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1 *A Novel Approach for Damage Assessment in Adhesively Bonded Composite Joints using*  
2 *Backface Strain Technique*

3  
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8  
9 **Abstract**

10 In this study, the backface strain (BFS) is measured by both digital image correlation (DIC)  
11 and fiber optic sensors (FOS) to detect the crack initiation and propagation in adhesively  
12 bonded composite single-lap joints (SLJ). BFS measures the resultant strain deriving from the  
13 positive strain, due to tensile load, and negative strain related to the bending moment. A  
14 point, called zero-strain point (ZSP), can be detected on the substrate surface of SLJ due to  
15 the concurrent effect of these positive and negative strains. The experimental activity shows  
16 that the value of the ZSP changes when the crack starts to propagate. Thus, this point can be  
17 used to monitor the service conditions of adhesive joints. The effect of joint dimensions on  
18 the position of the ZSP is investigated when the joint is subjected to quasi-static loading. In  
19 addition, the applicability of the method is investigated under a cyclic loading condition. The  
20 work shows that the ZSP can be used as an index to monitor joint healthiness. Furthermore,  
21 FOSs can be used for an in-situ monitoring of the joint.

22  
23 **Keywords:** Composites Single-Lap Joint (SLJ), Digital Image Correlation (DIC), Fiber Optic  
24 Sensor (FOS), Backface Strain (BFS), Structural Health Monitoring (SHM)

25 **1. Introduction**

26 In the past decades, it has been seen that composite materials have been increasingly used as  
27 alternatives for metals, mainly due to their good mechanical properties, the possibility to fabricate  
28 complex geometries, lightweight and high resistance against corrosion[1,2]. Consequently, this fast  
29 growth of composite applications in different industries like automotive, aerospace, civil and marine  
30 engineering has prompted to use reliable joining methods to connect small or large components [3,4].  
31 Up to now, mechanical fastening like bolts and rivets, welding and adhesive bonding are widely used  
32 techniques to join composite materials [5–7]. Adhesive bonded joints offer significant advantages  
33 over traditional mechanical joints, such as reduced weight, lower fabrication costs, improved damage  
34 tolerance, and the ability to join dissimilar materials without the corrosion concerns related to metal  
35 fasteners. Due to these benefits, these joints have found extensive applications in various industries  
36 including aerospace and automotive[1,3,8,9]. Therefore, it is important to fully understand the  
37 mechanical behavior of adhesive joints to apply proper strategies for monitoring these joints. The  
38 adhesives are expected to fail before composite substrates during the structure service life because  
39 they present lower mechanical properties. As a result, although there are also methods to improve the  
40 joints adhesive joints [10] they are designed with conservative safety margins [9,11]. Thus, it can be  
41 crucial in critical applications which demand high safety to develop non-destructive techniques that  
42 allow structural health monitoring (SHM) of the applications by warning at the initial stage of damage  
43 or providing reliable information about joint healthiness throughout service life. This enhances safety  
44 and reduces maintenance costs for those applications that need high reliability [12,13], and allows  
45 joint repair or replacement, when necessary, as well.

46 Various technologies and methods have been used to monitor the damage in composite joints [14–22]  
47 among which Digital Image Correlation (DIC) [23,24], and Fiber Optic Sensors (FOS) [25–28] were  
48 used in the present work. Fiber Bragg Grating (FBG) sensors are the most popular FOS, which work  
49 by etching micro-structure bragg gratings inside an optical fiber core, reflecting a specific light  
50 wavelength [29]. This wavelength changes when an FBG is subjected to external mechanical or  
51 thermal load, which allows accurate measuring of strain. Due to the small size, FBGs might be  
52 embedded in the joint, but this may affect the mechanical properties of the specimens. DIC is a non-  
53 contact method which can inspect large areas based on the images acquired by high-frequency and  
54 resolution cameras [30]. DIC works based on comparing pixel by pixel of each acquired image with  
55 the previous image or a chosen reference image to measure the surface displacement and  
56 consequently the strain in the specimen. The drawbacks of the DIC are the difficulties while preparing  
57 the samples, limited damage type detection, extensive data acquisition and the impossibility of using  
58 it as an SHM methodology.

59 Backface strain (BFS) measurement technique that could be used as an NDT method was introduced  
60 in 1986 by Abe and Satoh [31] to study crack formation in spot-welded joints. As it is obvious from  
61 the method's name, the first step is to measure the strain on the back surface of the specimen using  
62 one or more approaches. This technique has been applied to adhesively bonded joints, resulting in  
63 numerous investigations [12,13,31–35] that aim to efficiently detect adhesive joint damage. The BFS  
64 measurement method is particularly effective for evaluating the presence of hazardous cracks [12,13].  
65 Usually, this method involves placing strain gauges on the external surface of the bonded joint, known  
66 as the backface. Zhang et al. [13] used a measuring point by installing strain gauges at the overlap's  
67 end, focusing on the increased bend caused by cracks. Solana et al. [33] used the BFS by measuring  
68 the strain on the backface by using strain gauges and monitoring the ones with the largest strain  
69 gradient. Considering the BFS method, many researchers tried to monitor the adhesively bonded SLJs  
70 damage by placing strain gauges on the joints where stress concentration is high [12,13,33]. However,  
71 establishing the optimal location for these gauges is challenging due to the mixed-mode nature of  
72 SLJs as a result of their geometry, in particular with the inhomogeneous structure of composite  
73 materials. In composite materials, the back faces could be influenced by the size of the adopted  
74 measuring system in connection with the size of the microstructure of the constituents of the materials  
75 (fiber or tow sizes). As shown by Boursier et al. [36], the size and location of the strain gauges highly  
76 influence the measure of the deformation which can lead to values of the elastic properties that are  
77 50% higher compared to the reference value. Different works[37,38] attempted to use the BFS  
78 technique, employing arrays of strain sensors, to monitor crack propagation in SLJs and detect strains  
79 in different positions within composite SLJs. Moreover, there is the possibility of embedding sensors  
80 within composite laminates closer to the crack [39]. Therefore, FBG sensors were attached on the  
81 specimen internal surface to estimate how they would behave when placed in the laminate. This  
82 allowed the researchers to spot and track crack growth in a bonded joint during fatigue testing. In  
83 SLJs, crack initiation and propagation can be monitored by detecting the position of the BFS profile  
84 peak [13]. The position of this strain profile peak has been confirmed to closely correspond with the  
85 crack tip location [12]. The correlation between the crack front and the BFS peak location in SLJs  
86 depends on factors like adhesive fillet presence, materials used, and substrate mechanical properties.  
87 Preisler et al. [32] employed the zero-strain point within the region exhibiting the most significant  
88 change in longitudinal strain for monitoring structural damage. ZSP is a point where the strain is zero  
89 due to the concurrent effect of tensile and bending strain. Under normal, undamaged conditions, there  
90 is no longitudinal strain present, independently of the applied load.

91 Different parameters are proven to have a noticeable effect on the general mechanical behavior of  
92 SLJs [40–42]. These parameters include substrate materials, adhesive type [1,41], overlap length [43],  
93 adhesive thickness [44,45], joint width [41,42,46], fillets at the edges [47], and surface treatment [48].  
94 Regarding the bonding area dimensions and adhesive types, previous works mainly investigated the  
95 effect of these parameters on properties like peak force, elongation, shear stress, normal stress, peel

96 stress [41,42]. Two main adhesive types, polyurethane-based and epoxy-based, have been extensively  
 97 studied in different sectors including the automobile and aerospace industries. Polyurethane adhesives  
 98 are popular due to their capacity to withstand larger deformations, and their sealing ability [49,50].  
 99 Epoxy adhesives are of interest because of their ability to join similar and dissimilar materials, as well  
 100 as having good fatigue properties, and resistance against impact [51–53].

101 This research activity focuses on monitoring the crack initiation and following its propagation in  
 102 composite single-lap joints with different bonding area dimensions subjected to quasi-static and cyclic  
 103 loading. Therefore, a large campaign of tests was carried out using DIC to monitor the deformation of  
 104 the backface of the SLJ. The results were also validated by fiber optic sensors due to their ability. As a  
 105 result, zero-strain ZSP was identified on the backface of the joint. The monitoring of this point  
 106 provides enough information to analyze the behavior of SLJs and the health condition of SLJs over  
 107 the service life. Moreover, the effect of bonding area geometry including Overlap length (L), Joint  
 108 width (W) and Substrate thickness (T) on the position on ZSP was investigated. This comprehensive  
 109 research activity on the effects of different parameters on ZSP position using the DIC and fiber optic  
 110 sensors allowed an elaboration of a strategy to monitor SLJ in both online and offline modes. Finally,  
 111 having the methodology confirmed, it is proposed to use it with fiber optic sensors in real  
 112 applications. The work addresses different open points in the literature. Realistic thicknesses and  
 113 sizes of the composite substrates were used to assess any limitation of the ZSP technique. The  
 114 activity is focused on composite materials which present two phases, matrix and resin, to evaluate  
 115 any possible effect and limitation of the adopted technique. Cyclic loading was used to  
 116 demonstrate that the ZSP can detect the damage and that the change of ZSP is not solely related  
 117 to the effect of the overall damage. Further, a comparison of the strains between fiber optic  
 118 sensors and DIC techniques shows that the optics sensors can be used for SHM applications. The  
 119 optical sensors, compared to strain gauges offer the possibility to continuously measure the strain  
 120 along a line while strain gauges can just provide local information that is more complex to be  
 121 analyzed and installed.

## 122 2. Experimentation

### 123 2.1. Materials and design of experiments

124 A bi-component polyurethane adhesive called ADEKIT A236/H6236, made by the Sika (CH), was  
 125 utilized in this investigation. This glue may be used in a variety of applications and sectors, including  
 126 transportation, marine, automotive, and aerospace, according to the technical data sheet. The  
 127 mechanical properties of this adhesive were studied and reported in [41,42] as given in Table 1. On  
 128 the other hand, a carbon fiber/epoxy prepreg weave, XPREG XC130, was used for the substrates. This  
 129 prepreg presents a real weight of 210 grams per square meter (gsm) and it is a 3k reinforcement which  
 130 combines a high strength TR30S fiber with a 2x2 twill weave (the fibers orientation is 0/90). The  
 131 main mechanical characteristics of this prepreg are given in Table 2.

Table 1 Mechanical properties of adhesive (Polyurethane ADEKIT A 236/H 6236) [41,42]

E (MPa)	278
SIG ultimate (MPa)	13
Elongation (%)	22
Density	1.35

132

Table 2 Mechanical properties of the carbon fiber composite material [54,55].

	Mean Value
Density (kg/m <sup>3</sup> )	1450
Poisson's ratio	0.12
Longitudinal modulus (MPa)	58,000
Longitudinal tensile strength (MPa)	440

Longitudinal compressive strength (MPa)	453
Longitudinal compressive ultimate strain	0.096

133

134 To investigate the effects of bonding area dimensions on the mechanical behavior of the joints,  
 135 including damage initiation and propagation, samples were manufactured with various adherend  
 136 thicknesses ( $T1 = 0.88$  mm,  $T2 = 1.76$  mm,  $T3 = 3.52$  mm), joint widths ( $W1 = 10$  mm,  $W2 = 20$  mm,  
 137  $W3 = 30$  mm), and overlap lengths ( $L1 = 10$  mm,  $L2 = 20$  mm). Figure 1 shows the SLJs sketch with  
 138 the considered dimensions. The area between the loaded edge and non-loaded edge on the outer face  
 139 of the substrate is called backface. These three parameters were also used to name the specimens. For  
 140 example,  $L1W2T3$  represents a specimen with an overlap length of  $L1$ , a joint width of  $W2$ , and an  
 141 adherend thickness of  $T3$ . A Design of Experiment based on these parameters is provided in Table 3,  
 142 with three repetitions for each sample. The adhesive thickness was  $t_{\text{adhesive}}=1.10$  mm, as recommended  
 143 by the datasheet for adhesive. A fixture was used to align the joints, employing Teflon spacers to  
 144 achieve the desired thickness.

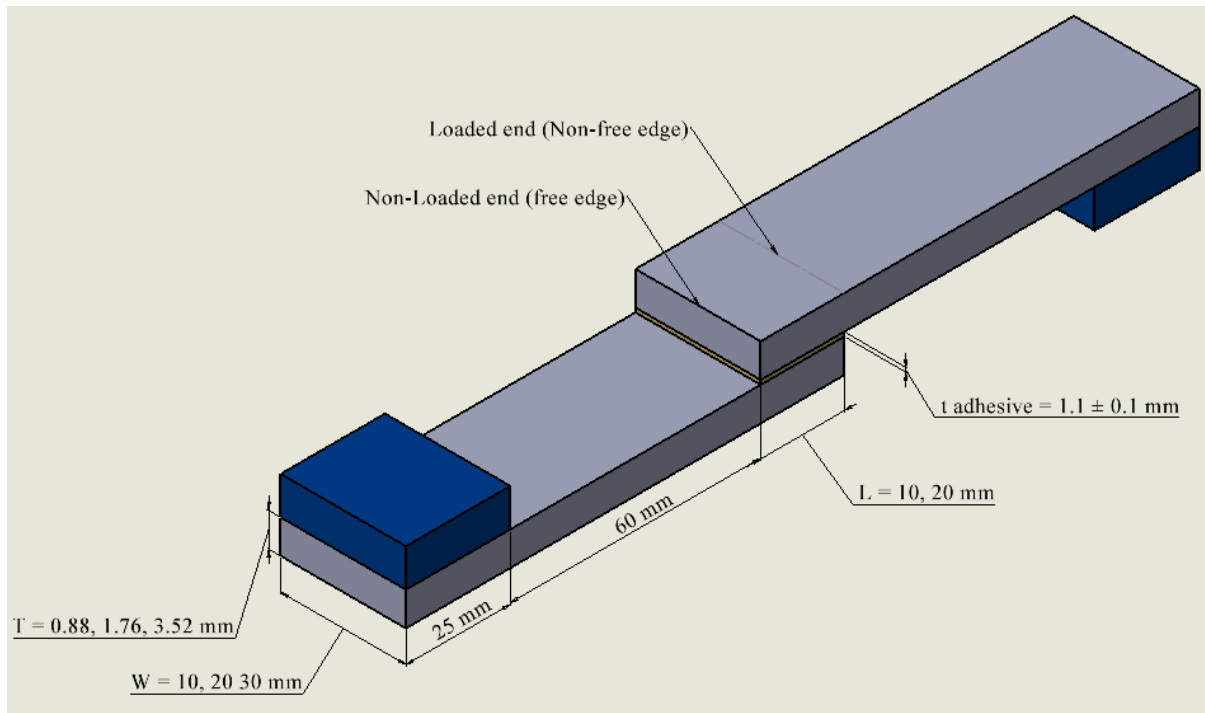


Figure 1. SLJ geometry (L: overlap length, W: joint width, T: substrate thickness, and  $t_{\text{adhesive}}$ : adhesive thickness)

145

Table 3. SLJ design of experiments [41,42]

Parameters		T1 (0.88mm)	T2 (1.76mm)	T3 (3.52mm)
L1 (10mm)	W1 (10mm)	L1W1T1	L1W1T2	L1W1T3
	W2 (20mm)	L1W2T1	L1W2T2	L1W2T3
	W3 (30mm)	L1W3T1	L1W3T2	L1W3T3
L2 (20mm)	W1 (10mm)	L2W1T1	L2W1T2	L2W1T3
	W2 (20mm)	L2W2T1	L2W2T2	L2W2T3
	W3 (30mm)	L2W3T1	L2W3T2	L2W3T3

146

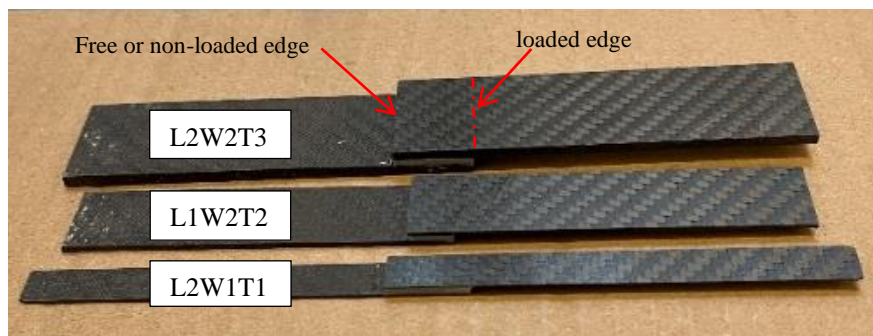
## 147 2.2. SLJ specimen manufacturing, FOS installation, and speckle pattern for DIC

148 The preparation of the SLJs followed the same procedure detailed in papers published by the same  
 149 authors[41,42]. In brief, laminates with varying numbers of layers (2, 4, and 8 layers) were made

150 using hand layup method, vacuumed, cured in an oven, and then, cut into the desired dimensions. The  
151 surface preparation of the substrates was conducted by abrading the joint area with sandpaper and  
152 cleaning it with acetone. The joints were assembled using a handmade mold to align the joint, and the  
153 adhesive was cured in two steps. First, it was cured at ambient temperature, followed by a post-curing  
154 process in an oven at 70°C for 16 hours, as specified in the manufacturer's datasheet. Excess adhesive  
155 was removed after curing to prevent increased and uncontrollable joint stiffness and strength. To  
156 obtain the desired adhesive thickness Teflon spacers with the same thickness were used. Moreover, to  
157 have good control of the adhesive thickness throughout the overlap length, a weight was applied on  
158 the upper substrate in a way that covers all the bonding area. Moreover, a set distance of 85 mm from  
159 both ends of the bonding area is also thought to separate the start of the bonding region from the end  
160 of SLJ (Table 1).

161 When the SLJ samples were prepared (Figure 2a), optical fibers were installed on both outer surfaces  
162 of the joint area, i.e., outer surfaces of substrates. Both outer faces on both sides of the SLJs were  
163 considered to observe if this fiber could measure the same deformations on both outer sides (faces) of  
164 the joints. This optical fiber is installed in a way that it has two lines of attachment on each side of the  
165 joints with overlap length size. Therefore, a total of 4 lines (parts) from a single optical fiber were  
166 attached to the SLJ outer faces in the overlap direction. This lets us to have the information about the  
167 deformation on two lines on each side. Figure 2b shows the installed fiber only on one surface of the  
168 joint. To ensure the fiber is straight and without any bends, they are maintained in a slightly tensile  
169 position and attached to the joint area using an isocyanate fast glue.

170 Finally, the specimens were painted to be recognizable by the Digital Image Correlation (DIC) tool.  
171 For this purpose, the bonding area is first painted with white color and then a speckle pattern is  
172 produced by spraying the black color as random points. It is tried to make the pattern randomly  
173 formed with black and white points considering an approximate ratio of 1 (Figure 2c). At the end, two  
174 tabs of 25 mm were applied in the clamping area, as shown in Figure 1, to avoid misalignment while  
175 applying the load.



a)

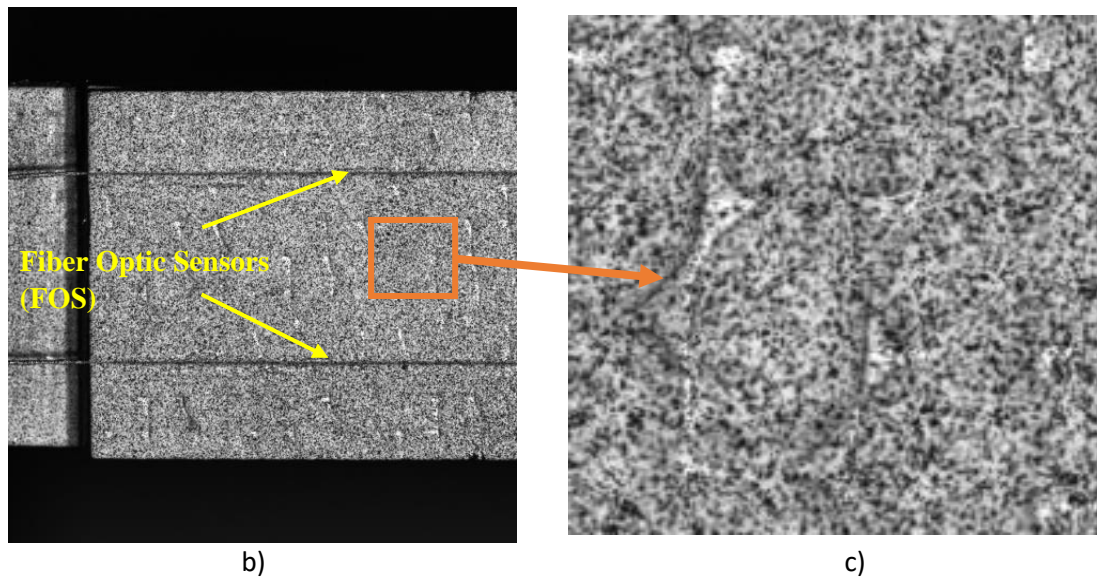


Figure 2. Specimen preparation; a) prepared SLJs; b) SLJ with optical fibers (the one installed on the surface in front of DIC); c) pattern for DIC.

### 176 2.3. Test apparatus:

177 Tests were performed using servo-hydraulic Instron (Norwood, MA, USA) machine 8801 at a  
 178 crosshead velocity of 5 mm/min. The test apparatus is shown in Figure 3. In addition, to observe and  
 179 measure the displacement contours on the surface of the SLJs a Digital Image Correlation (DIC) tool  
 180 from Correlated Solution (Columbia, SC, USA) was used in 3D mode. The lenses were of type  
 181 Rodagon Smart Focus 80mm. The image acquisition was done by VIC-Snap software at a rate of 20  
 182 Hz which provides enough detailed data from each test. Further, DIC and Instron were synchronized  
 183 to correlate the recorded load and crosshead displacement with each image. To minimize the  
 184 processing time and the amount of data collected, making the correlation analysis feasible, it was  
 185 required to restrict the frame that the software processes to a smaller area of interest surrounding the  
 186 specimen. The software generates a rectangular array of subsets inside the area of interest during this  
 187 operation. Subsets are square portions of the picture, spaced by the same distance (the step size) both  
 188 in vertical and horizontal directions. Here, the subset size is 47 pixels and the subset spacing is 5  
 189 pixels. Finally, a strain acquisition system, LUNA Odisi 6000 system (Virginia, USA), that uses Fiber  
 190 Optic Sensors (FOS) was used to simultaneously acquire the strain. The LUNA system works on the  
 191 Rayleigh backscattering effect. The presence of impurities reflects the light travelling along the fiber,  
 192 thus allowing continuous measurement of the strain [36]. This system takes advantage of high-  
 193 definition optical fiber sensors and can provide thousands of strain and temperature measurements per  
 194 meter for each fiber. The optical fibers manufactured by ThorLabs (Newton, New Jersey, USA) have  
 195 been used in these tests. Gauge pitch is the distance between two successive acquisition points in the  
 196 optical fiber length. The smallest resolution possible with the employed optical fiber in this study is a  
 197 gauge pitch of 0.65 mm, and this value was adopted. Thus, it is possible to have 30-31 strain sensors  
 198 along an overlap of 20 mm considering the used gauge pitch. This is not possible by using strain  
 199 gauges, because of the size, neither with Bragg's optical fibers that use grating lengths of 1 or 3.5  
 200 mm. Another reason for using the optical fiber is that contrary to the DIC, the optical fibers can be  
 201 installed on a real component, e.g., car parts, to provide the active and in-situ measurement of the  
 202 strain.

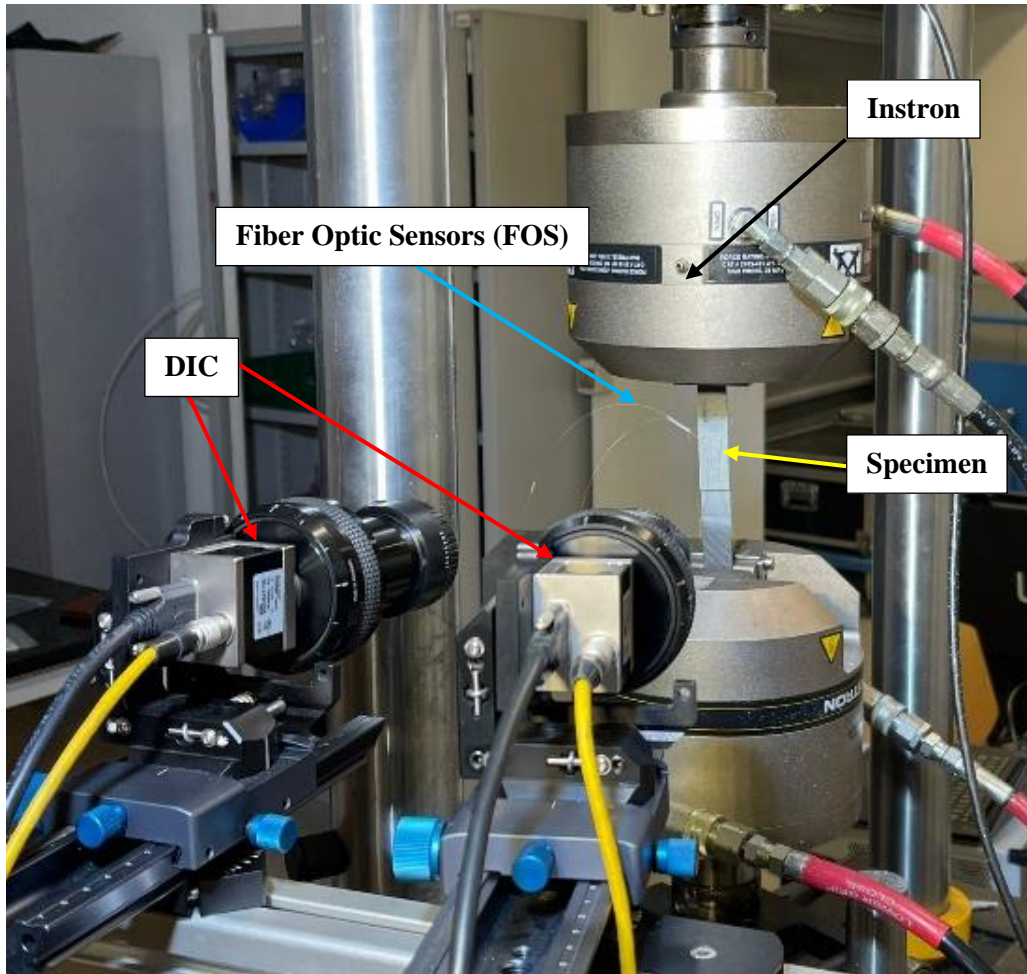


Figure 3 Test setup

203 **3. Results and discussion**

204 **3.1. General response of the joints under tensile loading**

205 Based on the test campaign that has been carried out in this study it is possible also to analyze how  
 206 joint dimensions can affect the response of a single lap joint. The effects of each parameter on joint  
 207 response including, peak load, displacement at peak load, adherend normal stress, adhesive shear and  
 208 peeling stresses are already discussed in detail in previous publications [41,42]. The tests done for this  
 209 study also confirm the results obtained in [41,42]. Three samples of each configuration mentioned in  
 210 Table 3 were tested. Each configuration presented good repeatability. For the sake of brevity, one out  
 211 of three curves are shown in Figure 4a. Moreover, Figure 4b, and c, shows the scatter for the peak  
 212 force (F) in relation to the displacement at peak load (d). In Figure 4b, and c, the substrate thicknesses  
 213 are represented by three different colors blue, red and yellow colors for T1, T2 and T3, respectively.  
 214 The scatter is very limited for these types of tests, and the averaged values for W1, W2 and W3 are  
 215 shown by the symbols solid circle, cross, and empty square, respectively. The values in the in Figure 4  
 216 show that all three parameters (L, W, and T) significantly influence the peak force and joint stiffness  
 217 (the slope of the initial linear part of the load-displacement curve). The larger the bonding area the  
 218 higher the peak force and the joint stiffness. The analysis of data in Figure 4 and all the repetition of  
 219 the tests show that W is more influential than L and L is more influential than T on the load capacity  
 220 of the joints. However, the effect of W on joint stiffness is greater than the effects of L and T.  
 221 Moreover, after the test, specimens were carefully inspected and different types of damages including  
 222 adhesive, cohesive, thin layer cohesive and mixed mode were observed as shown in Figure 5.  
 223 According to [41,42] increasing the thickness of the substrate leads to a more uniform distribution of

224 shear and peel stresses and a reduction of the peaks in the overlap ends. The adhesive in the center of the joint is compressed due to locally negative peel stress, and this compression is more pronounced  
 225 the joint is compressed due to locally negative peel stress, and this compression is more pronounced  
 226 in joints with thicker substrates. Therefore, the thicker the substrate the more cohesive the damage  
 227 surface was.

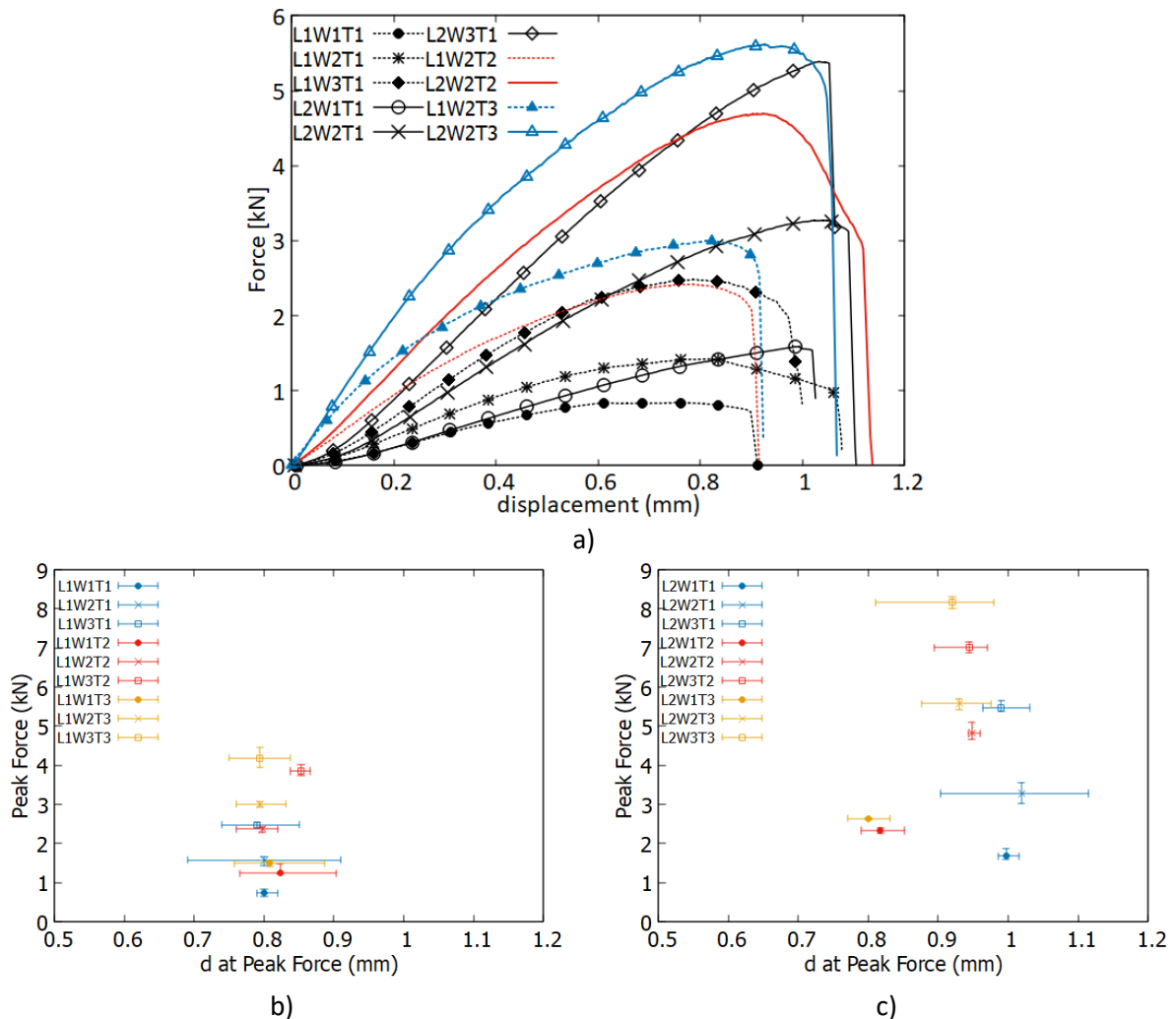


Figure 4. Tensile response of the joints. a) Load-displacement curves all the specimens, b) scatter for samples with overlap L1, c) scatter for samples with overlap L2

228

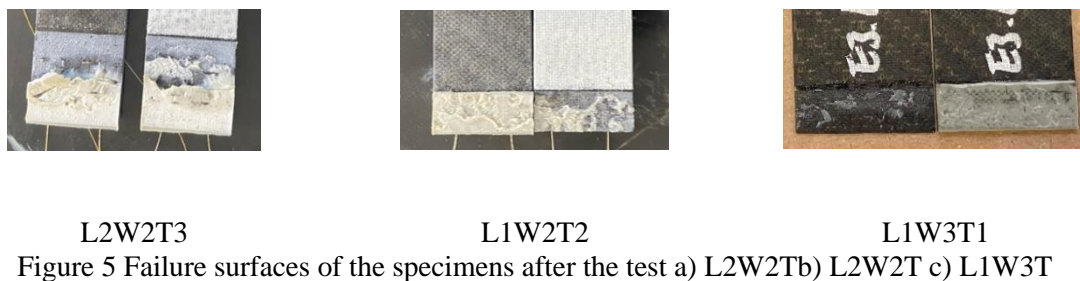


Figure 5 Failure surfaces of the specimens after the test a) L2W2Tb) L2W2T c) L1W3T

### 229 3.2. Definition of Zero-Strain Point (ZSP) using DIC

230 Generally, SLJs undergo a mixed-mode loading mainly due to the geometry and the eccentricity of  
 231 the tensile load as shown in Figure 6. As a result, the specimens also experience bending moment,

232 shear and peel stresses. The tensile loading causes positive strain in the substrates whilst the bending  
233 moment makes the substrates' outer face (backface) experience mainly a negative strain. The  
234 concurrent effects of these two types of strains on the overlap length will result in a point on the  
235 external surface (backface) of the substrate where the strain is zero. This point is called Zero-Strain  
236 Point (ZSP). The behavior and importance of ZSP is described using Figure 7 as follows.

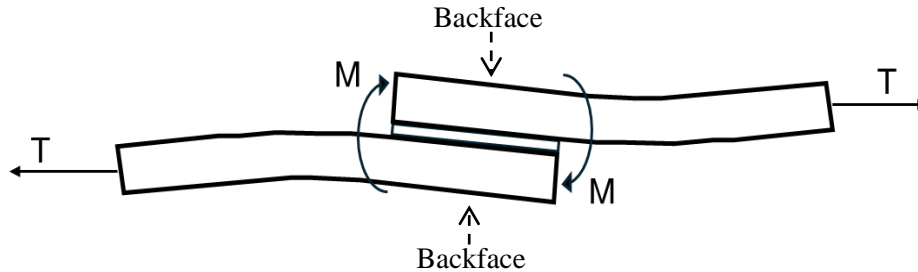


Figure 6 schematic of load eccentricity on SLJ.

237  
238 Figure 7a,b,c, and d show, how the ZSP works for the specimen L2W1T1, taken as an example. In  
239 this specimen, the overlap length is 20 mm, the substrate thickness is 0.88 mm, and the joint width is  
240 10 mm. After processing the images using VIC-3D software the strain contour map is shown over the  
241 overlap length in Figure 7a. Larger positive strain values have been found in the middle area of the  
242 joint (reddish contour) whilst negative values are observed in the vicinity of the joint edges. As can be  
243 seen in Figure 7a, different points along the overlap length have been chosen to monitor the strain  
244 history. Each point is the average of all the strain values over the joint width, e.g., the black point is  
245 the average of all strain values on the dashed yellow line. Therefore, each point is a representative of  
246 all the points with different positions on the joint width while they have the same position on the  
247 overlap length. Afterwards, the strain history for these points is shown in Figure 7b. Most of the  
248 points experienced either positive or negative strain from the beginning of the test. There are only a  
249 few points very close to each other in which the strain is zero and remains zero up to a certain time,  
250 that is, to a certain load level. Those points are the candidates for ZSP.

251 Another way to visualize the ZSP is to look at the strain history of overlap length (the black line in  
252 Figure 7a) as it is shown in Figure 7c. In this figure, each curve is the strain along the overlap (black line)  
253 at a certain time or load. As indicated by a circle, many curves are passing a common point with  
254 the zero value of strain located at 17.4 mm. These curves represent the strain distributions on the  
255 overlap length when the joint is still undamaged. When the damage starts propagating in the joint, the  
256 curves do not cross the ZSP (black circle point) anymore. It is observed that the DIC was not able to  
257 record the displacement and strains very close to the edges of the joint, especially the unloaded edge  
258 of the bonding area. This is because when the specimen moves or rotates, and the damage grows, the  
259 light and the focus worsen, losing resolution. Subsequently, a rise in the strain history (red oval in  
260 Figure 7c) might be observed at the joint edge, especially at the unloaded edge.

261 Figure 7d demonstrates the ZSP behavior with respect to the load-displacement curve of the SLJ,  
262 illustrating how the strain changes in this point as the load increases. As can be seen, as long as the  
263 load-displacement curve is in the elastic zone the strain in the ZSP is approximately zero. As the  
264 damage starts growing and the load-displacement curve exits the elastic zone the ZSP records  
265 negative strains up to the joint failure. In other words, ZSP is the point where strain is initially  
266 approximately zero and remains unchanged until the damage starts propagating in the joint, after  
267 which the strain in ZSP increases negatively up to the point of joint failure. The ZSP for a joint could  
268 be found experimentally using DIC and Fiber Optic Sensors. DIC could serve as a preliminary  
269 analysis to design an in-situ analysis that uses Fiber Optic Sensors or strain gauges to monitor the  
270 health conditions of the joint.

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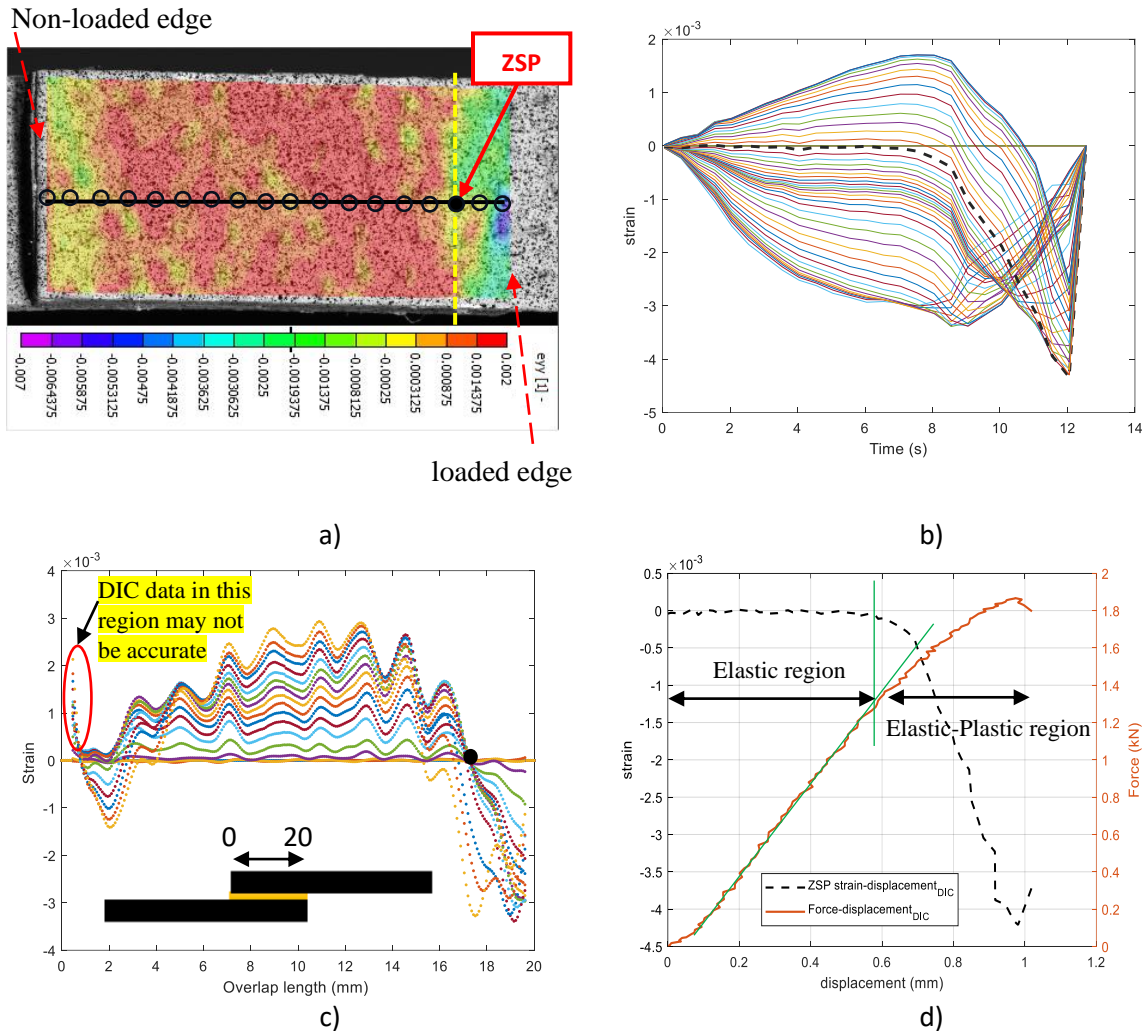
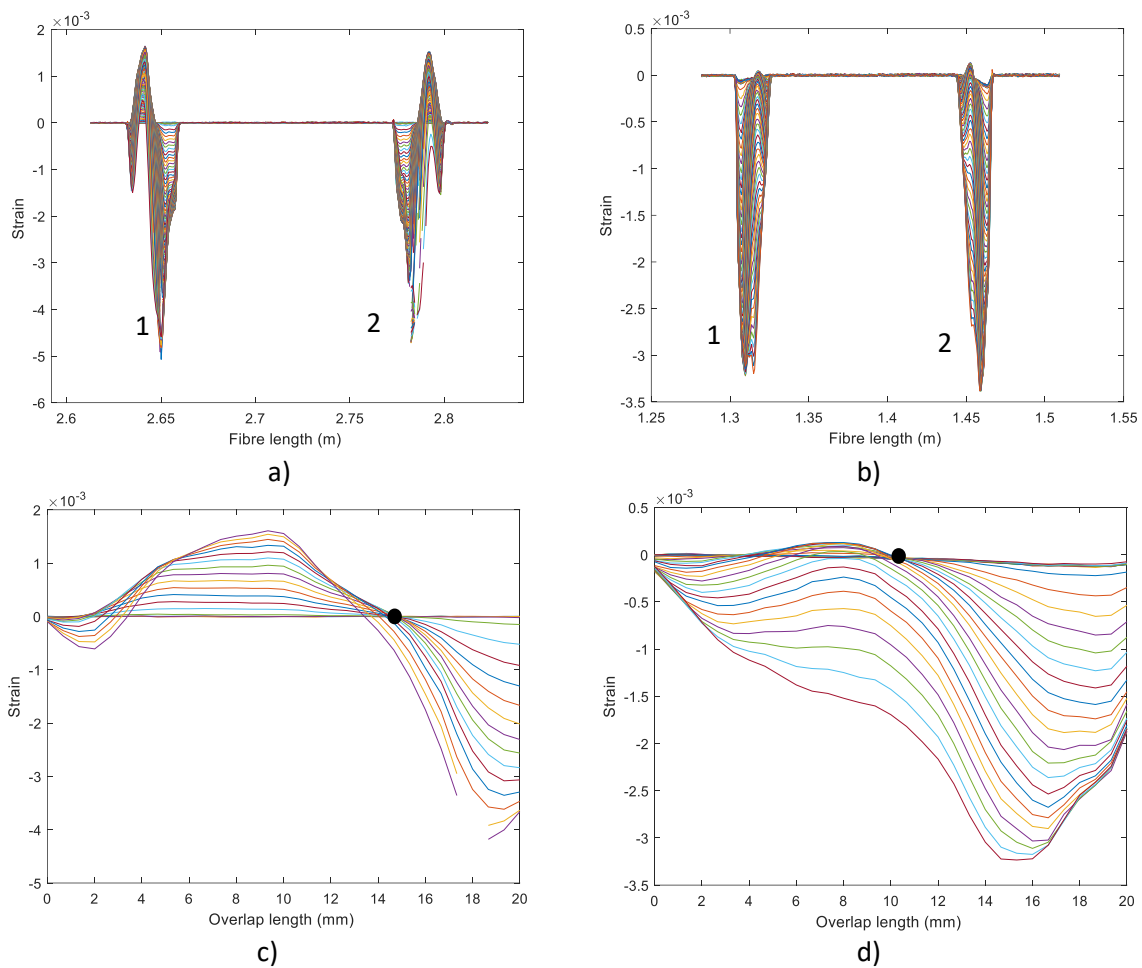


Figure 7 Zero strain point (ZSP) behavior in a joint, e.g., L2W1T1. a) Strain map on the joint area backface b) Strain history of different points on the joint backface (the black dashed line is the strain history of ZSP) c) Strain history of the overlap length on the averaged line (black line) d) Concordance between the ZSP strain curve and joint Force-displacement

### 277 3.3. Validation of the ZSP using optical fiber sensors

278 In Section 3.2, the DIC analysis illustrated that the ZSP is trustworthy enough to predict the behavior  
 279 of a joint. However, this methodology using DIC cannot be used as an in-situ methodology. For this  
 280 reason, optical fibers have been adopted and studied to assess whether they can lead to reliable results.  
 281 Samples L2W2T2 and L2W2T3 were equipped with fibers, on both sides of the overlap area, as  
 282 reported in Section 2.1. Figure 8a, and b show, respectively, the strain signals recorded by fibers  
 283 installed on the backfaces (two on each face) of samples L2W2T2 and L2W2T3. For a better  
 284 visualization only two fibers are shown in Figure 8a,b. The maximum positive and negative strains are  
 285 different for each sample. L2W2T2 experienced a maximum positive and negative strain of  $1.5e^{-3}$ ,  
 286 and  $-5e^{-3}$ , respectively. In case of sample L2W2T3, these values are  $8e^{-5}$ , and  $-3.3e^{-3}$ ,  
 287 respectively. Therefore, by increasing the substrate thickness from T2 to T3 the absolute value of

288 positive and negative strain reduces by 95% and 34%, respectively. Since the results of each fiber  
 289 were approximately the same (Figure 8a,b) as the others, only one of them (Figure 8c,d) is chosen and  
 290 explained. For example, for specimen L2W2T2, Figure 7a, the first signal and for L2W2T3 (Figure  
 291 7b) the second signal was chosen. Figure 8a,b show that the specimen with a thicker substrate  
 292 experienced lower strain and this is due to the higher stiffness that the thicker substrate exhibits. Due  
 293 to the relatively high acquisition frequency, in Figure 8c,d, one out of each 10 curves was selected for  
 294 a better visualization and understanding of the data. The ZSP is clearly visible and shown with black circles.  
 295 This analysis carried out with the optical fibers led to the same outcomes found with DIC  
 296 analysis, reported in section 3.2, on the ZSP. Finally, Figure 8e,f show both the evolution of the strain  
 297 in ZSP from optical fibers and DIC vs. crosshead displacement matching different stages of the  
 298 specimen force-displacement curve. As can be seen, very similar results were obtained by comparing  
 299 the strains measured by optical fibers and DIC methodology. Another point to be noticed is that the  
 300 rise in the unloaded edge is not visible here in optical fiber sensors curves. This is as a result of the  
 301 Fiber Optic Sensors that can measure the strain also at the joint ends proximity if they are well bonded  
 302 on the surface.



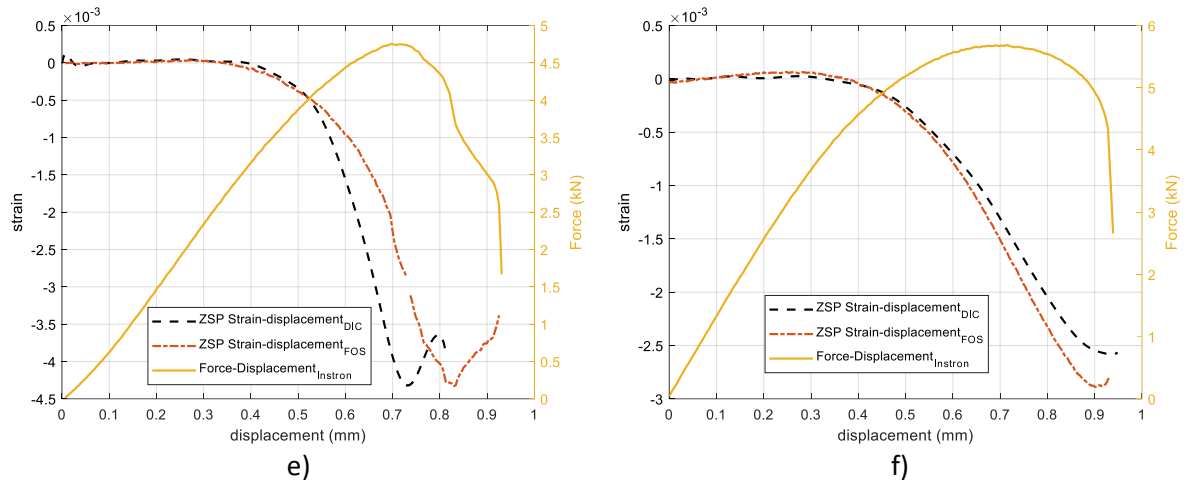


Figure 8 ZSP for specimen L2W2T2 and L2W2T3 using both FOS (LUNA) and DIC a) FOS (LUNA) signals for L2W2T2 b) FOS (LUNA) signals for L2W2T3 c) 1<sup>st</sup> signal is selected and filtered for L2W2T2 d) 2<sup>nd</sup> signal is selected and filtered for L2W2T3 e) ZSP strain and force-displacement of L2W2T2 f) ZSP strain and force-displacement of L2W2T3

### 303 3.4. Damage progression in the joint

304 Monitoring the backface strain with both DIC and optical fiber sensors provides also more  
 305 information about how the damage propagates inside the joint. Figure 9a,b,c,d,e,f,g,h and i show the  
 306 progressive damage of the specimen as well as the change of the strain in ZSP during the test. The  
 307 strain contour is chosen and fixed based on the strain range in the ZSP so that it remains the same  
 308 during the test. The dashed yellow line represents the ZSP on the overlap length. As can be seen at the  
 309 primary stage of loading, Figures 8a, b, c, d and e, the ZSP starts appearing on the surface of the  
 310 substrate near the non-free edge of the bonding area. The contour color remains the same up to  
 311 damage initiation (Figure 9f). Then the damage starts propagating in the bonding area from both ends  
 312 of the joint. The damage propagation from both ends is accompanied by recording the negative strain.  
 313 However, the quantity of the negative strain is larger on the non-free end of the joint where the ZSP is  
 314 formed. The results of the DIC on the free end of the joint might not be very precise due to some  
 315 noise sources, (e.g., light and focus) and that is why in some strain history graphs at the end of the  
 316 joint a sharp increase in the strain might be seen. However, the result that the damage propagates from  
 317 both ends but mainly from the loaded end is also supported by the optical fiber sensor which does not  
 318 present the DIC problems since it is properly bonded on the surface during the test. In Figure 8c,d it is  
 319 observed that the negative strain is present on both ends of the joint because the quantity of the  
 320 negative strain on the loaded end is much larger. Figure 9g, h, and i illustrate how the strains in the  
 321 ZSP become negative due to the damage propagation.

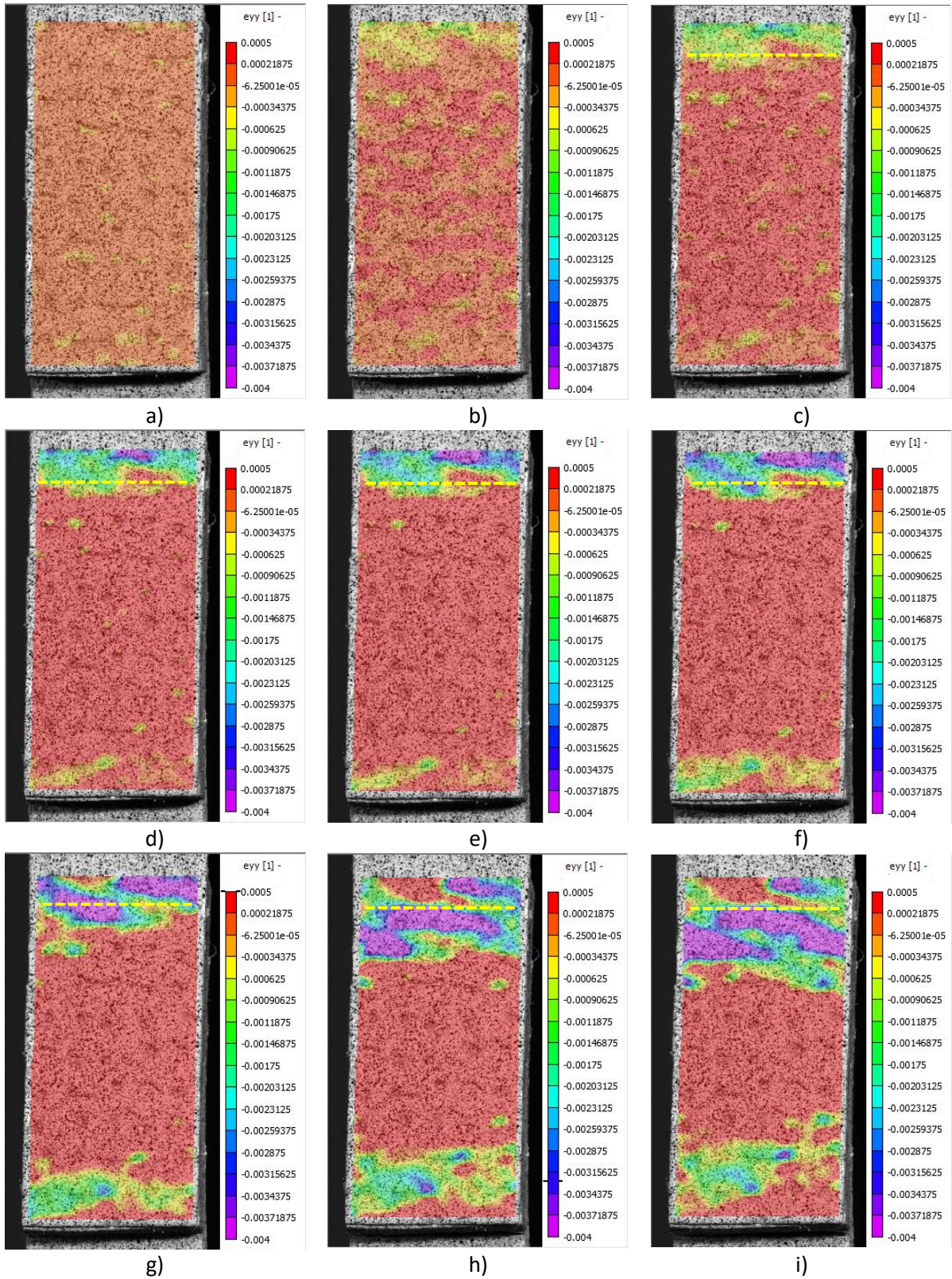


Figure 9 Damage progression in the joint L2W2T1 a) clamped specimen (Initial condition) b) primary stage of loading (70N) c) elastic zone: the ZSP appears (193 N) d) elastic zone (562.1N) e) elastic zone (1000N) close to damage initiation f) ZSP gains strain: Damage initiated (1380N) g) Damage progression (1653 N) h) Damage progression (1867 N) i) Damage progression up to the rupture (1796N)

### 322 3.5. Effect of bonding area geometry on the position of ZSP using DIC

323 Having the ZSP introduced and verified, the question of this section is: does the bonding area  
324 geometry change the location of the ZSP? To answer this question, as already anticipated in section  
325 2.1, a design of experiment has been conducted which considers the overlap length (L), joint width  
326 (W) and substrate thickness (T). After the tests have been done and monitored with the DIC the  
327 results are explained as follows.

328 Figure 10a, b, c, d, e and f show the strain distribution on the overlap length for all the specimens  
329 (same as explained in section 3.2) with substrate thickness T1. In particular, Figure 10a, c and e (left  
330 part of Figure 10) report the strains along the overlap at fixed L1 and T1 and for W1, W2 and W3  
331 respectively. Figure 10b, d and f (right part of Figure 9) report the strains along the overlap area for  
332 SLJ prepared with L2, T1 and the three different widths W1, W2 and W3. This analysis shows that  
333 considering a fixed overlap length and substrate thickness, the position of ZSP remains approximately  
334 unchanged by increasing the joint width. For specimens with T1, ZSP is located at  $7.3\pm 0.4$  mm and  
335  $16.8\pm 0.5$  mm respectively for the overlap length of L1 and L2. This implies that the effect of the joint  
336 width is negligible on the position of the ZSP. This is probably due to the lack of influence of the joint  
337 width on the response of SLJs [41,42]. Considering the joint width and substrate thickness, it can be  
338 concluded that the position of the ZSP moves toward the bonding area edge which is loaded as the  
339 overlap length is increased.

340 As the effect of W has proven to be negligible, for the substrate thicknesses T2 and T3 only W2 has  
341 been considered for further analyses. Figure 11a, c (left part of Figure 11) show the result for the  
342 specimens with substrate thickness T2, and Figure 11b, d (right part of Figure 11) show the result for  
343 the specimens with substrate thickness T3. For the specimen with a substrate thickness of T2, the ZSP  
344 is located at  $5.3\pm 0.2$  mm and  $14.2\pm 0.2$  mm, respectively, when the overlap length is L1 and L2. For  
345 the specimen with a substrate thickness of T3, the ZSP is located at  $3.5\pm 1$  mm and  $10\pm 0.2$  mm,  
346 respectively, when the overlap length is L1 and L2. As illustrated in the analysis reported in Figure 10  
347 and Figure 11, by increasing the substrate thickness, the strains on the overlap length tend to be closer  
348 to zero or negative. This is because thicker and stiffer substrates experience less strain, which can be  
349 observed by comparing L1W2T1 (Figure 10c), L1W2T2 (Figure 11a), and L1W2T3 (Figure 11b).  
350 Additionally, increasing the substrate thickness causes the ZSP to shift toward the center of the joint  
351 or to the other zone of the joint near the free end of the bonding area (Figure 12). This can be ascribed  
352 to the prevailing negative strain caused by the bending moment with respect to the positive strain  
353 caused by tension when the substrate is thicker. Finally, by comparing the results for specimens with  
354 different substrate thicknesses (Figure 10 and Figure 11) it is illustrated that as the substrate thickness  
355 increases the positive strain values on the overlap length becomes smaller. This is because the thinner  
356 substrates undergo deformation more easily than they can be recorded by strain measuring tools. This  
357 implies that the backface strain method is more reliable and evident in specimens with thinner  
358 substrates.

359

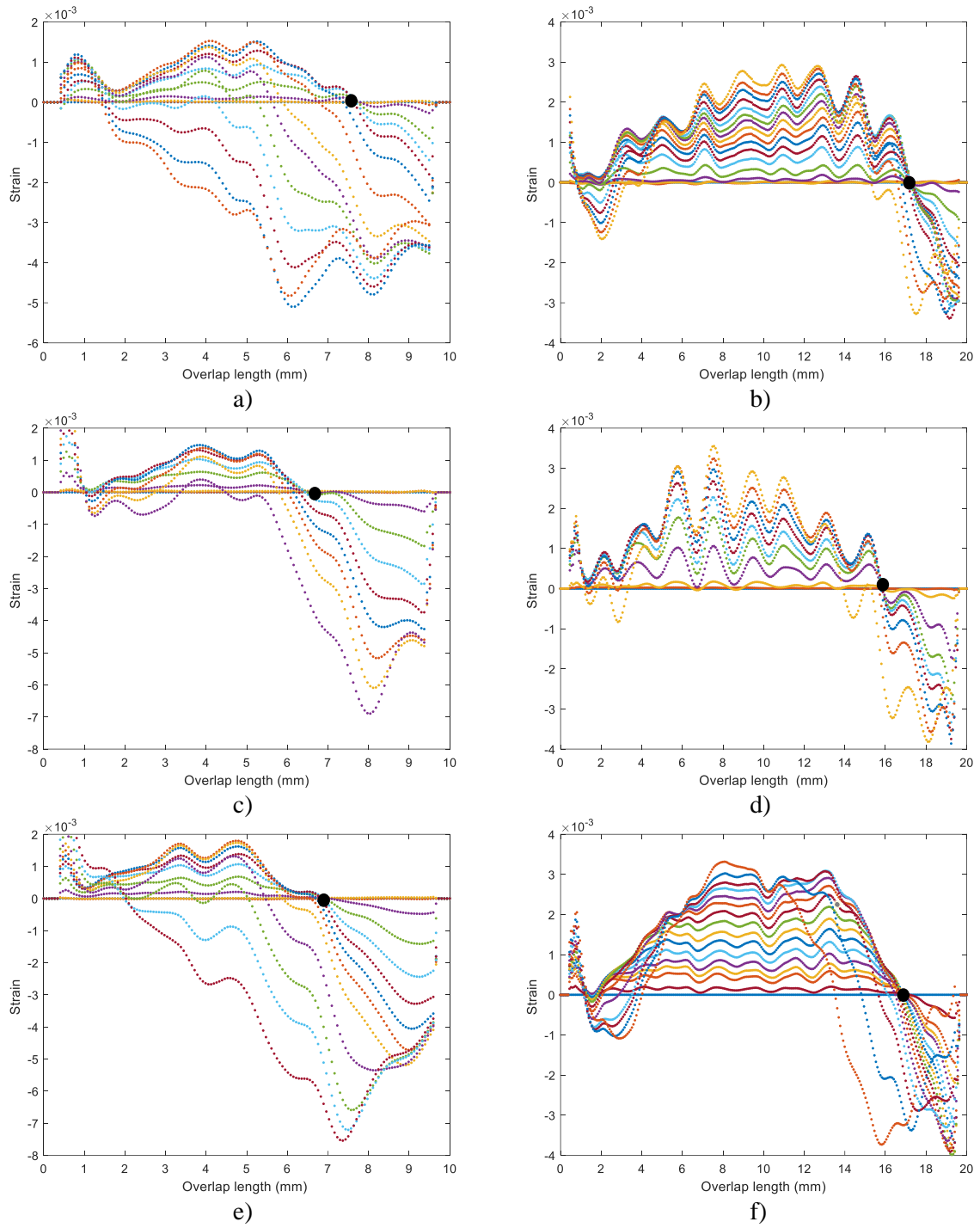


Figure 10 effect of bonding area dimension on the position of ZSP for substrate T1 a) L1W1T1 b) L2W1T1 c) L1W2T1 d) L2W2T1 e) L1W3T1 f) L2W3T1

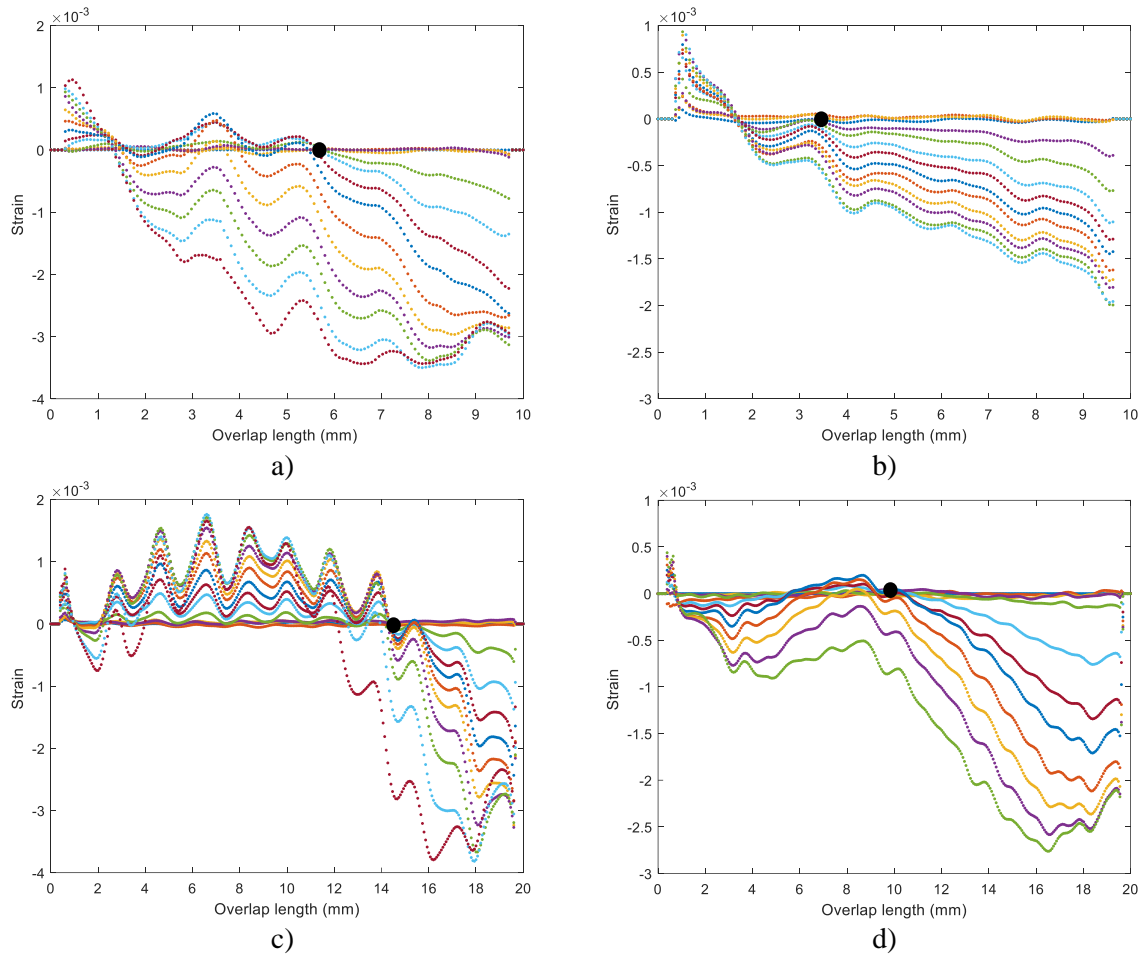


Figure 11 ZSP position for specimen with substrate thickness of T2 and T3 a) L1W2T2, b) L1W2T3, c) L2W2T2, d) L2W2T3

361 To summarize the effect of joint area dimension on the position of ZSP, Figure 12 provides an  
 362 overview of the results for all the joints together. The joint overlap length is normalized in order to  
 363 include also the effect of overlap length in one figure. In general, the substrate thickness played the  
 364 most important role in the position of the ZSP. The second important parameter is the overlap length,  
 365 and finally, the joint width showed the least importance. That is why a generic letter W is used in  
 366 Figure 12.

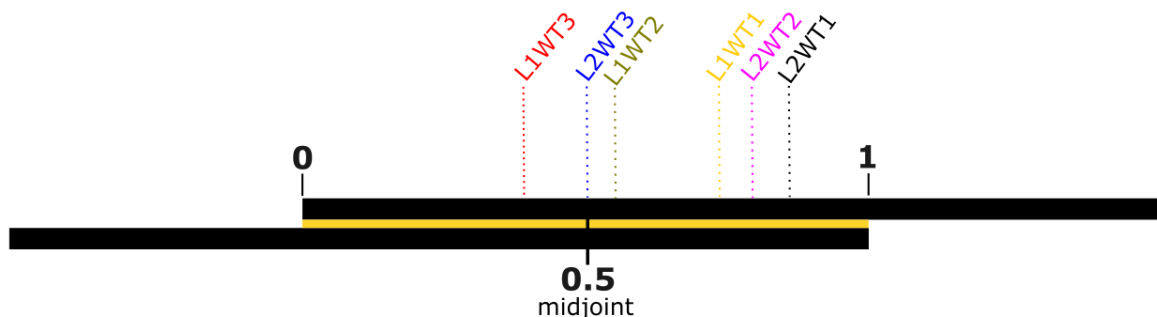


Figure 12 Summarizing the effect of joint dimensions on the position of ZSP (normalized overlap length)

367 Another point that is worth mentioning is that the strain map for composite substrates looks wavy (for  
 368 example, Figure 7c) when the DIC is used to acquire the strain due to the intrinsic texture of  
 369 composite materials. A microscopic image of the composite substrate is shown in Figure 13a. It is

370 mentioned in section 3.2 that each nominated point on the overlap length (Figure 7a) is the average of  
 371 all the points on the joint width with the same position on the overlap length. For example, the orange  
 372 point (Figure 13a) is the average of the strain on the orange line and the blue point is the average of  
 373 the blue line. Each line includes both warp and weft but not with the same ratio. This concept is  
 374 emphasized in Figure 13b. As can be seen, the blue line can contain more resin, more warp with  $E_{fl}$   
 375 (longitudinal modulus) and less weft with  $E_{ft}$  Young modulus. Whilst, the orange line contains less  
 376 resin, less warp with  $E_{fl}$  (transversal modulus) and more weft with  $E_{ft}$  Young modulus. Usually, the  
 377 modulus of the yarn in the longitudinal direction is higher compared to its modulus in the transversal  
 378 direction ( $E_{fl} < E_{ft}$ ). Therefore, the peaks can be related to the sections (the orange line which contains  
 379 more of  $E_{ft}$ ) with a smaller resultant Young modulus because based on the Hooke law those parts  
 380 undergo larger strain. Based on the same approach, valleys can be due to the sections (the blue line  
 381 which contains more of  $E_{fl}$ ) with larger resultant Young modulus.

382 On the other hand, the strain history obtained from the optical fibers (Figure 8c,d) is smooth in  
 383 comparison with the ones obtained by DIC. The reason is related to the high resolution of the DIC  
 384 analysis. On the other hand, the optical fiber sensors use a gauge pitch as a measuring point (Section  
 385 2) of 0.65 mm which does not allow to detect the peaks and valleys in the analyzed area. Furthermore,  
 386 as the backface strain for specimens L2W2T2 and L2W2T3 were also measured by the optical fibers  
 387 it is possible to compare the optical strain history of these two samples with the ones of DIC.  
 388 Comparing Figure 8c with Figure 11c and Figure 8d with Figure 11d, it is evident that both strain  
 389 measuring devices indicate the same point at the ZSP on the overlap length. The only difference is  
 390 that the optical fibers record more precise data at the edges as explained in Sections 3.2 and 3.3.

391

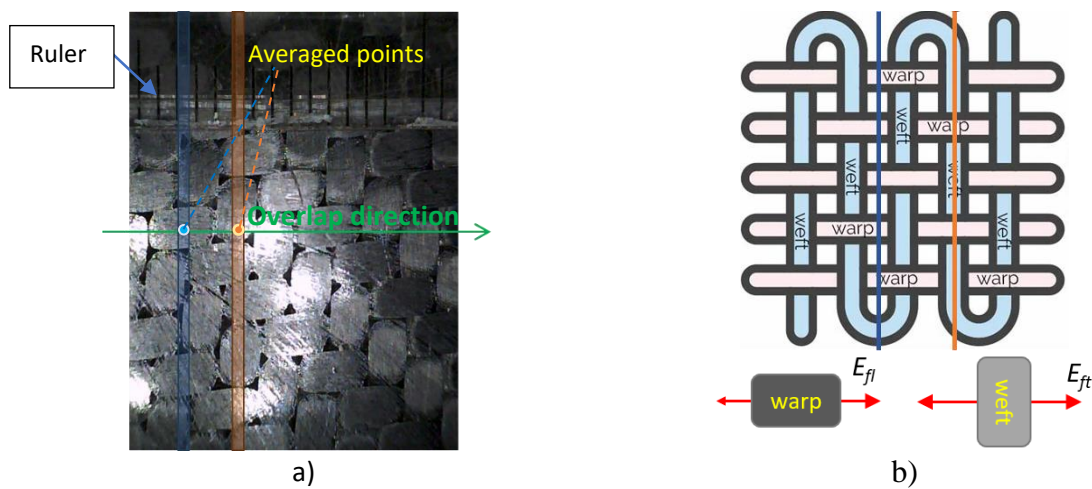


Figure 13 Composite substrate texture a) microscopic image of the laminate b) Ideal schematic of the laminate texture

#### 392 4. Cyclic loading

393 The results presented in Section 3 demonstrated that the ZSP method can be detected with both DIC  
 394 and optical fibers. Further, these methods can monitor the damage initiation and propagation in SLJs  
 395 with different bonding area dimensions under normal tensile loading. However, structures and  
 396 adhesive bonding joints could practically be subjected to cyclic or fatigue loads. In this section, the  
 397 effect of cyclic loading on damage initiation and propagation of an SLJ using both DIC and optical  
 398 fiber is studied. The ZSP method is employed as the criteria for the prediction of joint behavior.

399 Sample L2W1T2 (L=20 mm, W=10 mm, and T=20 mm) was used to study how the strain in the ZSP  
 400 varies under cyclic loading and whether the strain in ZSP changes from zero when plastic deformation  
 401 is accumulated in the joint. A six-cycle loading was considered in a way that in each cycle the load

402 increases at a constant velocity of 5 mm/min up to a certain amount, and then unloading starts with  
 403 the same velocity up to 50 N. After that, the next cycle starts considering the same velocity for  
 404 loading and unloading. The maximum load for the first, second, third, fourth, fifth and sixth cycles  
 405 are, respectively, 1 kN, 1.5 kN, 2 kN, 2.2 kN, 2.4 kN, and up to the sample rupture (for this sample  
 406 happened at approximately 2 kN). Figure 14 shows the load-displacement curve for sample L2W1T2  
 407 subjected to the mentioned cyclic loading. As can be seen in Figure 14, after the first and second cycle  
 408 the joint is still undamaged, and the unloading curve is following the loading curve. The quite small  
 409 variation in the displacement is due to the initial clearances of the joint. In the third cycle, the peak  
 410 load falls on a line which passes the first and second cycles' peaks. This could be interpreted as the  
 411 healthiness of the joint up to the third cycle peak load. However, there is a difference (approximately  
 412 28%) between the third unloading curve and the first loading curve, which signals the damage  
 413 initiation. After the third cycle, the cycles' peaks are not in a line anymore which again indicates that  
 414 the damage has already been initiated. Moreover, the difference between the fourth unloading curve  
 415 and the first loading curve becomes even larger (approximately 70%). In the fifth cycle, this  
 416 difference is 150% and the crack grows noticeably in the joint. Finally, the sixth cycle is where the  
 417 crack grows up to the joint rupture.  
 418

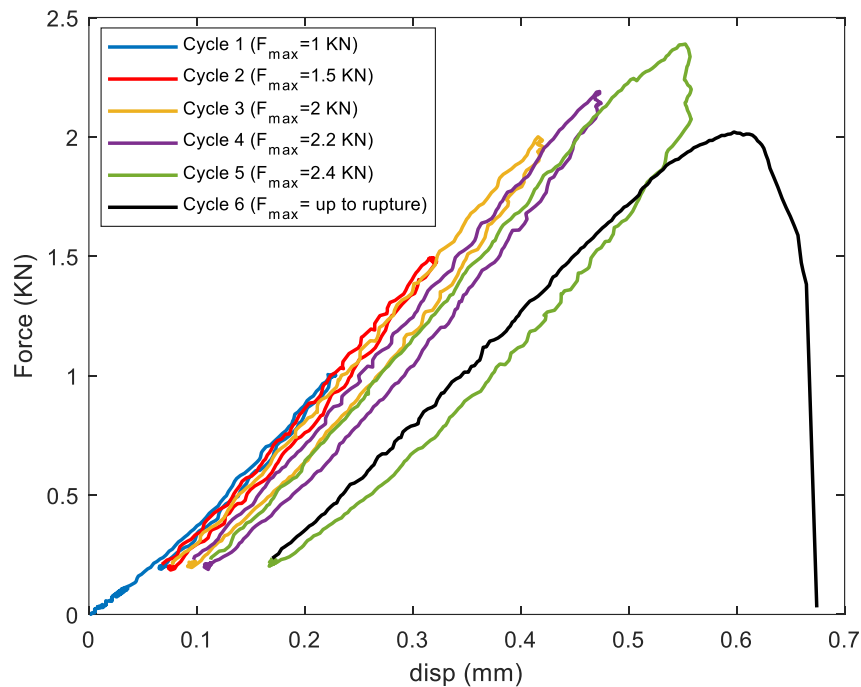


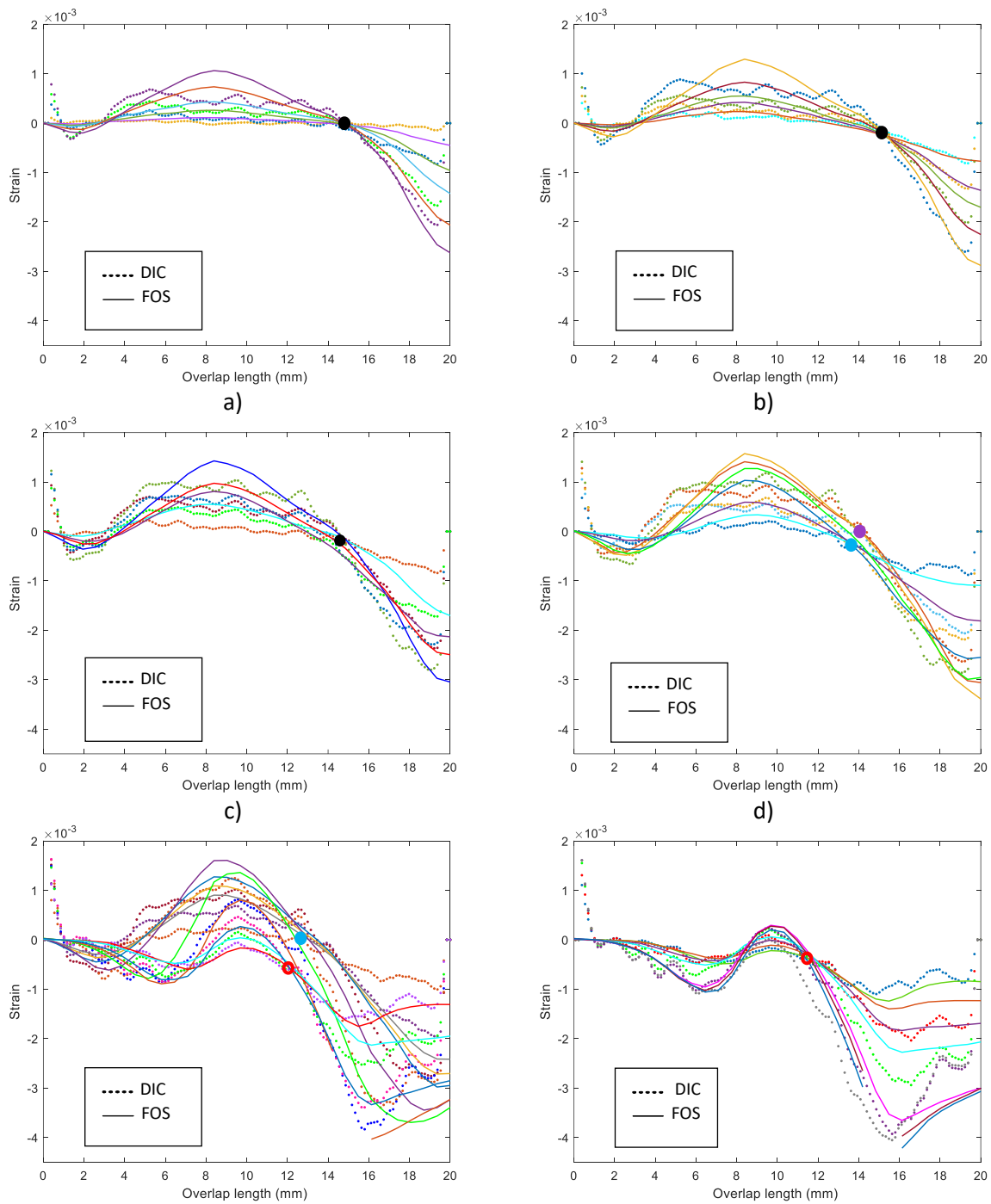
Figure 14 Load displacement curve for sample L2W1T2 under cyclic loading

419 Having the loading cycles explained, Figure 15a, b, c, d, e and f illustrate the strain on the backface of  
 420 L2W1T2 overlap length at each complete cycle. The solid lines are representatives of the data from  
 421 optical fibers, and the dashed lines represent the data from DIC. As can be seen in Figures 14, the  
 422 maximum recorded strains by the optical fiber are larger than the maximum strain recorded by the  
 423 DIC. This is because of the texture of the composite materials and the fact explained in detail in  
 424 section 3.5 about the waviness of DIC strain histories on the overlap length. For the same reason,  
 425 looking at the strain curves from the DIC data, a sort of plateau is visualized in the mid-area of the  
 426 joint.

427 According to the results of Figure 14, after the first and second cycle the joint is still in a healthy  
 428 condition, and this could be verified by results provided in Figure 15a,b. Figures a and b show that  
 429 the ZSP has still a value of zero strain after the first and second cycles. In the third cycle (Figure 15c)  
 430 the damage initiates as the ZSP starts recording a small negative value. However, before the crack  
 431 starts propagating the unloading starts. The ZSP is located initially at 15 mm (shown with a black  
 432 circle) and remains at the same position until the end of the 3<sup>rd</sup> cycle. In the 4<sup>th</sup> cycle, ZSP is shown  
 433 with the purple circle. It can be seen that the ZSP is slightly shifted to the left close to 14 mm, i.e., the

434 crack propagated but to a small extent and again unloading starts. After the crack stopped propagating  
 435 in the unloading part, a new point (blue circle) appears on the graph (Figure 15d) with a negative  
 436 constant value (close to zero) over time. The position of this point is where the ZSP will appear in the  
 437 next cycle. This is because the effective overlap length of the joint decreases after each cycle in such a  
 438 way that after each cycle it can be assumed that the loading is being applied to a joint with a shorter  
 439 overlap length. This new point appears in the unloading part of the cycle and exactly when the crack  
 440 stops propagating. As the unloading part of each cycle is close to the loading part of the next cycle  
 441 (Figure 14), this point represents the ZSP for the next cycle. In 5<sup>th</sup> cycle (Figure 15e), the blue circle  
 442 defines the ZSP which is at the same position predicted in the 4<sup>th</sup> cycle. Here, the crack propagates to  
 443 a large extent, but the joint has not yet reached the rupture. Therefore, the position of the new ZSP  
 444 will be estimated in the unloading part as the empty red circle. Finally, in the 6<sup>th</sup> cycle (Figure 15f),  
 445 the crack propagates completely, and the substrates are detached.

446



e)

f)

Figure 15 Backface strain distribution at each cycle up to the rupture for specimen L2W1T2 a) cycle 1 ( $F_{\max} = 1$  kN): healthy condition b) cycle 2 ( $F_{\max} = 1.5$  kN): healthy condition c) cycle 3 ( $F_{\max} = 2$  kN): damage initiation d) cycle 4 ( $F_{\max} = 2.2$  kN): small damage propagation e) cycle 5 ( $F_{\max} = 2.4$  kN): noticeable damage propagation f) cycle 6 ( $F_{\max} = 2$  kN): damage propagation up to rupture

447 In cyclic loading, there are two ways to analyze the joint. The first one is that at each cycle it can be  
 448 assumed that the loading is being applied to a new SLJ with its own ZSP. It is enough to monitor the  
 449 related ZSP strain at each cycle and understand the behavior of the joint as it is done for a normal SLJ  
 450 subjected to tensile loading. As in real components, it might not be possible to install the DIC because  
 451 of its dimensions, and as explained before the effective overlap length of the joint changes in each  
 452 cycle it might not be precise to use strain gauges. Therefore, to use this approach optical fibers are the  
 453 most useful tool to be employed by monitoring the initial ZSP continuously. Figure 16a shows the  
 454 strain history versus time for points on the overlap length the same as already explained in section 3.2  
 455 for Figure 7b. Solid lines show DIC data while dashed lines present optical fiber data. In Figure 16a,  
 456 different cycles can be easily distinguished. In general, when the strain increases in absolute value it  
 457 means the sample is in the loading phase of the cycle otherwise the sample is in the unloading phase.  
 458 Therefore, after each absolute minimum value of strain, the next cycle is going to start. As expected,  
 459 there are not too many points with a strain value of zero when the joint is still in healthy condition.  
 460 Those points are representative of the ZSP which correspond to the black circles in Figure 15a, b  
 461 and c. By plotting the strain history of the original ZSP vs time as well as Force vs time in the same  
 462 graph (Figure 16b) the performance of ZSP and the behavior of the joint can be explained better. As  
 463 explained previously in this section based on Figure 14 and Figure 15, and according to Figure 16b,  
 464 the joint is in a safe condition up to the peak of the third cycle because the ZSP strain remains  
 465 approximately around zero. In the unloading phase of 3<sup>rd</sup> cycle, a small drop can be seen in the ZSP  
 466 strain curve. This might signal the damage initiation, but it is not yet confirmed because ZSP might go  
 467 back to zero value at the end of the unloading phase. Since the curves are being filtered there is a  
 468 possibility to find a point very close to the real ZSP instead of the real ZSP itself. This will result in an  
 469 oscillation close to zero in the found ZSP value. In the 4<sup>th</sup> cycle, the ZSP starts gaining value before  
 470 reaching zero value. This confirms that the damage was initiated in the previous cycle. Up to the 4<sup>th</sup>  
 471 cycle, the crack starts propagating by the force reaching its maximum value and in the unloading  
 472 phase. In the 5<sup>th</sup> cycle, the propagation starts shortly before the peak load, and in the loading phase  
 473 with a drastic drop in the ZSP value at peak load. Finally, in the 6<sup>th</sup> cycle, the crack starts propagating  
 474 shortly after the loading started and the joint arrives at the rupture at peak force.  
 475

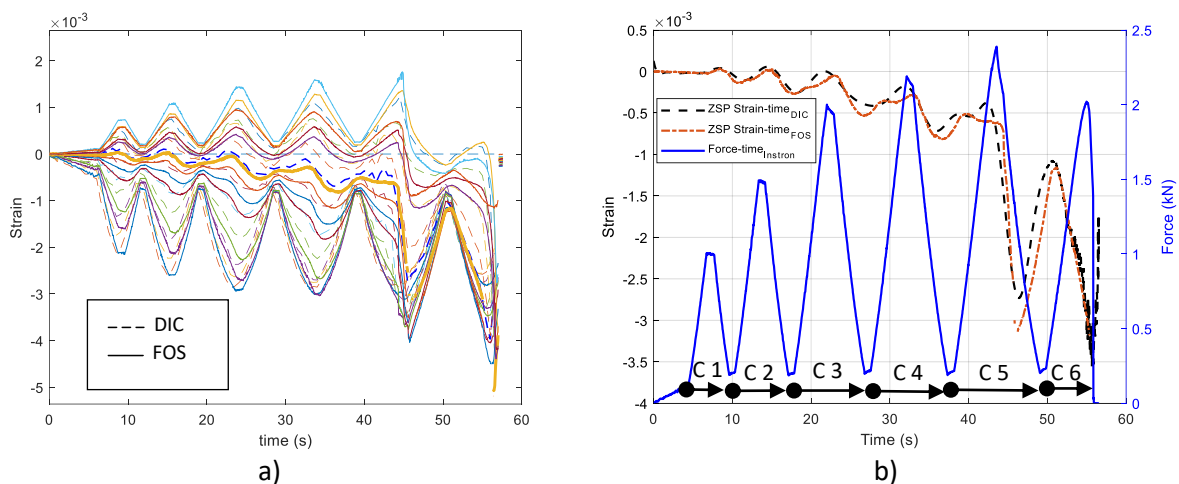


Figure 16 ZSP strain using DIC and FOS (LUNA) as well as L2W1T2 force diagram versus the time

477 **5. Conclusion**

478 The present work aims to propose the so-called zero strain point (ZSP) as a criterion to  
479 monitor the health condition of composite single lap joints. Furthermore, the effectiveness  
480 and reliability of this method were studied when the joint dimension (in particular, adherend  
481 thickness, joint width, overlap length), and loading type (quasi-static and cyclic) change. To  
482 validate the results tests were performed with DIC (digital image correlation) system and  
483 Fiber Optic Sensors. The drawn conclusions are as follows:

- 484 • Considering both cyclic and static tensile loading conditions, the ZSP point  
485 can be utilized as a criterion for adhesive SLJs to predict the damage  
486 initiation and propagation up to the rupture. This fact was verified precisely  
487 with both DIC and optical fiber results.
- 488 • According to the optical fiber results, both sides of SLJs (both loaded and  
489 fixed adherends) experience approximately the same strain. Therefore, to the  
490 ZSP method, it is enough to observe the strain on the backface of one  
491 adherend.
- 492 • Based on the DIC backface strain map, the damage initiates and propagates  
493 from both ends of the bonding area taking into account that the propagation  
494 is slightly faster from the loading side of the joint.
- 495 • The joint width showed negligible effect on the position of ZSP in joints with  
496 both adhesive types.
- 497 • In joints with larger overlap lengths, the passage from positive to negative  
498 strain allows for better detection of the ZSP position. Therefore, the ZSP is  
499 more reliable in joints with larger overlap lengths.
- 500 • Increasing the substrate thickness causes the ZSP to move toward the middle  
501 or free edge of the joints. the same results were obtained by decreasing the  
502 overlap length.
- 503 • When the substrate thickness is relatively large, and the overlap length is  
504 relatively short, only negative strains are observed in joints. Therefore, the  
505 ZSP might not be clearly visible, and this implies a limitation on the  
506 application of the ZSP.
- 507 • The strain history on the SLJs' overlap length is wavy when analyzing the  
508 DIC data due to the texture of composite materials. Conversely, it is smooth  
509 when the FOS (LUNA) data is being considered because the strain will be  
510 recorded based on the optical fiber deformations.
- 511 • In cyclic loading, although each cycle has its own ZSP which can be used as  
512 the criterion to observe the joint condition after the damage initiation, it  
513 would be easier and more effective to use the primary ZSP before the  
514 damage initiation to monitor the joint behavior.
- 515 • Although DIC might not be installed on a component to monitor the healthy  
516 condition of the joint, optical fibers could be mounted in order to do an  
517 online and in-situ monitoring of the joints.

518 **Declaration of AI and AI-assisted technologies in the writing process:**

519 During the preparation of this work, the author(s) used ChatGPT 4 and Quillbot to improve  
520 the text's grammar. After using this tool/service, the author(s) reviewed and edited the content  
521 as needed and take(s) full responsibility for the publication's content.

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524

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