes, where expensive DIC system is not needed.

METHODOLOGY

After a detailed process of preparation of repaired composite test specimen is given, testing procedure with DIC system is explained. Finally, FE model and test correlation results are presented.

Specimen Preparation

Test specimens used in this article is proposed by [Ahn, 2000] for uniform and stepped double lap repairs as shown in Figure 1 and Figure 2, respectively.

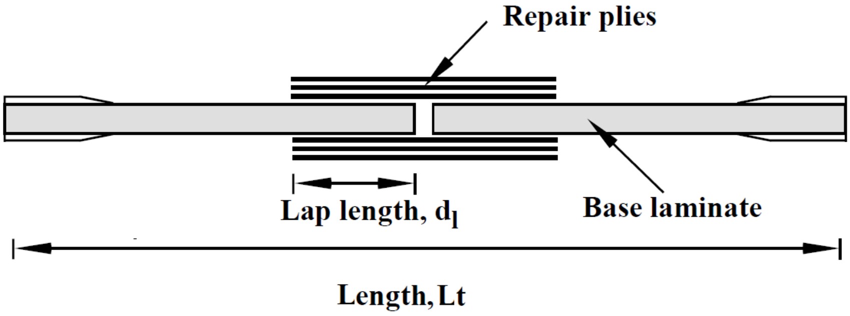

Figure 1: Uniform Double Lap Repair Tensile Test Specimen [Ahn, 2000]

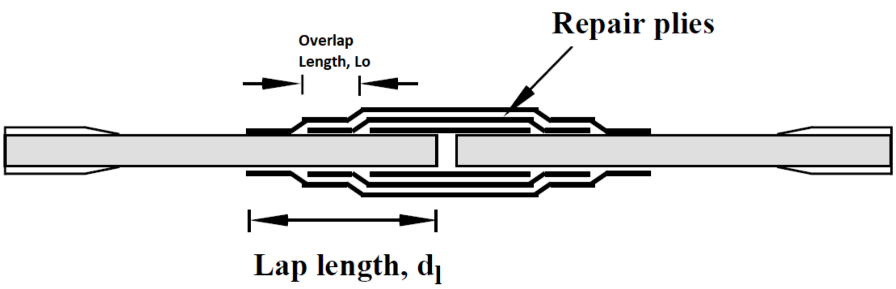

Figure 2: Stepped Double Lap Repair Tensile Test Specimen [Ahn, 2000]

Test specimens are composed of two parts, namely parent (Base laminate) and repair patch (Repair plies). Parent material is carbon fiber UD prepreg. The material is laid up by hand and cured in autoclave for construction of flat plate representing an intact aircraft structural part. In order to simulate the damage, part is divided into two equal parts. A mandrel which is cut from the plate is placed between two plates to provide 5.00mm gap between parent plates. The repair patch is laid up on to two parts of parent plate for a given stacking. Each set of specimens have same stacking for parent material but different stackings for repair patch. Also overlap lengths differs for all sets. Close to the edges of the parent material dummy patches are laid up to provide support while curing the other side of the repair. Note that, mandrel is covered by 2 layers of release band for easy removal after completion of the specimens, see Figure 3.

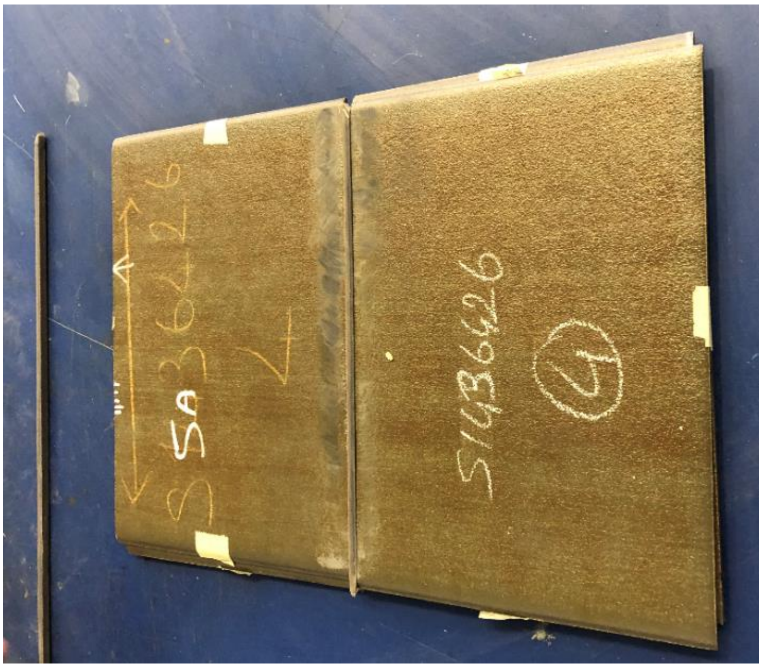

Figure 3 Parent flat plates and mandrel just before laying up the repair patch

The materials of the repair patch are a carbon-epoxy system. Dry carbon fabric material is wet laid up by epoxy resin. In this project used technique is as follows: Dry fabric is placed on to a release film. Then with correctly mixed and weighted epoxy, carbon fabric is wetted, evenly and another release film is placed on the carbon epoxy layer as shown in Figure 4.

Figure 4 Wet lay up of dry fabric

The wetted fabrics are cut with the help of templates to its final shape and given orientation. The release films are removed and cut fabrics are laid up to build repair patch as shown in Figure 5.

Figure 5 Repair pacth before placing on the parent material

Repair patch is placed on to the parent plate to its exact location which is already marked. Next important step, the vacuum bag is applied with heat blankets. To control the heat blanket, thermo-couples are placed on the part such that evenly distributed heat is ensured during the cure. Vacuum is applied under atmospheric pressure, Figure 6 .

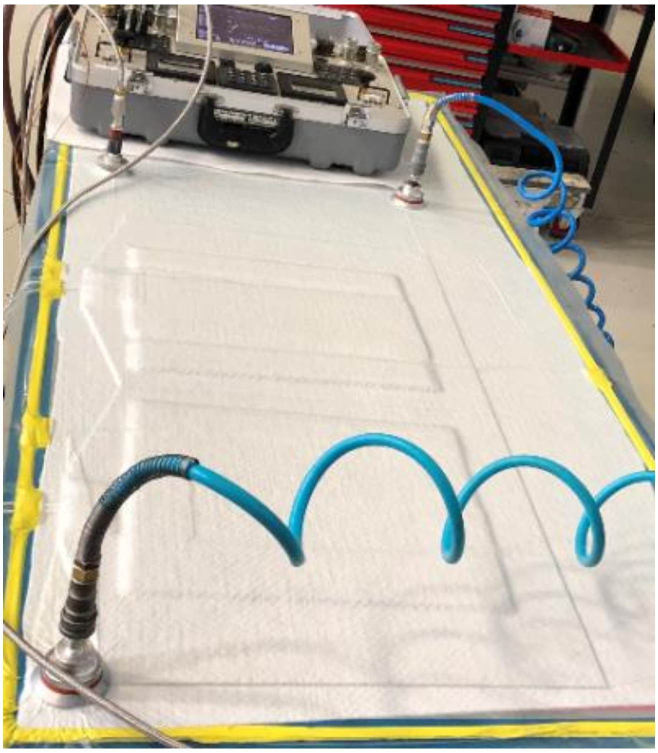

Figure 6 Curing of repair patch

Cure cycle is controlled with the help of specific machine which not only controls vacuum and temperature level to be constant during dwell time but also controls the ramp rate and cooling rate of the temperature. Cure cycle is taken from the specification sheet of the epoxy.

As the specimens are repaired on one side, all these processes are repeated for the other side of the repair.

Using this process, uniform and stepped double lap repair specimens are manufactured. Specimens gage area are prepared as stochastic paint surface for DIC measurements as shown in Figure 7.

Figure 7 Repaired Composite Test Specimens

In addition to repaired composite specimens, pure tensile test specimens with parent and repair materials are prepared for reference tests. Tensile tests are performed according to [ASTM D3039/D3039M, 2014] standard.

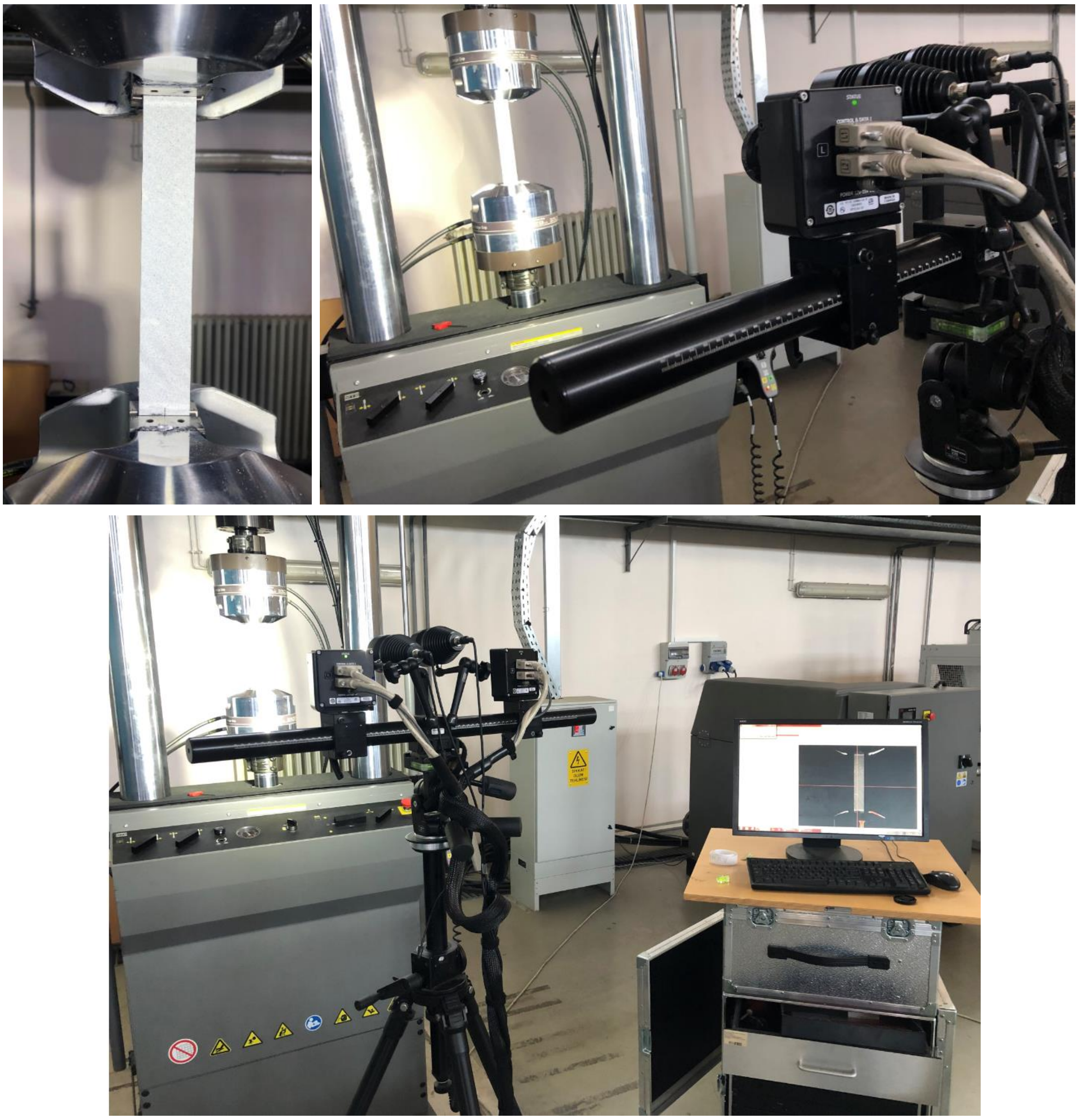
Figure 8 Tensile Testing Using DIC System

The longitudinal and transverse strain data on the stochastic paint surface is evaluated by ARAMIS software [ARAMIS v6.3 User Manual,2011]. Displacements are obtained at five different points. Two of them are located on the parent material next to the grips of the test machine. The area between these two points defines the total gage area. The other two points are on the parent material next to the repair patch. The area between these two points defines the repair gage area. The last point is on the repair patch in the middle of the total gage area. Using the displacement of these points, average strain values can be calculated for each region.

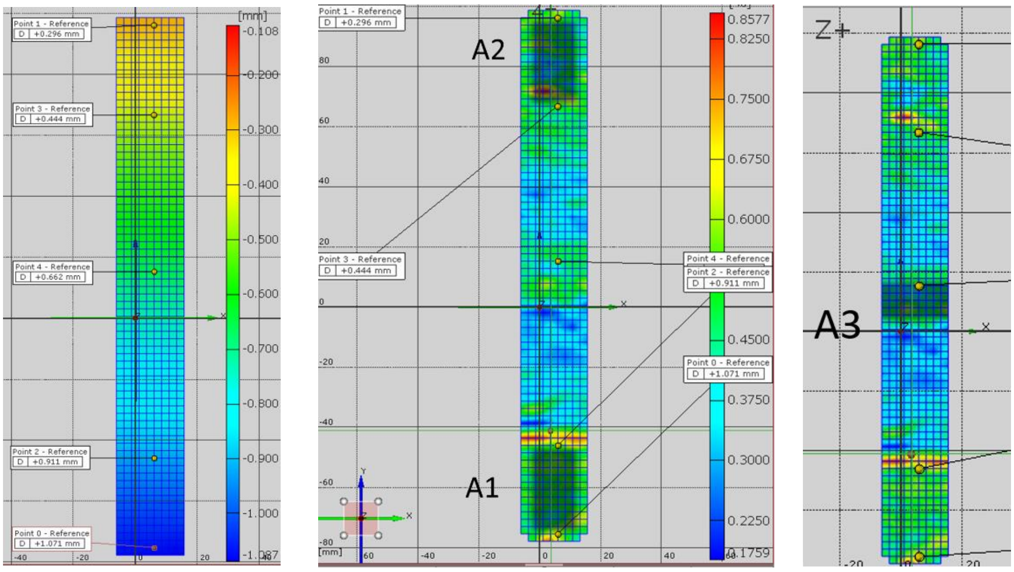

Figure 9 Test Results Evaluation Using DIC System

The average strain data are obtained for three different areas. The areas “A1” and “A2” are on the parent material. “A3” is on the repair patch in middle of the gage area where no parent material exists. Strains are measured in longitudinal and transverse directions. The size of the measurement area can be chosen according to the specimen geometry. The high strain gradient or high load transfer regions have to be excluded from the measurement to get correct measurement.

The repaired composite tensile test specimens have different strain regions due to the main load is transferred to the repair patch from the parent material and back to the parent material. Therefore, total gage area must be painted for DIC measurement. Consequently, different strain regions hence load transfer can be observed.

DIC measurement system used in this paper provides measurements from one side of the specimen. The back side measurements are important to prove that there is no bending effect during the test. Bending of the repaired specimens are very likely to happen, because of their production procedure explained above. One side of the repair patch is cured first and the other side is cured in another cure cycle. The measured specimens are in good alignment such that no bending effect is expected.

Finite Element Modeling of Repaired and Plain Tensile Test Specimens

For each specimen type, a separate FEM is prepared using ABAQUS 6.14. Four different models are used, first two models represent the tensile specimens without repair for parent material, see Figure 11, and repair patch, see Figure 10, separately. The remaining two models represent repaired tensile test specimens for uniform repair, see Figure 12, and stepped repairs, see Figure 13. Due to the symmetry 1/8th models is used as shown in Figure 10. Only the gage area, which can be defined as the area between the jaws of the test machine, is considered.

For all models, 3D solid (C3D8) elements are used. Each ply thickness is modeled with single element. Composite layup properties with single layer are assigned to the solid elements with the correct orientation. The symmetry boundary conditions are applied to the symmetry planes which are x-symmetry, y-symmetry and z-symmetry. Test machine jaws are assumed to be very stiff compared to the test specimen. Therefore, same displacement boundary conditions e.g., 0.4mm, to all nodes coinciding with the end surface are applied.

The first model for plain tensile testing, see Figure 10, is used for the repair patch material properties. The specimen is composed of 10 plies with all (0/90) orientation. Repair material is a plain fabric carbon epoxy material.

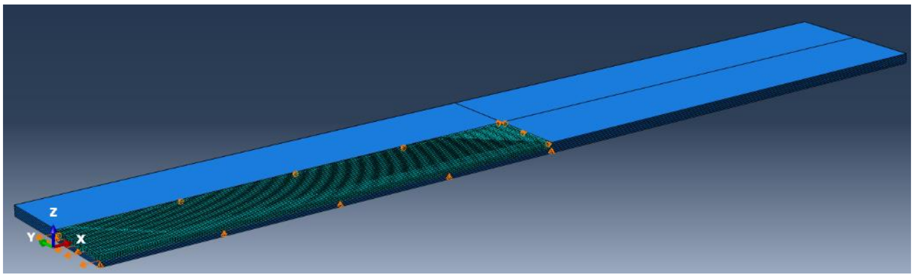

Figure 10 FEM for Plain Specimen of Repair Patch Material

The second model for plain tensile testing, see Figure 11, is used for the parent material properties. The specimen is composed of 24 plies with quasi isotropic properties, $[0/45/90/-45]_{3s}$. Parent material is a uni-directional carbon epoxy material.

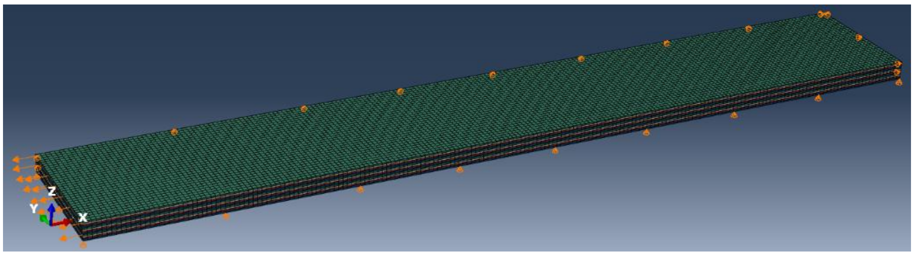

Figure 11 FEM for Plain Specimen of Parent Material

The third model represents the uniformly repaired tensile testing, see Figure 12. The specimen is composed of parent material part and the repair patch part. The parent material part has the same properties with the second model. Repair material part has 6 plies with the stacking $[(0/90)/(45/-45)/(0/90)]_s$. Overlap length of repair and parent parts is 20mm along loading direction. The distance between parent material parts is 5mm which represents the damage.

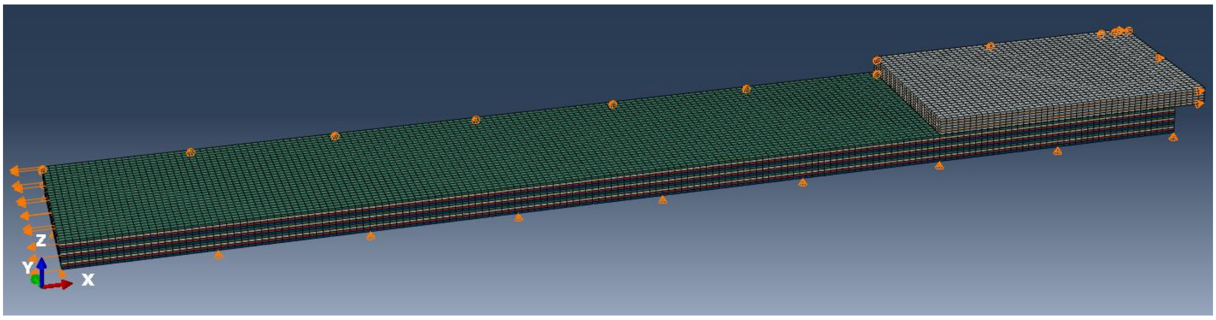

Figure 12 FEM for Uniform Double Lapped Repair Specimen

The last model represents the stepped repaired tensile testing, see Figure 13. The specimen is composed of parent material part and the repair patch part. The parent material part has the same properties with the second model. Repair material part has 6 plies with the stacking

[(0/90)/(45/-45)/(0/90)]$_s$. Overlap length of each repair ply on the parent part is 10mm along loading direction. Total overlap length is 60mm. The distance between parent material parts is 5mm which represents the damage.

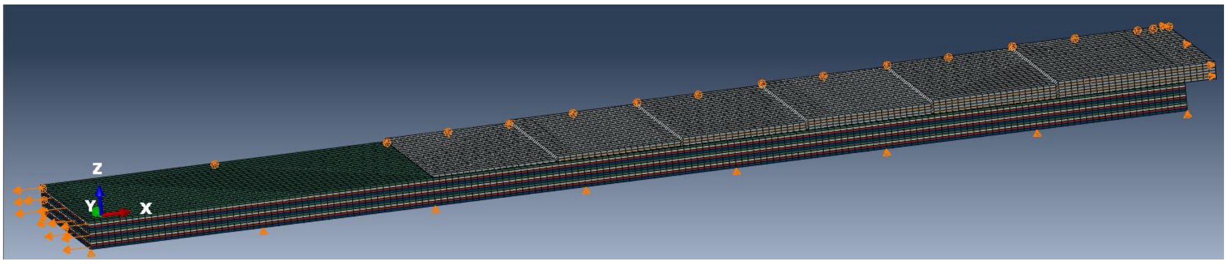

Figure 13 FEM for Stepped Double Lapped Repair Specimen

Test Results Correlation

Each test result is evaluated for the correct stiffness value.

First load - displacement graphs are plotted for all types of specimens. Displacement readings from actuator and from DIC measurement system are presented in Figure 14 and in Figure 15, respectively. Next, load strain diagrams are investigated for longitudinal strain, ε11, and transverse strain ,ε22 in Figure 16 and in Figure 17, respectively.

In figures following notation is used for clarity:

A: Parent material plain tension test specimen

B: Repair material plain tension test specimen

C: Uniformly repaired plain tension test specimen

D: Stepped repaired plain tension test specimen

There are differences observed in the load-displacement curves obtained from FE analyses and the test machine results. The load value of the test results are obtained from the actuator reading and similarly displacement results are read by from the actuator displacement values. The differences between two curves can be explained by the compliance of the test machine. The below figures reveal that the test machine provides more compliant results for all type of test specimens

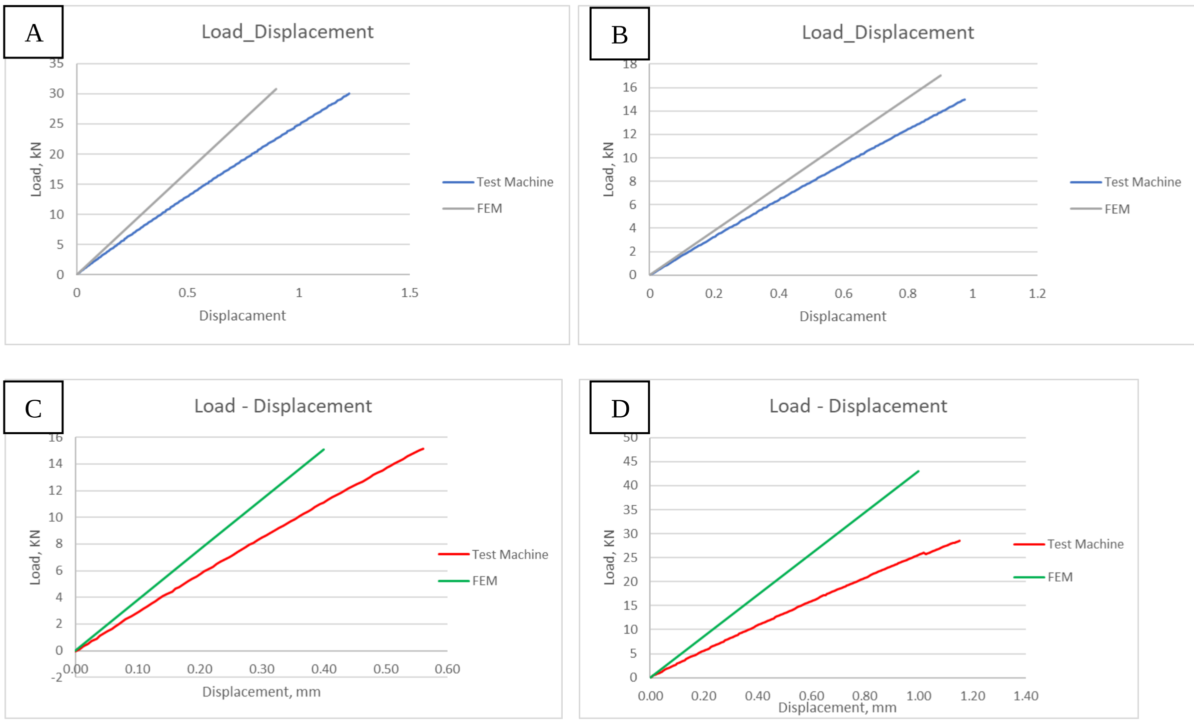

Figure 14 Load - Displacement Graphs from Test Machine

To overcome the test machine compliance effect, direct displacement measurement on the specimen is taken with the help of DIC system. The positions of upper most and the lower most measurement points are recorded at zero load level. The ratio of gage length and their distance gives a correlation factor, which is applied to the displacement value at each load level. The displacement value is the difference of the distances between two points at the present load level and the zero load level. The load – displacement curves obtained with this methodology are in good agreement with the FEM results for all type of test specimens.

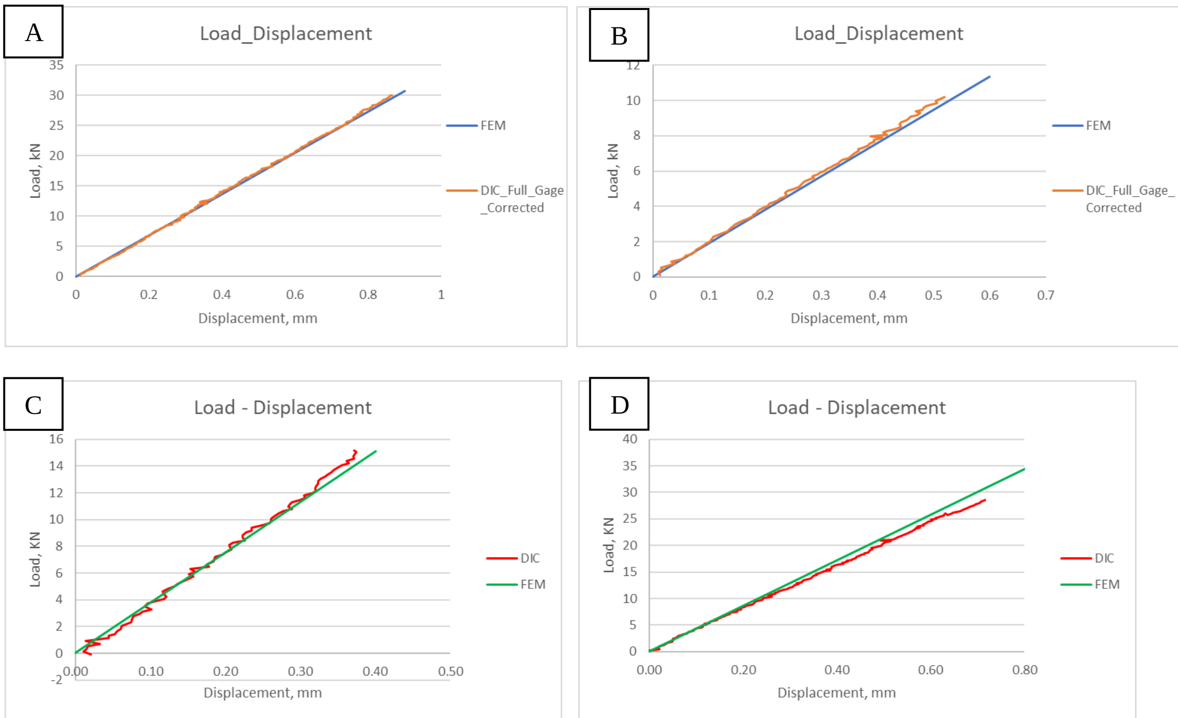

Figure 15 Load -Displacement Graphs from DIC system

The strain readings from DIC system is directly compared with FEM readings for corresponding data evaluation region as shown in Figure 16 for loading direction, ε11, and in Figure 17 for transverse direction, ε22.

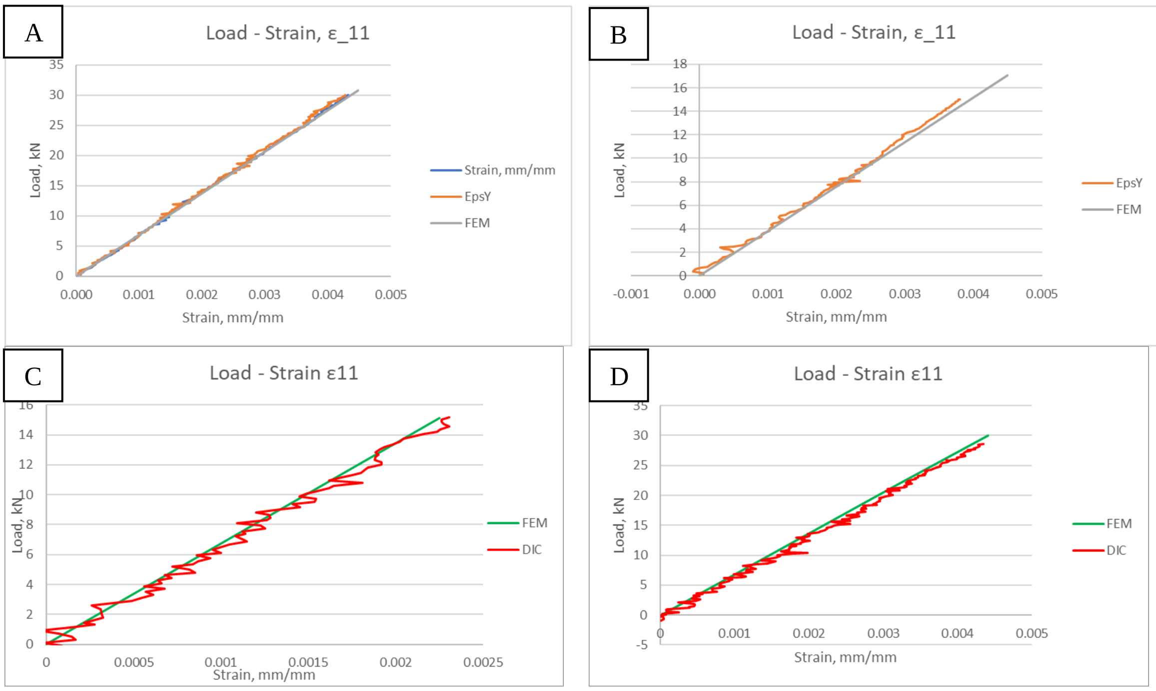

Figure 16 Load -Strain Graphs for Loading Direction

Transverse direction strains (ε22) will provide the information for Poisson's ration v12. As the strain values are small compared to loading direction more fluctuations are observed on the test readings. However, the main trendline curves are in good correlation with the FEM results.

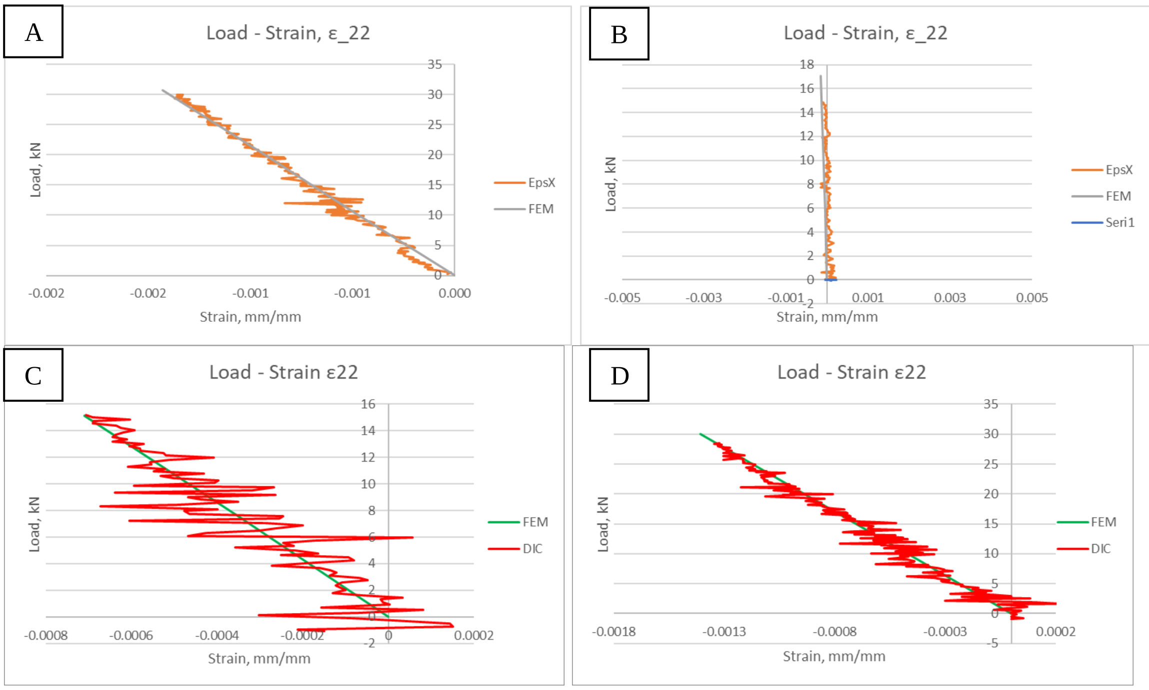

Figure 17 Load -Strain Graphs for Transvers Direction I

Concluding remarks

There are many studies for tensile testing and FEM correlation in literature. This study aims to provide a special comparison between FEM and testing of composite repaired specimens. The DIC measurement provides more reliable displacement results over the test machine displacement reading. The machine compliance is very important for high modulus tensile testing. The disadvantage is that, DIC reading requires more pre and post studies. One sided reading is another drawback.

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