Effect of Strain Rate on Adhesively Bonded Single Lap Joints

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ABSTRACT

In this paper, the effect of strain rate on adhesively bonded single lap joints of similar and dissimilar adherends (Aluminum and Carbon fiber composites) with several adhesives was investigated. The experiments were conducted based on three different sets of substrate combinations that included 1) Al 6061 – CFRP, 2) Al 6061–Al 6061 and, 3) CFRP-CFRP using three different adhesives that included a high strength epoxy, a quick set epoxy, and a urethane-based adhesive. The manufactured single lap joints were initially tested under tensile loading conditions using a screw-driven universal tensile machine to achieve strain rates of 0.0015 s^{-1} and 0.15 s^{-1}. Here, the bond strength and peak loads were determined. Furthermore, using the digital image correlation (DIC) system, the local and global strain distributions were investigated within the adhesive bond line. Initial results revealed a clear effect of strain rate on the peak load and shear lap strength. In addition, DIC analysis revealed evidence of strain concentrations at the lap ends as well as major strain distributions within the weld line. Furthermore, a combination of adhesive and cohesive failure modes was evident after low magnification analysis. Finally, these results can be utilized for analysis and design purposes of adhesive joints of similar and dissimilar materials that may be subjected to various strain rates.

1. INTRODUCTION

Adhesively bonded composite single and double lap joints are widely used in the aerospace and automotive industry for structural and assembly joining (1). These joints should be able to resist impact loads, providing high impact strength and high deformation before failure. The joints must therefore be able to absorb substantial amounts of energy during impact, but at the same time be capable to maintain the integrity of the structures. Adhesive joints are an improved alternative to mechanical joints in most of the engineering applications as they provide uniform stress distribution along the bonded area which enables higher stiffness and load transmission. Typical values of strength of the adhesives varies from 5 MPa up to 50 MPa. However, in the literature it indicated, larger the bonding area higher the strength of the lap joint (2). Failure modes occurring in an adhesive are mostly cohesive or adhesive failure. Adhesive failure occurs due to the intermolecular forces acting between adherend and adhesive while the cohesive failure is due to

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the intermolecular forces inside the adhesive or adherend (1). In order to achieve a good level of interfacial strength, surface preparation on substrates, joint configuration and adhesive properties have to be considered (1). An appropriate surface treatment must be used to achieve to maximize the molecular contact between the substrate and adherend during the bonding process as this gives high surface area energy. Manual roughening of the bonding surface and cleaning with a degreaser is an example of a surface treatment (3). Gentey and Aufry stated that using a sol primer and degreasing/HNO_3 increases the failure load (4). In addition, it has been found that good surface preparation (i.e. a good surface treatment combined with a good primer application) not only increases the load at break but it also increases the reliability of the results (5-7). Sensitivity to rust is a crucial factor to consider while preparing the surface of the substrates. Yoa and Zu polished steel plates on both sides to remove any rust within the bond area and then applied acetone to the steel plate to further clean the surfaces (5). Adhesives can be categorized using a wide range of parameters. When considering the functionality of adhesives, these materials can also be classified as structural and non-structural. The difference between structural adhesives and non-structural adhesives is that structural adhesives have high strength to support high loads. Epoxies, phenolic and urethanes are examples of structural adhesives, and synthetic rubbers and polyesters are examples of non-structural adhesives. Epoxy resins are one of the most common types of adhesives used to bond dissimilar metals as they exhibit low creep, high toughness, good corrosion and chemical resistance, good gap filing capabilities, good heat resistance, low cost and flexibility in the joint design (8-10).

Joints should be designed in order to minimize stress concentrations. As a result, research works have mostly focused on uniform shear stress distributions in the adhesives to attain higher failure loads at break. It has been found that the joints made with high strength adhesives are more likely to fail prematurely in the composite before failure in the adhesive occurs (10). When the joint is very large then the adhesive selected should have a cure time that is sufficiently long to allow for the application time (1). Curing time for the adhesives is different for different applications. Halliday studied about the shear strength and facture toughness for different curing time and temperature ranging from 20 days to 423 days and found out that when the joint is aged in water at 70˚C for 423 days the shear strength was reduced by 25 % and the fracture toughness was reduced by 15% (3). The adhesive thickness also plays a major role in determining the strength of the joint. Research experiments have been conducted to investigate the effect of adhesive thickness on the strength of SLJs (11,12). An increasing fracture toughness with increasing adhesive thickness for single lap joints was found, as well as decrease in lap-shear strength as the adhesive layer thickness increases for ductile adhesives (9).

A number of research projects have been conducted in order to investigate on the effect of joint geometry, overlap length, adhesive thickness and it was found that as the overlap length increased, the ultimate failure load increased as well, as did the equivalent stiffness of the joint (4-13). Moya-Sanz studied different geometrical configurations of single-lap joints, such as adherend recessing and chamfering of the adherends and adhesive effect on the mechanical strength of the joint in terms of failure load, eccentricity of the load, and the peak peel stress and concluded that the depth recess was found to be the responsible for reducing peak peel stress because of the decrease in the cross-section at the end of the overlap (2). Ying Yan investigated the tensile performance of adhesively bonded single CFRP lap joints and predicted the failure modes and damage initiation to be adherend delamination failure, sometimes accompanying with some fiber pull-out was also found (13). Anyfantis used strain gage sensors to study damage initiation occurring in the adhesive bond line and concluded that for single lap joints, the effect of the adhesive thickness and stiffness ratio is negligible compared to the effect of the overlap length to the stiffness and strength of the joints (10).

Yao and Zhu test FRP/steel hybrid lap joint under different temperatures and different strain rates ranging from 0.625, 1. 25, 2.5, 5 m/s. The dynamic behaviour at different loading speeds was captured using Phantom v7. 3 high speed digital camera at a sampling rate of 20,000 frames per second (fps), and analyzed using a digital image correlation (DIC) method. Here, the average bond strength, toughness, bond strength displacements and FRP strain distributions were presented. It was concluded that the bond strength increased with the loading speed and the same trend was followed regarding shear stiffness. It was also obsevred that a high strain region was located near the joint edge where the load is applied as compared to the center of the overlapping area (5). The specific location and magnitude of the maximum principal strain in the adhesive fillet region were determined using high magnification 2D DIC (14).

2. EXPERIMENTATION

In this research project, a number of experiments were conducted on single lap joints based on similar and dissimilar adherends. The materials used include aluminum 6061 with a thickness of 2 mm and woven carbon fiber composites (Figure 1) with a thickness of 1.58 mm.

Figure 1: Woven carbon fiber/epoxy composite.

In order to bond the similar and dissimilar substrates, three adhesive systems were used, these include a quick-setting epoxy two-part urethane adhesive system and two high strength, two-part epoxy adhesives where one of them has a cure time of 45 min at 140˚ F and other is a quick set epoxy. All the adhesives chosen were two-part adhesives as they are stable at room temperature prior to mixing.

The ASTM D1002 (15) and D5868 (16) standard test methods were used to investigate the apparent shear strength of single-lap-joints of adhesively bonded metal specimens by tension loading of similar and dissimilar adherends. Figure 2 shows a schematic representation of SLJ geometry used in this research project. Here, the recommended overlap length was 12.7 ± 0.25 mm and the computation for maximum permissible length was provided which showed that an overlap length of 15.5 mm would be permissible for the adherends chosen (15).

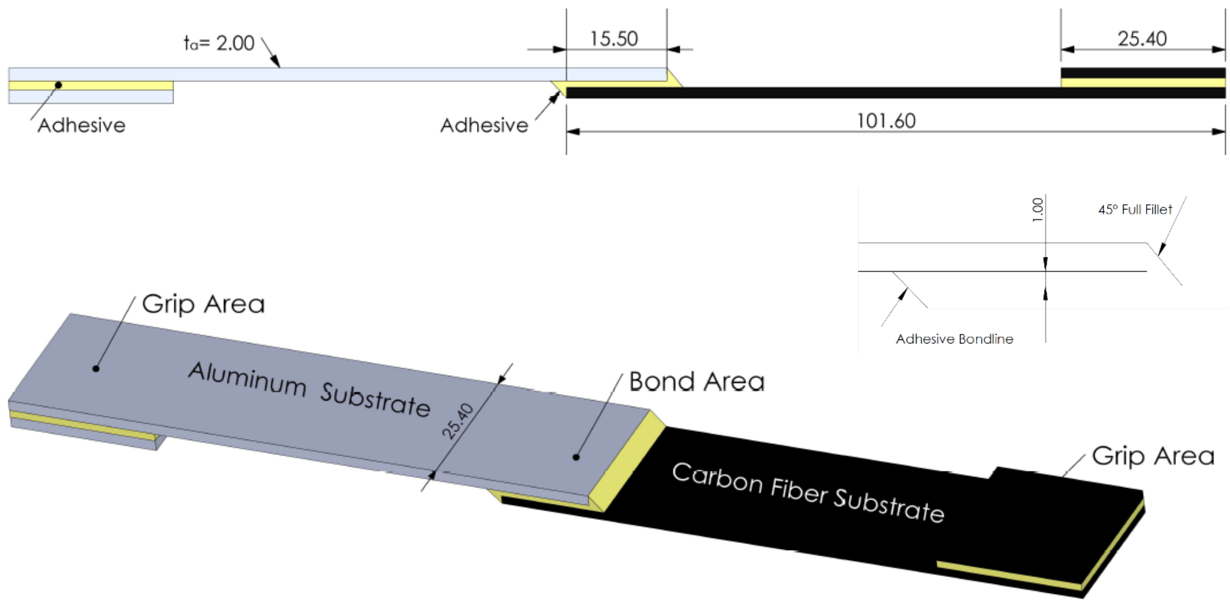
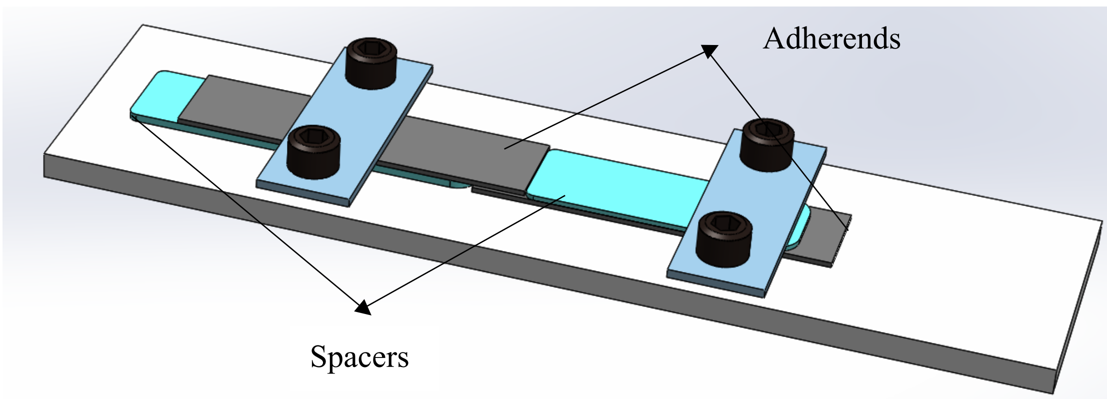


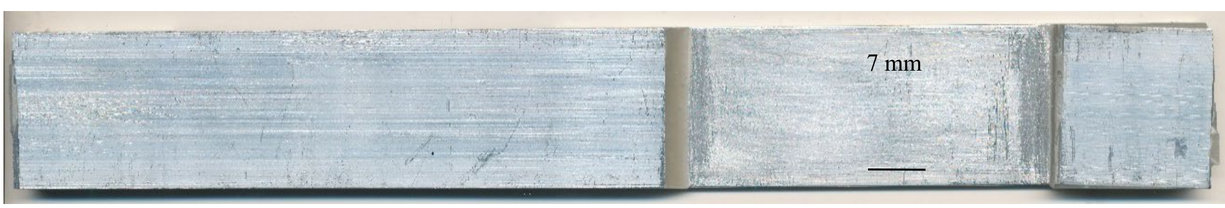
Figure 2: Single lap joint geometry (not to scale, dimensions in mm).

Here, the substrates such as aluminum and carbon fiber composites were cut with dimensions of 101.6 × 25.4 mm. The carbon fiber substrates were cut using a water-cooled disk cutter whereas the aluminum panel was cut using a hydraulic horizontal metal cutting band saw. A sanding operation was performed to the bonding area with a 180 Grit silicon carbide abrasive sheet. The sanding operation was performed in order to remove any oxide layer formed and to increase the substrate roughness. Following this, the abraded bonding area was cleaned and degreased using acetone for three times.

A lap joint fixture was designed to manufacture all the specimens in a similar manner as shown in the figure 3a. The adhesive bond line thickness was controlled by using chamfered spacers in order to keep the thickness uniform. The use of chamfered spacers is one of the most effective ways to control the bond-line thickness and reduce the peel stress. The angle of the fillet was chosen to be 45° (17). All the chamfered spacers were of the exact thickness required to produce a bond-line thickness of 1 mm for each joint. Then, the two-part adhesive was mixed as per the manufacturer's instructions and applied to the bond and grip area of the bottom panel. The top panels were placed in position and pressure was applied, the excessive adhesive was removed, and the lap joint was allowed to cure for the required time and temperature. The high strength epoxy was cured for 45 min at a temperature of 140˚ F, the quick set epoxy was cured for one hour at room temperature with applied pressure and fully cured in one day and the urethane adhesive took 45 min at room temperature to fully cure. After the cure time was achieved and the adhesive was well set, the spacers were removed, and the lap joint was sanded using a polishing machine to remove any excessive adhesive oozed out during the curing cycle. The specimens were then cleaned with water to remove dust accumulated during polishing. Three sets of each combination were manufactured (Figure 2b).



(a)



(b)

Figure 3: (a) Lap joint fixture overview (not to scale) (b) Manufactured lap joint

After successfully fabricating the specimens using the required cure temperature and pressure, the specimens were ready for tensile testing. A total of nine combinations were chosen which differ in the adherend combination and adhesive type. A nominal adhesive thickness was chosen as 1 mm after performing a round of quasi static testing of SLJ 1 with three different adhesive thickness (0.5 mm, 1.00 mm, 1.5 mm). Initial experimental results shown in the figure 4, for the single lap joints clearly highlight that thickness of 1.00 mm showed the maximum values of lap shear strength indicated by peak failure load and hence was chosen as a parameter to perform the experimental study. Table 1 shows the SLJ Systems investigated in this research project under tensile loading conditions.

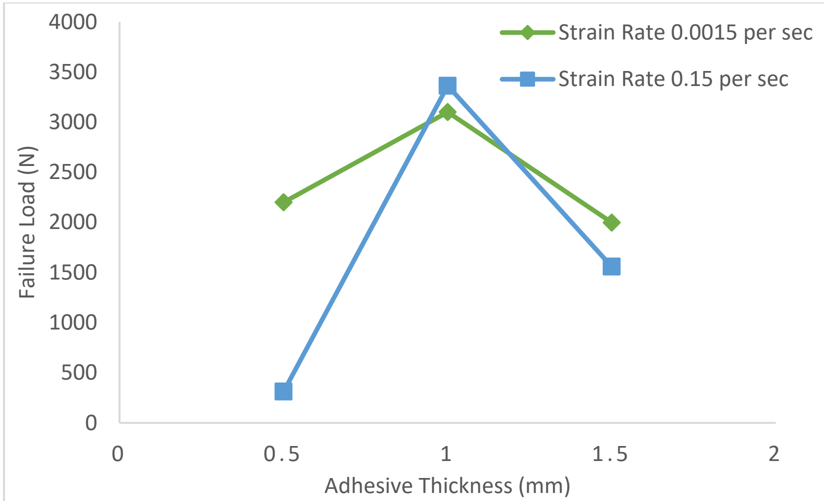
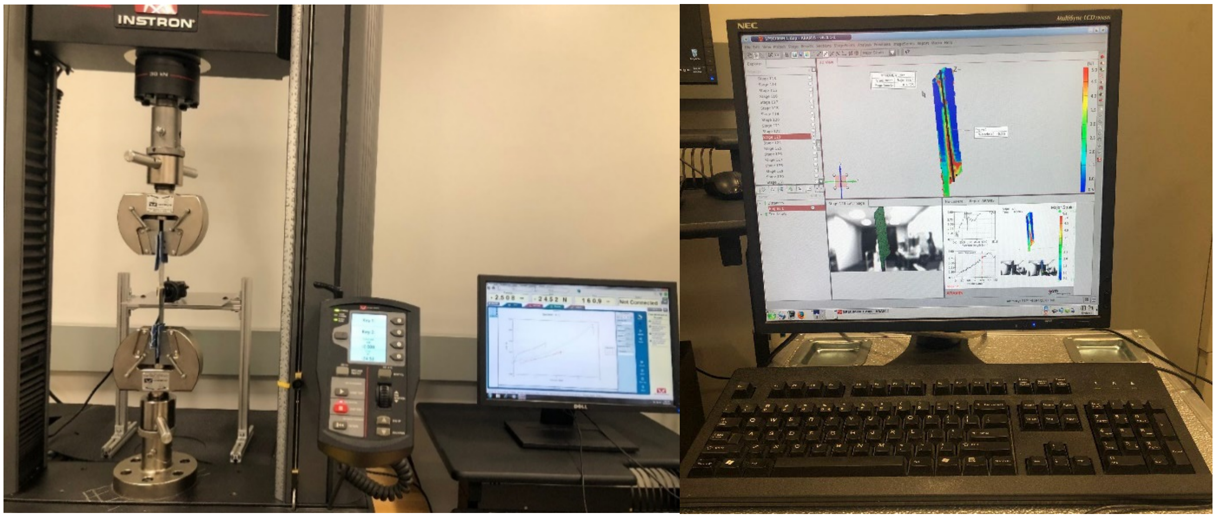


Figure 4: Effect of adhesive thickness for Aluminum - Aluminum SLJs.

Case	Substrate 1	Substrate 2	Adhesive Thickness	Overlap Length	Adhesive Type
SLJ 1	Al 6061	Al 6061	1.00 mm	15.5 mm	Quick Set Epoxy
SLJ 2	Al 6061	CFRP	1.00 mm	15.5 mm	Quick Set Epoxy
SLJ 3	CFRP	Al 6061	1.00 mm	15.5 mm	Quick Set Epoxy
SLJ 4	Al 6061	Al 6061	1.00 mm	15.5 mm	High Strength Epoxy
SLJ 5	Al 6061	CFRP	1.00 mm	15.5 mm	High Strength Epoxy
SLJ 6	CFRP	Al 6061	1.00 mm	15.5 mm	High Strength Epoxy
SLJ 7	Al 6061	Al 6061	1.00 mm	15.5 mm	Urethane Based System
SLJ 8	Al 6061	CFRP	1.00 mm	15.5 mm	Urethane Based System
SLJ 9	CFRP	Al 6061	1.00 mm	15.5 mm	Urethane Based System

Table 1: SLJs considered investigated under tensile loading conditions

Experimental tests were conducted on a screw-driven universal tensile testing machine at a strain rates of 0.0015 s^{-1} and 0.15 s^{-1} which account to a crosshead speed of 1.4 mm/min and 140 mm/min. During the testing, the load and displacement values were recorded using an Instron 4958 (Fig. a). Additionally, local and global strain distributions were monitored using a non-contact strain measurement technique known as DIC (Digital Image Correlation) as shown in figure 5b. In this research, DIC was mainly used to analyze and document deformations to understand the behavior of the lap joint during tensile loading conditions. The analysis of lap joint was done using a 2D measurement technique which required the calibration of a single camera. For this project, the images were captured using a single digital camera of frame rate of 2 fps for a strain rate of 0.0015 s^{-1} and 60 fps for a strain rate of 0.15 s^{-1}. To analyze the image in the DIC Software, the specimen needs to be prepared with a high contrast stochastic pattern with typical spray paint to clearly allocate the pixels in the image as shown in figure 6. These images were imported in the 2D project and linearly computed using appropriate facet size and facet step. The software used a correlation algorithm and tracked the grey values in the local facets and hence calculated the transformation parameters and deformation facets were determined. Following this, a post processing technique was used to export the linear technical strain which was derived from the strain gradient tensor and then the stress vs strain graphs were plotted accordingly.



(a) (b)

Figure 5: (a) Experimental setup for quasi static testing (b) GOM Correlate Software Snapshot

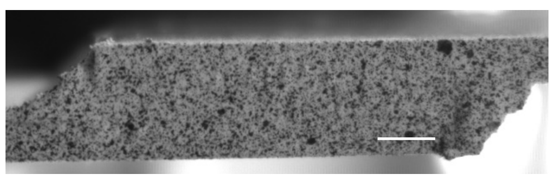


Figure 6: Typical speckle pattern required for the deformation analysis on DIC.

3. RESULTS

In this research project, the effect of strain rate on adhesively bonded single lap joints was investigated under various loading conditions. The specimens were tensile loaded under displacement control at two different strain rates of 0.0015 s^{-1} and 0.15 s^{-1}. Here, a number of different combinations of adhesives and substrates were experimentally used to analyze the breaking load and deformation behavior of each combination of substrates and adhesives. During testing, the load and displacement data was recorded.

Figure 7 shows the peak load of SLJ systems tested under tensile loading conditions at varying strain rates. These experimental results clearly reveal an effect of strain rate on the peak load of the SLJ systems investigated in this study. Furthermore, it is evident that such effect is more pronounced on the urethane based adhesive systems with the peak load increasing from approximately 1200 N to value of almost 5000 N for the Al – Al joints and reaching maximum values close to 9000 N for the CFRP - CFRP joints.

In order to get a better understanding of the mechanical behavior of the SLJ systems investigated in this study, a non-contact digital image correlation system was used to monitor the deformation of the joint along the bond-line region. Initially, a virtual strain gauge was placed on the bond region and oriented parallel to the loading axis. The technical strain measured by this method was used in combination with the stress calculated from the recorded level.

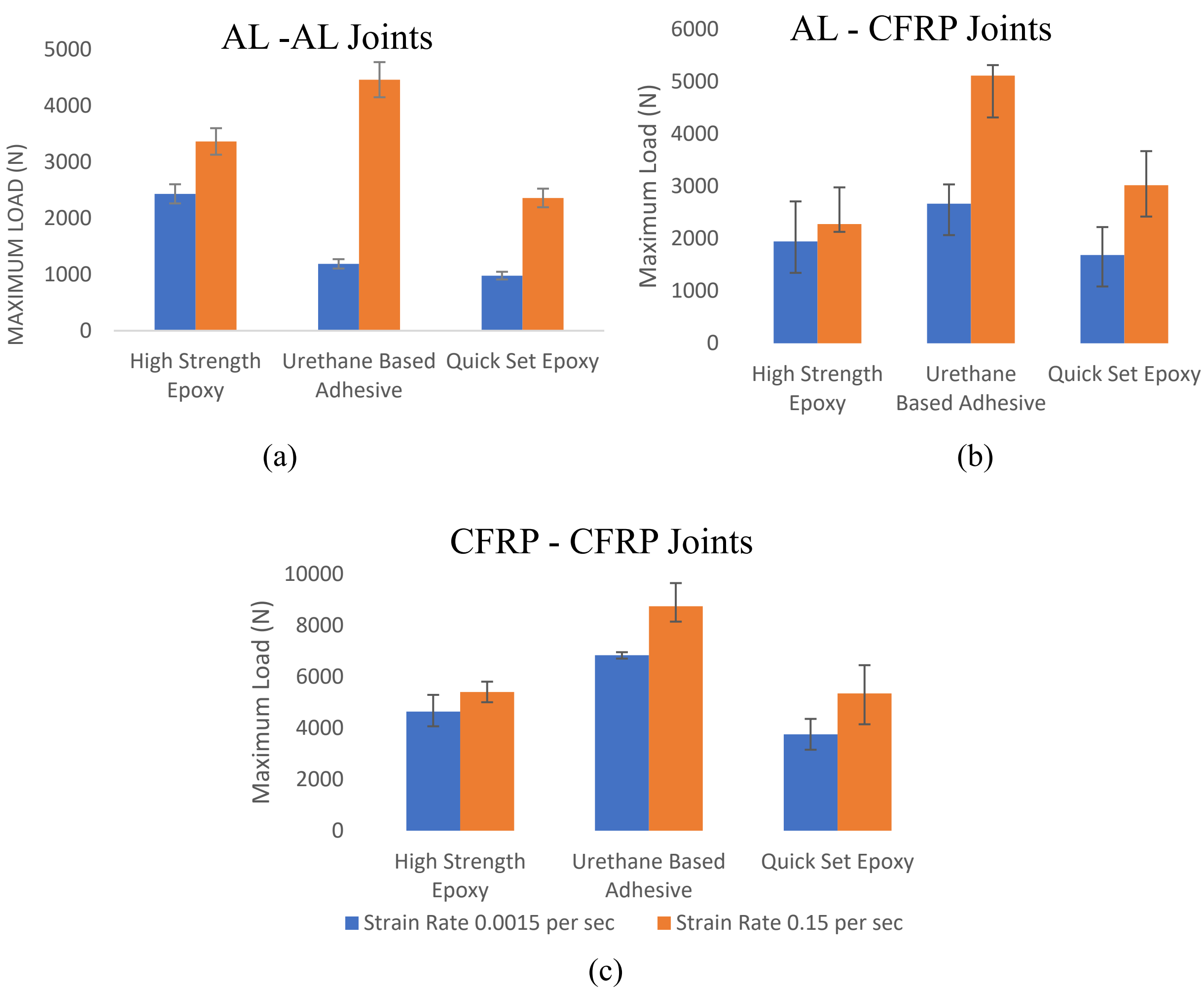


Figure 7: Average peak load of SLJ systems tested under tensile loading conditions at varying strain rates.

Figure 8 shows typical stress strain graphs of the single lap joints systems investigated under tensile loading at a strain rate of 0.0015 s^{-1}. From the figure, it is evident that for the Al-Al Lap joint with high strength epoxy shows the highest the maximum lap shear strength of approximately 7 MPa and peak strain of approximately 1.6% whereas the similar adhesive with quick set characteristics showed lower shear strength of approximately 2.5 MPa. In addition, it is evident that urethane adhesive has shown to have double the ductility than the epoxy adhesives i. e. 2.6 % and lap shear strength of approximately 3.2 MPa. When analyzing the experimental results of Al-CFRP joints, the maximum lap shear strength among the three adhesives was highest for urethane adhesive at approximately 7.23 MPa. The two epoxies had almost similar lap shear strength with high strength epoxy averaging 4.95 MPa and the quick set epoxy averaging 4.28 MPa. Similar to the Al-Al substrate combination, even here the urethane adhesive joint (SLJ 8) had shown the highest ductility with an average peak strain of 1.49 % whereas the high strength epoxy had the lowest peak strain i. e. 0.25 % and had a brittle type of fracture. After testing the CFRP- CFRP combinations, the peak shear strength of the urethane adhesive was approximately 17.49 MPa with an average peak strain of approximately 3.03 % followed by the quick epoxy set with an average shear strength of 8.23 MPa and peak strain of 1.82% then the high strength epoxy exhibited an average lap shear strength of 10.82 MPa and an average peak strain of 0.58%. These results clearly highlight the importance of considering the adhesively bonded joint as a system. The interaction between adhesives and substrates results in joints with different characteristics and different mechanical properties. Here, the combination of urethane-based adhesive boned to CFRP substrates offered significant values of bond strength under SLJ loading conditions of quasi – static loading rates.

Figure 9 shows the typical stress vs strain graphs of the single lap joints investigated under tensile loading conditions at a strain rate of 0.15 s^{-1}. From the figure, it is evident that when analyzing the trend for all the cases of lap joints for different substrate combinations, a similar behavior is apparent. Here the urethane-based adhesive exhibited the highest lap shear strength and highest peak strain followed by quick set epoxy and finally high strength epoxy. Furthermore, from the graphs, it is evident that as the strain rate increased, the quick set epoxy exhibited a decrease in strain to failure with an associated increase in shear strength when used to bond the CFRP to itself and to Al. However, when used to bond Al - Al, the increase in the shear strength was not associated with a decrease in strain to failure, once again highlighting the importance of adhesive - substrate interaction on the overall behavior of the joints under varying strain rates under tensile loading conditions. Finally, it was revealed that the single lap joints were able to withstand a higher levels of shear stresses as the strain rate was increased suggesting that they could be considered for application that may be subjected to quasi-static or quasi-dynamic loading rates.

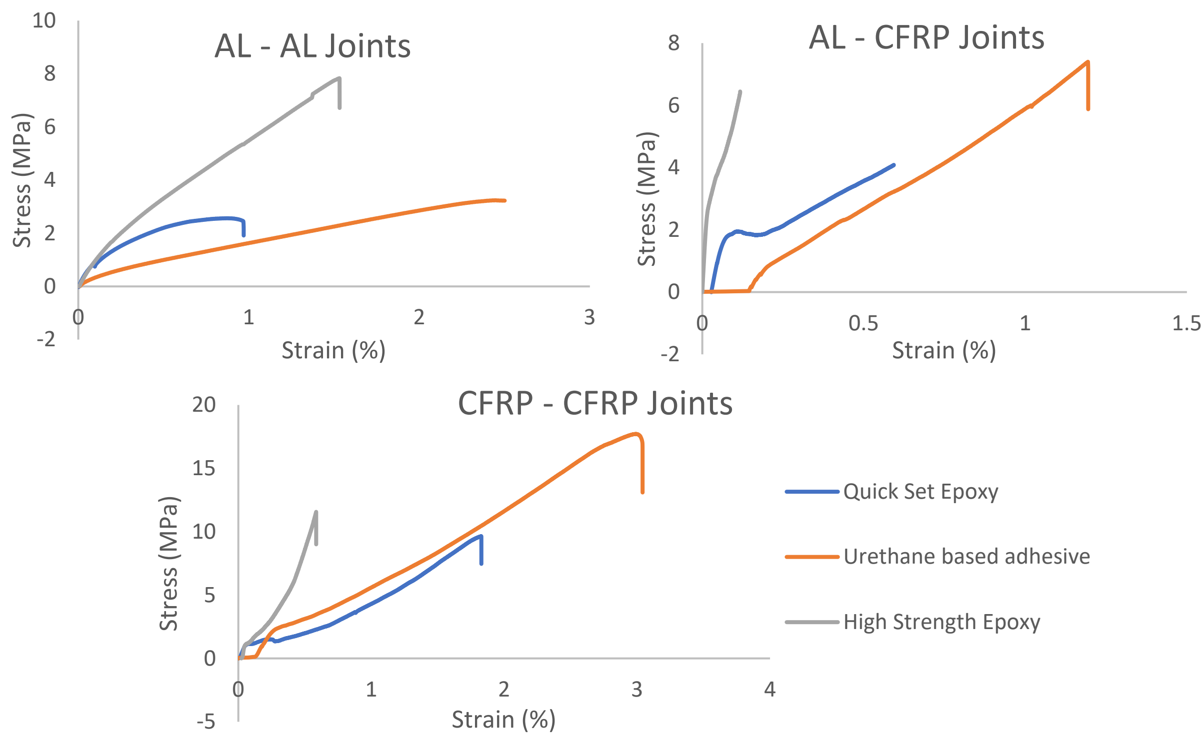


Figure 8: Typical stress vs strain graphs for the single lap joints at a strain rate 0.0015 s^{-1}.

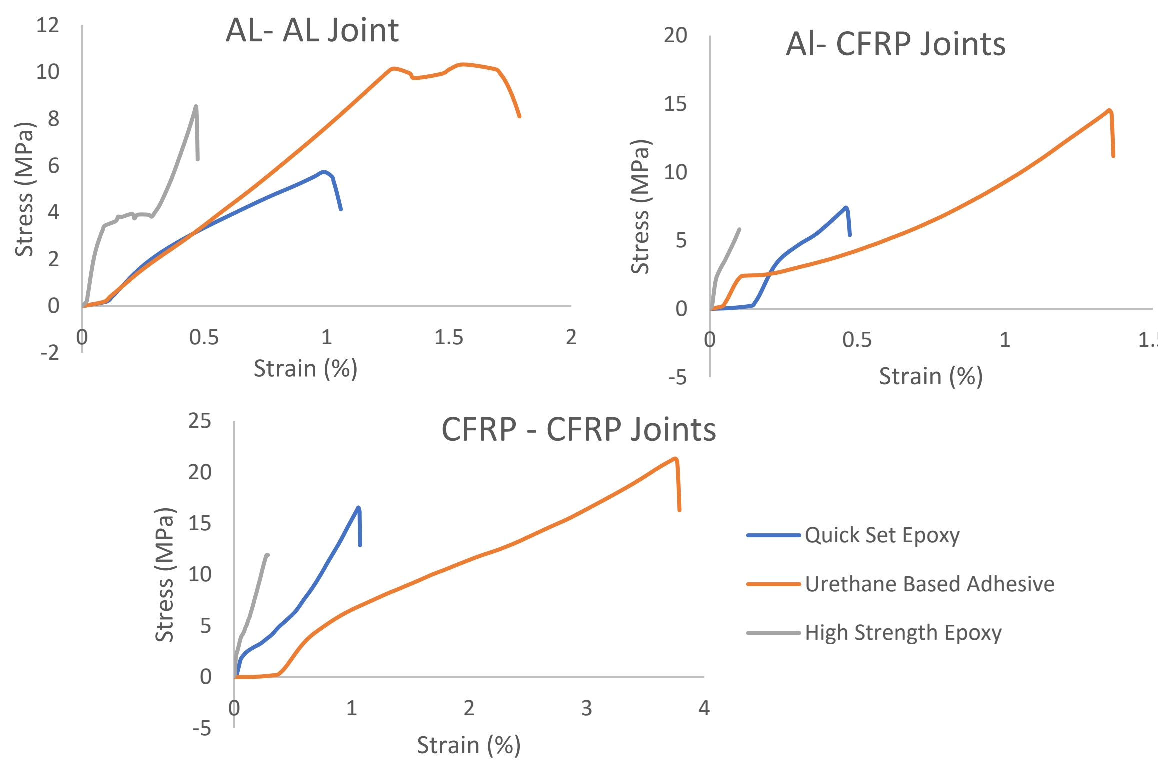


Figure 9: Typical stress vs strain graph for the single lap joints at a strain rate 0.15 s^{-1}.

Figure 10 shows low magnification optical micrographs of the fracture surfaces of SLJ based on CFRP bonded to CFRP using a slow cure epoxy resin and tested under tensile loading conditions at the strain rate of (a) 0.0015 s^{-1} and (b) 0.15 s^{-1}. Included in the figure are snapshots revealing typical strain distributions obtained by the DIC system from such SLJ systems of the corresponding strain rates (c) and (d). From the figure, it is evident that the main failure mechanism was cohesive under both strain rate with the crack propagating within the composite material. Furthermore, the results provided by the DIC system revealed that the shear strain remain uniform along and across the bond line at both strain rates until the fracture took place.

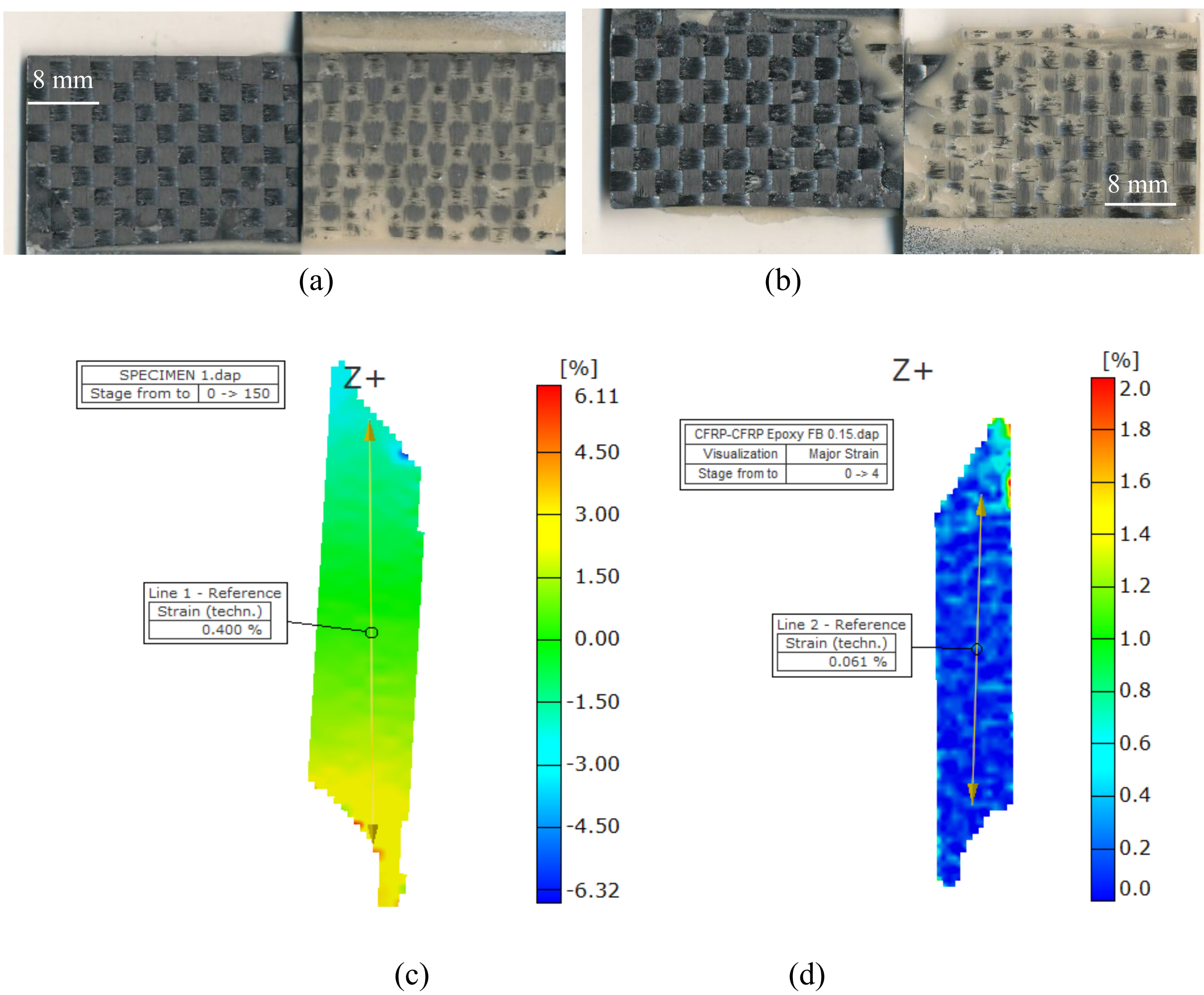


Figure 10: Low magnification optical microgrphs of CFRP – CFRP SLJ bonded with high strength epoxy tested at (a) 0.0015 S^{-1} (b) 0.15 S^{-1} and corresponsing strain distributions (c) and (d).

Figure 11 shows low magnification optical micrographs of the fracture surfaces of SLJ based on Al bonded to CFRP using the urethane based adhesive and tested under the same loading conditions and strain rates. Similarly, the strain distributions are also included in the figure (c) and (d). From the figure it is evident that in this system fracture took place in a combination of adhesive and cohesive types of failure. Furthermore, it is also evident that there is a significant variation of stress across the bond region which resulted in higher values of longitudinal and shear strain to failure. Moreover, it is also evident that such strain distribution is less pronounced across the bond region as the strain rate was increased, highlighting the effect of strain rate on the mechanical behavior of the SLJ system.

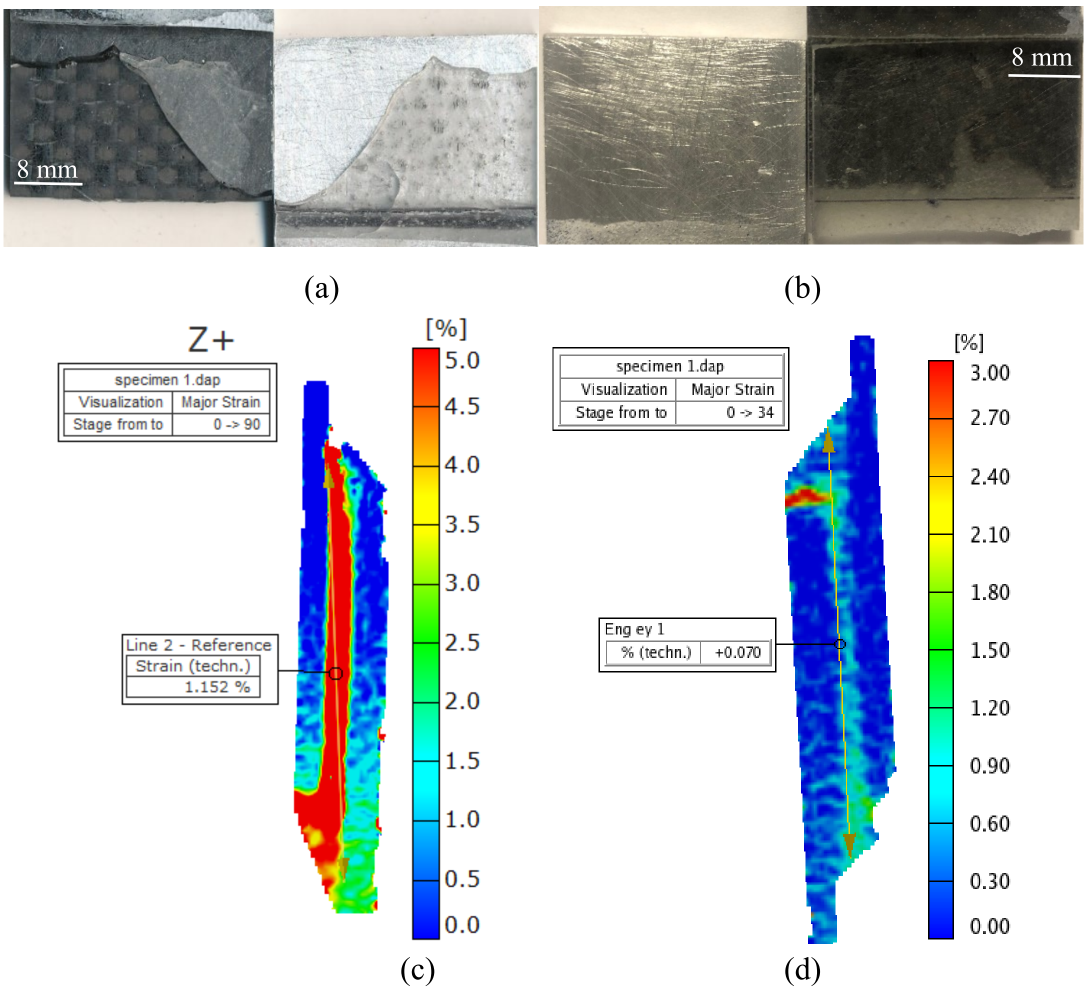


Figure 11: Low magnification optical microgrphs of Al – CFRP SLJ bonded with quick set epoxy tested at (a) 0.0015 s^{-1} (b) 0.15 s^{-1} and corresponsing strain distributions (c) and (d).

Figure 12 shows variation of major strain along the overlap region for Al-CFRP with urethane based adhesive joint at a strain rate of 0.0015 s^{-1}. The figure highlights the importance of measuring the strain distribution along and across the bond region. Here, it is evident that the strains reach lower value close to the substrates and higher values towards the center of the bond thickness.

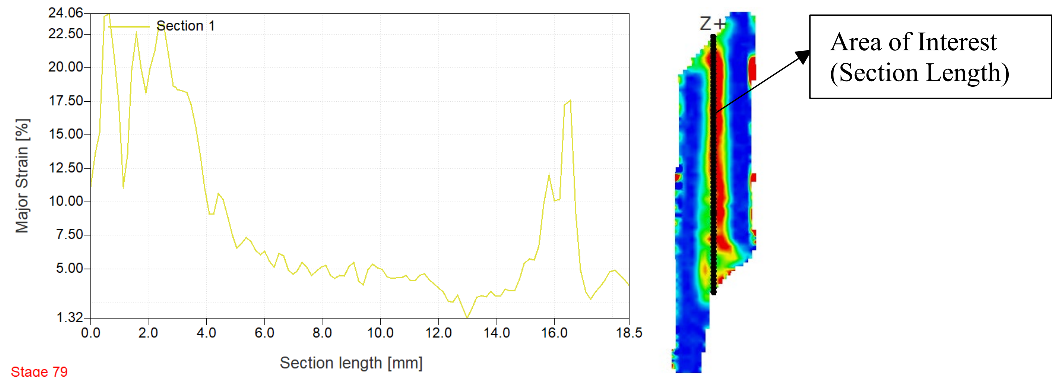


Figure 12: Variation of major strain along the overlap region (x/L) in the bondline from DIC.

Figure 13 shows the maximum principal strain as a function of the applied load for the Al- Al single lap joint bonded with the urethane based adhesive at a strain rate of 0.0015 s^{-1}. From the figure, it is clear how as the longitudinal strain increase, so is the concentration of the shear strain towards the central region of the adhesive. It is also evident that the maximum values of strain are always located towards the edges of the bond region. Such strain concentrations were also evident in the rest of the SLJ system investigated in this project.

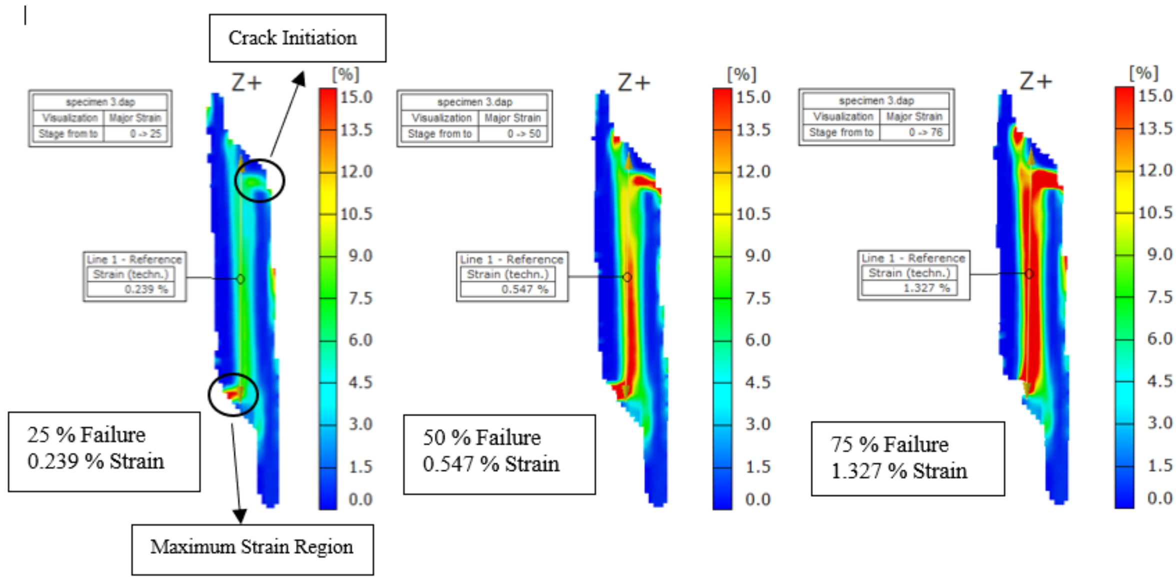


Figure 13: Principal strain along the bondline as the function of load level for the Al - Al single lap joint bonded with the urethane based adhesive at a strain rate of 0.0015 s^{-1}.

4. CONCLUSIONS

In this paper, the effect of strain rate on the mechanical behavior of SLJ systems based on similar and dissimilar adherends and using a number of adhesives was investigated. Experimental results revealed a unique interaction between substrates and adhesive materials. Here, the urethane-based adhesive offered the highest values of peak load and shear strength. Furthermore, optical microscopy analysis revealed the failure mechanisms present under such loading conditions. Finally, DIC investigations highlighted the strains localization and distribution and its variation with the strain rate. Such information is very important for the design of structural joints that may be subjected to various loading conditions.

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