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Experimental investigation of the fatigue behavior of Short Fiber Reinforced Polymers using specimens of highly coherent fiber orientation

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Abstract

The mechanical behavior of injection molded Short Fiber Reinforced Polymers is usually investigated by testing specimens extracted from injected plates at different orientations with respect to injection main flow direction. A characteristic layered microstructure through the plate's thickness results from the manufacturing process: fibers preferentially align parallel and perpendicular to the main flow direction in the outer layers (shells) and in the inner layer (core), respectively. This peculiar microstructure hinders the evaluation of local properties of each individual layer, which are highly fibers orientation dependent. Material properties of each layer may largely differ to each other, so the local response to the applied load. This would lead to a stress distribution across the specimen thickness which varies as the fiber orientation does. Moreover, the mechanical properties of each layer could vary independently over cycling load, therefore altering the stress distribution further throughout a fatigue test. Local properties of individual layers together with their stiffness degradation trend are required to model the fatigue behavior of these materials. An experimental study was carried out to understand fatigue behavior of short fiber reinforced polymers using specimens of highly coherent fiber orientation by milling the extracted specimens to preserve only shell layer. Thus, fatigue characterization of each layer and comparison with multilayered specimens became possible. Tensile tests were also performed to support the analysis and discussion of the finding of the fatigue test. Digital image correlation technique was used to monitor the surfaces' displacements and strains of specimens throughout testing duration, and further support and verify experimental observations.

Key-words: short fiber reinforced polymers, fatigue, fiber orientation, shell-only, digital image correlation, stiffness degradation

Abstract in lingua italiana

Il comportamento meccanico dei polimeri rinforzati con fibre corte stampati ad iniezione viene solitamente studiato testando campioni estratti da piastre iniettate con orientamenti diversi rispetto alla direzione del flusso principale di iniezione. Dal processo di produzione risulta una caratteristica microstruttura stratificata attraverso lo spessore della piastra: le fibre si allineano preferibilmente parallelamente e perpendicolarmente alla direzione principale del flusso rispettivamente negli strati esterni (gusci) e nello strato interno (nucleo). Questa peculiare microstruttura ostacola la valutazione delle proprietà locali di ogni singolo strato, che dipendono fortemente dall'orientamento delle fibre. Le proprietà del materiale di ciascuno strato possono differire notevolmente tra loro, quindi la risposta locale al carico applicato. Ciò porterebbe a una distribuzione delle sollecitazioni sullo spessore del provino che varia con l'orientamento delle fibre. Inoltre, le proprietà meccaniche di ciascuno strato potrebbero variare in modo indipendente in base al carico ciclico, alterando quindi ulteriormente la distribuzione delle sollecitazioni durante una prova di fatica. Le proprietà locali dei singoli strati insieme alla tendenza al degrado della rigidità sono necessarie per modellare il comportamento a fatica di questi materiali. È stato condotto uno studio sperimentale per comprendere il comportamento a fatica dei polimeri rinforzati con fibre corte utilizzando campioni con orientamento delle fibre altamente coerente mediante fresatura dei campioni estratti per preservare solo lo strato del guscio. Pertanto, è diventato possibile la caratterizzazione della fatica di ogni strato e il confronto con campioni multistrato. Sono state eseguite anche prove di trazione per supportare l'analisi e la discussione dei risultati della prova di fatica. La tecnica di correlazione delle immagini digitali è stata utilizzata per monitorare gli spostamenti delle superfici e le deformazioni dei campioni durante tutta la durata del test e per supportare e verificare ulteriormente le osservazioni sperimentali.

Parole chiave: polimeri rinforzati con fibre corte, fatica, orientamento delle fibre, solo guscio, correlazione delle immagini digitali, degrado della rigidità

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Introduction

The use of injection molded short fiber reinforced polymers (SFRPs) shows a growing trend for various applications over the last years. In general, SFRPs display outstanding stiffness and strength to weight ratio, comparable to or even higher than metals. The superior properties SFRPs are provided by reinforcement effect of fibers, and it is dependent on fiber length. However, compounding and injection molding cause significant fiber breakage. The result of shortening the fibers is reduction of their reinforcing effect. There exist several manufacturing methods, which are able to manufacture continuous fiber reinforced polymers, such as hand lay-up, resin transfer molding, filament winding etc. What makes injection molding favorable, despite the reduced reinforcing effect, is the excellent mouldability and ability to manufacture lightweight structures of complex shapes at high rates. Injected molded SFRPs could be used for non-load-bearing applications such as air intake manifolds, wheel rims and engine cover or for load-bearing applications such as clutch pedals. SFRP components could be subject to either static or cyclic loading during their service lives. Therefore, the characterization of the static and fatigue behaviors of these materials has become crucial for a reliable and effective design of components.

Despite the many advantages of injected molded SFRPs, their anisotropic structure makes characterization of their properties challenging. The layered structure of SFRPs, where fibers tend to align in different orientations within each layer, is induced by the velocity profile of the molten material inside the mold cavity [1]. The layered structure of SFRPs is shown in Figure 0-1.

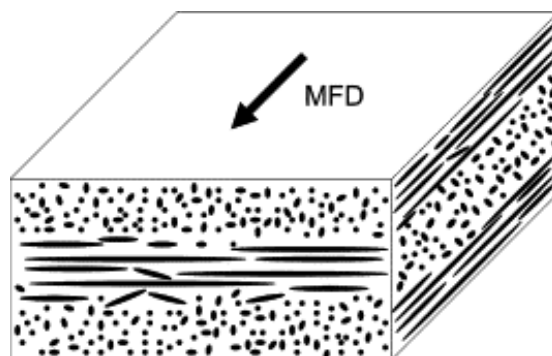


Figure 0-1: Layered shell-core-shell structure of an injected molded SFRP [2]

Fibers tend to orient perpendicular to mold flow direction in the middle section which is so called core layer. Conversely, they tend to align along the mold flow direction at the top and bottom section which are so called shell layers.

Characterization of the mechanical behaviors of SFRPs under static and cyclic loading is usually performed using as-molded (full) specimens by cutting the specimens out from the injected molded plates at different orientations as was shown in Figure 0-2. Beside the fiber orientation [2]–[7], several factors influence the static and fatigue properties of SFRPs: temperature [4]–[8], their moisture content [8]–[14], stress ratio [7], [15], the testing frequency [4], [16], [17], fiber content [18] and length [3], [18] etc. However, despite literature is rich in studies focusing on the SFRPs, the investigation on how each individual layer contributes to the overall fatigue behavior is somehow overlooked. This information could be crucial when modelling SFRPs' response to the cycling load for finite element fatigue simulations. Since stress may redistribute among the layers due to damage development over a fatigue test, knowing the static and fatigue strengths of each layer allows inferring how close that layer is to failure. More generally, the same reasoning holds for all the possible orientations. Testing full specimens provides limited information on the properties of each layer of SFRPs.

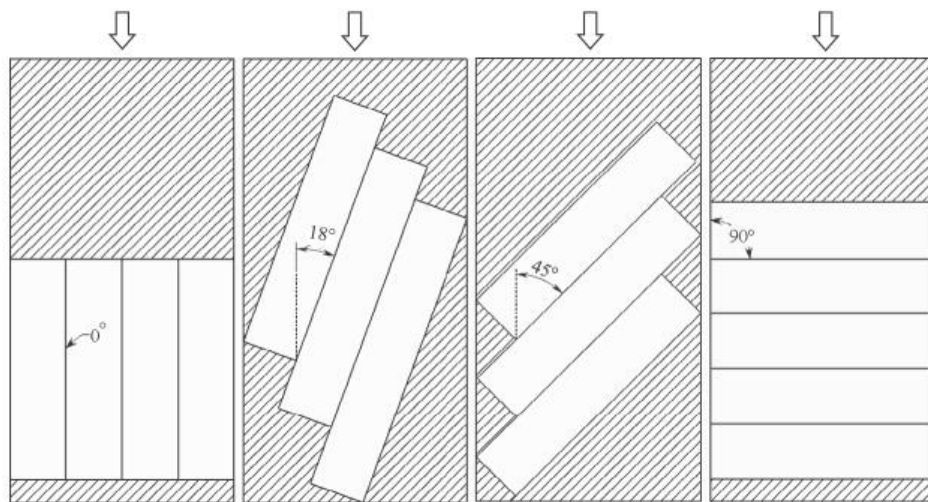


Figure 0-2: Specimens cut out from plates at different orientations

This work aims to investigate local properties of the layers. In this scope, some specimens were milled to preserve only the shell layers where fibers tend to orient in a preferential direction. Testing both milled and full specimens in quasi-static and fatigue tests would instead provide additional information on the properties of the individual layers of SFRPs. Stiffness degradation of both full and milled specimens during fatigue tests were monitored to further understand the fatigue mechanisms of

the SFRPs. Stiffness degradation is aimed to be used to understand how failure mechanisms take place in SFRPs. In [19], it is observed that milled specimens display stress concentration around fillet radii, since they failed around fillet radii unlike full specimens. Digital Image Correlation (DIC) method was used to assess if milled specimens are affected by stress concentration around fillet radii and also to further support the experimental results.

In Chapter 1, a literature review is reported. It includes previous studies and knowledge about the thesis subject and tools used such as DIC. Chapter 2 describes material, specimen manufacturing, testing conditions for both fatigue and tensile tests. Results of the experimental activity related to fatigue tests and tensile tests are reported in Chapter 3. Chapter 4 provides a further discussion of the results reported in Chapter 3. Finally, all conclusions drawn in the whole work are summarized and emphasized in Chapter 5.

1. State-of-the-art

1.1 Overview of SFRPs

The major constituents of SFRPs are reinforcing fibers and matrix which acts as a binder for the fibers. Thermoplastics and thermosets are the most used matrix materials for SFRPs. Although low density of polymers is the main advantage over metals, their tensile modulus and tensile strength are much lower than that of metals. Due to cross-links between molecular chains, the thermal stability of thermosets is their main advantage over thermoplastics. However, their low ductility and inability to be melted and reprocessed make them unfavorable to be used as a matrix material. Thermoplastics do not contain cross-links like thermosets, only weak secondary bonds are present between the molecular chains. Therefore, their mechanical properties highly depend on the environmental conditions since absence of cross-links make them highly temperature dependent due to weakening of intermolecular bonds with increasing temperature. They can also be hygroscopic, so their mechanical behaviors vary considerably with different humidity conditions. However, thermoplastics are highly ductile, where elongation-at-break can reach remarkably high values. They have high fracture energy which indicates that these materials can be used for toughening purposes which is a crucial contribution since reinforcing fibers are very brittle. They also can be reprocessed several times, with a certain degree of degradation, which is an important attribute for environmental reasons. Polyamides are the most widespread thermoplastic for fiber reinforced polymer industry.

Reinforcing fibers are the other main constituent of SFRPs. Fibers carry the highest portion of the load thanks to their higher stiffness than matrix material depending on the loading direction. They have lower density and much higher tensile strength and tensile modulus than steels. However, they cannot be used alone since they are very brittle. This is the reason they are used with matrix materials. While matrix materials contribute to ductile behavior of composites, fibers increase the strength and stiffness. Glass fiber is the most widespread one mainly due to its low cost among all available fibers. High tensile strength and high chemical resistance are other

intriguing properties of glass fibers. Although they have relatively lower tensile modulus, higher density, and lower fatigue strength over other commercial fiber materials, their cost advantage makes them the most used reinforcing fiber in the industry.

Anisotropy of SFRPs was induced by the presence of fibers which make mechanical properties of composites significantly dependent on direction. Moreover, injected molded SFRPs are characterized by a through-the-thickness high degree of anisotropy induced by different fiber orientation distribution due to the peculiar flow of the molten material during the injection process. The injection molding of the SFRPs results in a skin-shell-core layered microstructure in terms of fiber orientations [1], [3], [6], [20], [21]. Although the fiber orientation distribution through thickness depends on the process parameters such as melt temperature, mold wall temperature, filling time, position of gate/s, pressure, shape, and thickness of the part etc., the fibers tend to align parallel to the mold flow direction (MFD) within the shell layer, and transversally to the MFD within the core layer. A random fiber orientation distribution, instead, occurs in the very thin skin layer. The layered structure of an injected molded SFRP is schematized in Figure 1-1.

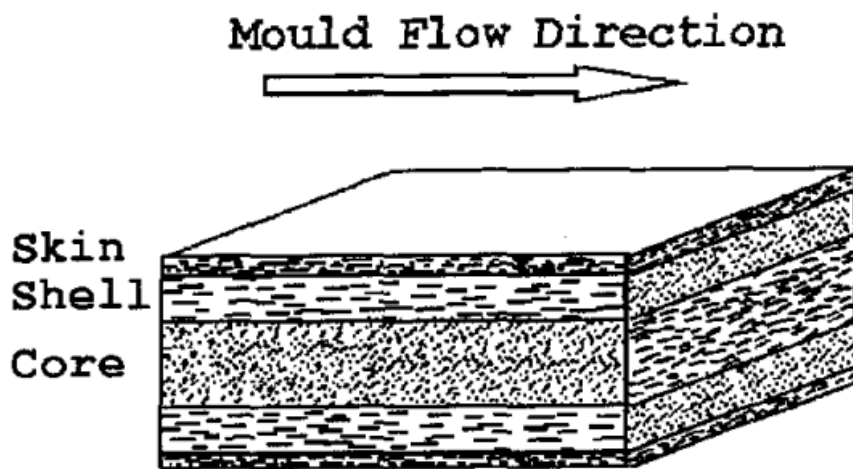


Figure 1-1: Skin, shell and core layers of an injected molded SFRP component [20]

The velocity profile of the molten material inside the mold cavity is the reason why injection molded SFRPs retain a layered structure. Several factors, such as adhesion between the mold wall and the melt, temperature variation of the melt, and shear thinning phenomenon affect the velocity profile of melt [20]. Molten material approaching the mold walls solidifies quickly since mold walls are colder than the melt. Since change of orientation of the fibers requires some time depending on their length and initial orientation, the result is a random distribution of fibers for a thin layer which is in contact with the mold wall (formation of skin layer).

Material flowing in between the walls is subjected to shear forces due to the adhesion between the mold wall and melt. The velocity profile of the melt, thus, should be parabolic where it is zero at the mold walls. However, the velocity profile is affected by temperature variation of the melt and shear thinning phenomenon. The final velocity profile of the melt would be as in Figure 1-2, where it can be assumed uniform in the middle and rapidly approaching zero close the mold walls (or frozen layer of material).

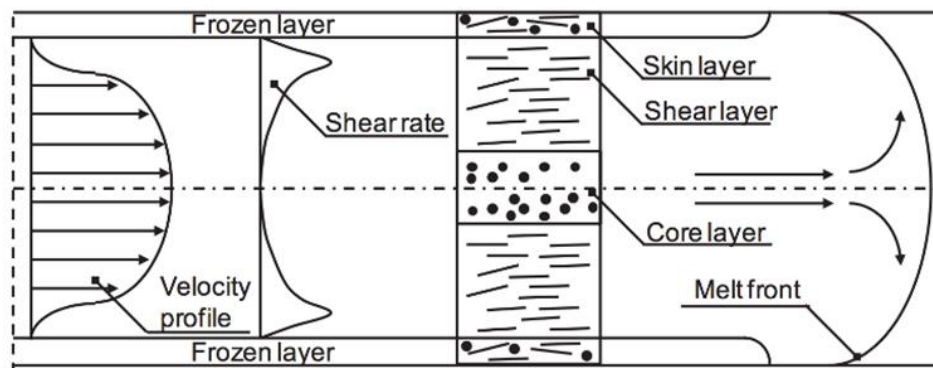


Figure 1-2: Schematic representation of velocity profile and fiber orientation of melt inside the cavity

Although the velocity profile is uniform-like in the middle, it is not constant as fibers travel from mold gate to melt front (or flow front). The thickness of the frozen material layer reduces from the mold gate to the flow front. This causes the fibers in the middle section to flow in an expanding cross-section which results in a diverging flow. Fibers not in the middle section are affected by shear flow.

The effect of diverging and shear flow to fiber orientation was shown in Figure 1-3 [20]. Due to the velocity variation of a single fiber at its ends, diverging flow rotates the fiber perpendicular to the mold flow direction. Conversely, shear flow rotates the fiber parallel to the mold flow direction.

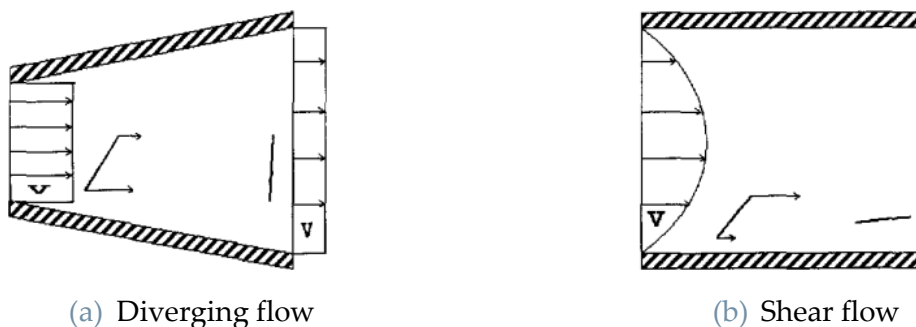


Figure 1-3: Effect of diverging and shear flow to the orientation of fibers [20]

As a result of this velocity profile, the fibers flowing close to the walls orient themselves along the mold flow direction under the influence of shear flow (formation of shell layer). The fibers flowing in the middle tend to orient perpendicular to the mold flow direction under the influence of diverging flow (formation of core layer). Furthermore, a through thickness orientation gradient depending on fiber length was reported in [3]. Shorter fibers tend to align in a random manner, whereas longer fibers, which improve mechanical properties more than the shorter ones, were more predominantly align in the mold flow direction. It is also reported that fiber concentration also varies through the thickness. It decreases from the core to the skin [1]. All these effects result in an anisotropic behavior of injected molded SFRPs.

1.2 Overview of mechanical behavior of SFRPs

The studies on the mechanical behavior of SFRPs were usually performed by extracting the specimens from injection molded plates in different orientations, as shown in Figure 1-4.

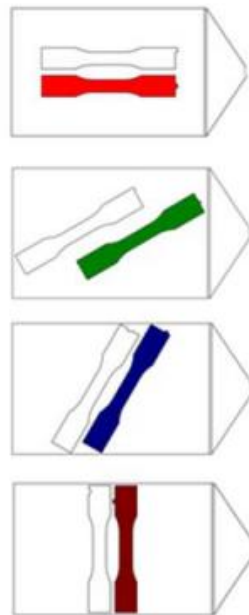


Figure 1-4: Specimens extracting in different orientations [22]

Tensile modulus, tensile strength, and fatigue strength of the SFRPs were reported to decrease from 0° to 90° full specimens, whereas strain-at-break increased in the same

order for full specimens [2], [4], [5], [23]. Stress strain curves of full specimens at different orientations was shown in Figure 1-5 [2].

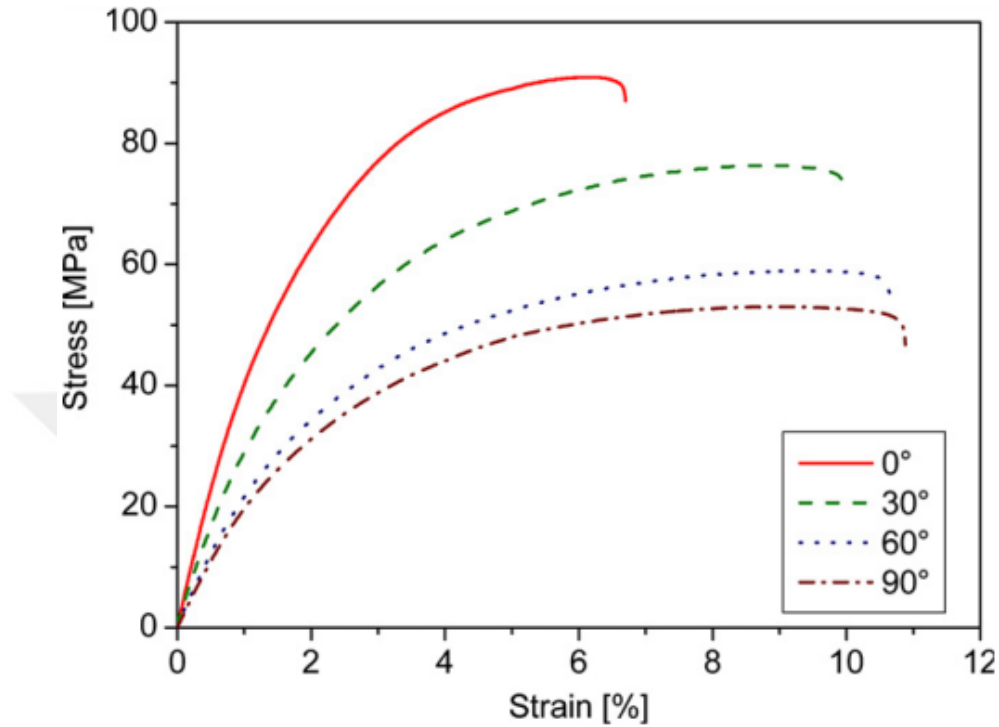


Figure 1-5: Stress–strain curves for full specimens at different orientations [2]

This behavior was expected since the shell layers are predominant with respect to the core layer for the specimens in those studies. It is well known that the tensile strength of unidirectional composite materials in fiber direction is much higher than in transversal one. The fibers, due to their very high stiffness with respect to matrix material, carry the highest share of the load in longitudinal direction. However, fibers generally behave as hard inclusions for transversal loadings and matrix carries the load. For a full 0° specimen, fibers in the shell layer are mainly aligned in the loading direction, and fibers in the core layer are mainly oriented transversally to the load. The situation is quite the opposite for a full 90° specimen. Therefore, higher values of tensile strength and modulus are expected for full 0° specimens.

Increasing strain-at-break from full 0° to full 90° specimens can be explained by high stiffness of the reinforcing fibers. For 0° full specimens, the fibers in the shell layers prevent large extension in the loading direction. For 90° full specimens, the shell layers are more compliant since the fibers are oriented in transverse direction. However, fibers in the core layers prevent extension of the specimen for full 90° specimens. If the relative thickness of shell layers is more than that of the core layers, contribution of shell layers to the overall behavior becomes more pronounced. That

is why increasing ductility was observed in the mentioned studies from 0° to 90° full specimens.

If thickness of core and shell layers are comparable, the behavior may change since the core layers contributes more to the overall behavior of the specimen. Therefore, strain at break could be higher at the intermediate values of orientation angle instead of full 90° specimens as in Figure 1-6 [3].

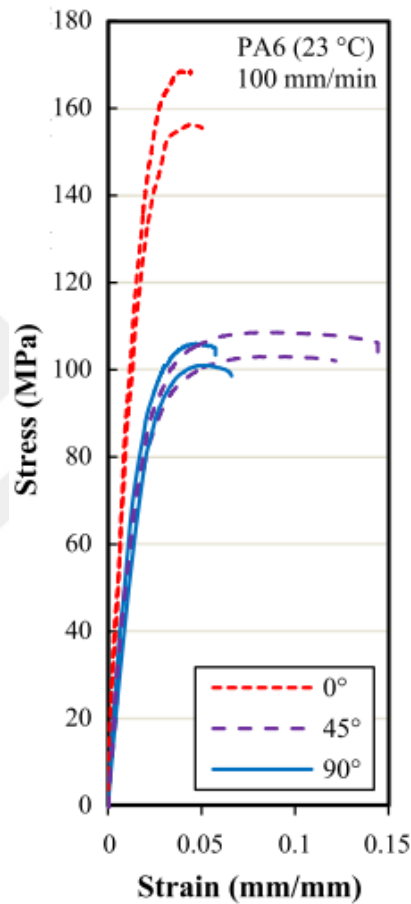


Figure 1-6: Stress–strain curves for full specimens at different orientations [3]

The loading condition in a uniaxial fatigue test with a positive load ratio is similar to that of a tensile test. It is a repetition of the same loading condition several times. Therefore, the same behavior with tensile strength of SFRPs was observed in fatigue strength for the same abovementioned reasons. A common way to describe fatigue limit of the materials is to plot an S-N curve. It correlates the applied stress (usually amplitude or maximum) to number of cycles to failure. Typical S-N curves for specimens in different fiber orientations is shown in Figure 1-7 [22].

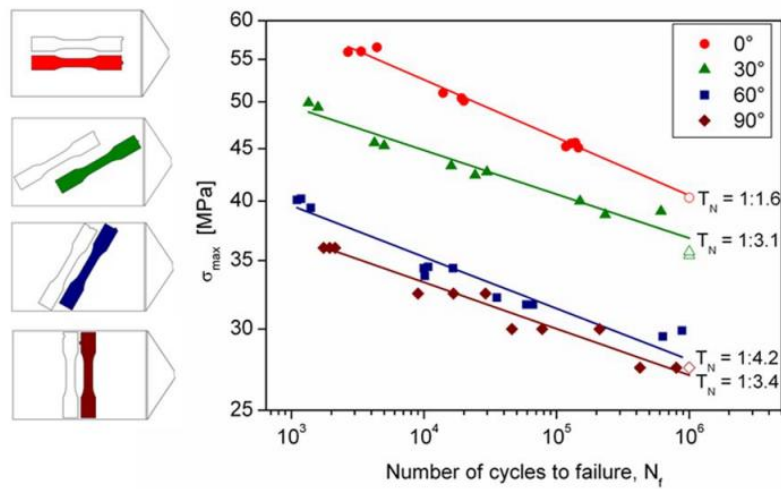


Figure 1-7: Specimens with different orientations and their S-N curves [22]

In order to further understand the effect of fiber orientation and thickness of the shell and core layers on the mechanical behavior of the SFRPs, tensile and fatigue tests were performed for PA6GF30 specimens in a previous study [2]. The injection parameters were adjusted so that the thickness of the core layer was relatively thin with respect to the thickness of the shell layers. Specimens with different orientation angles with respect to the mold flow directions were tested. Ultimate tensile stress and fatigue strength of the specimens seemed to be accurately predicted by using Tsai-Hill criterion as shown in Figure 1-8.

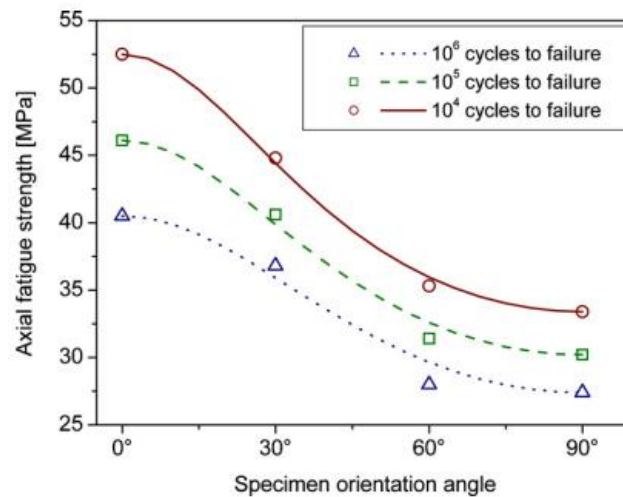


Figure 1-8: Experimental fatigue strength values and interpolation by Tsai-Hill like criterion [2]

The anisotropic behavior of fiber reinforced PA6 was also investigated in other studies by testing specimens with different thicknesses [6], [7]. It was observed that

the higher the thickness of the specimens, the higher the ratio between the core thickness and the total thickness. Tensile and fatigue tests showed that the degree of anisotropy of the SFRPs decreases increasing the ratio between the core thickness and the total thickness. Thus, the tensile properties in direction parallel and perpendicular to the specimen orientation were more similar. Tsai-Hill criterion again seemed to well estimate the tensile strength and the fatigue strength. However, for all the studies, the mold of the specimens and injection molding parameters were carefully designed and adjusted to have a thin core layer. Real components, however, could display core with not negligible extension. Therefore, it is crucial to evaluate the effect of the core layer on the local fatigue strength of the material. This could provide useful information to designers, especially in the framework of structural numerical simulations of the fatigue life of components.

Structural analysis, which accounts for fiber orientation obtained by an injection molding process are based on the Through Process Modelling (TPM) approach. The simulation will be able to account for anisotropic behavior of material, which is different for each element, given the relationship between the components of orientation tensor and material elastic properties [24]. Some analytical models such as Folgar-Tucker model is able to estimate how fiber orientation develops during an injection process [24]. Thus, the fiber orientation distribution of an SFRP part can be estimated by using commercial software in which these models are embedded.

TPM approach was used to understand the relationship between the fatigue failure and local stresses through the thickness of the specimens in another study [22]. Comparison of orientation distribution of an SFRP predicted by analytical models and measured experimentally by micro-computed tomography (μ CT) was performed. As it was shown in Figure 1-9, measured and estimated values of orientation tensors, which describes the orientation distribution, were quite close.

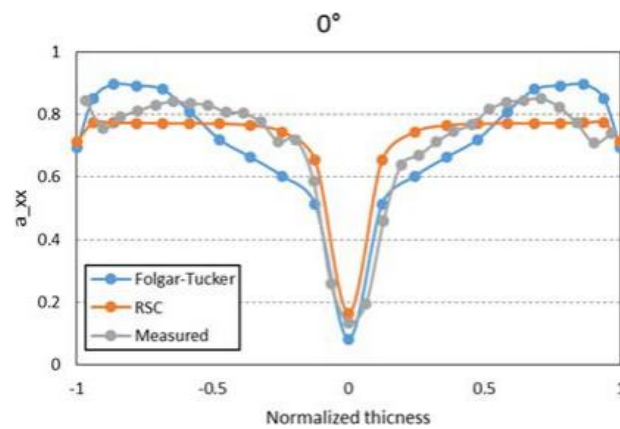


Figure 1-9: Comparison of orientation tensors of a 0° specimen between measured and estimated values [22]

After a TPM analysis was performed in the same study, it was observed that stresses in 0° layers were always predominant [22]. It was also observed that there was a correlation between the maximum local stresses and crack nucleation region. However, it is still to be determined which layer was the one failed first without data about stress redistribution across the specimen through the fatigue test. Therefore, the present study aims to fill this literature gap by the investigation of the static properties of SFRPs and monitor their evolution over fatigue tests using SFRPs with high fiber alignment to understand the role of each layer of full specimens.

1.3 Digital Image Correlation

Digital Image Correlation (DIC) technique is a way to obtain local displacement and strain field which often to be used to validate simulated quantities. Mechanical tests are performed on the specimens in order to characterize the mechanical properties of the materials and understand their behavior. There are many ways to obtain displacement and strain data of the tested specimens such as using crosshead and extensometer data. However, a strong assumption which is that the strain field is accepted as homogenous is made in this case. A material could show heterogeneous displacement and strain distributions for several reasons such as presence of voids or notches. In the case of SFRPs, the heterogeneous displacement field may be much more evident due to the anisotropic and heterogeneous microstructure of the material. Thus, obtained values of displacement and strain by using those methods are just average values. The DIC technique provides full-field displacement of the specimens unlike other methods.

DIC method is based on the identification of a certain region of interest within the image of the deformed structure with reference to the image of the undeformed structure. The technique requires at least a camera positioned to capture the specimen surface. The images are taken during the testing duration by starting from the image of the undeformed structure. A speckle pattern has to be created on the surface of the specimen prior to the testing as shown in Figure 1-10.



Figure 1-10: A speckled specimen

As a result of speckle pattern, the grey-scale values of each region which is so called as subset are guaranteed to be unique. The idea is to detect the deformation of each subset between the undeformed and deformed configuration. In Figure 1-11, a representation of a subset was shown both in undeformed and deformed configuration.

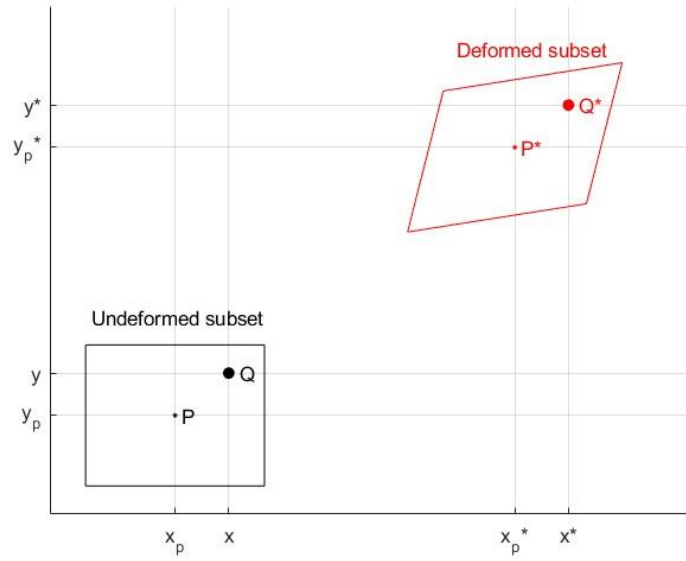


Figure 1-11: Deformation of a subset

Point P and P* are the subset centers for undeformed and deformed images, respectively. Point Q and Q* are the location of any points other than subset centers for undeformed and deformed images, respectively. The location of point Q* in the deformed image can be expressed as:

$$\begin{cases} x^* = x + u + \frac{\partial u}{\partial x} \Delta x + \frac{\partial u}{\partial y} \Delta y \\ y^* = y + v + \frac{\partial v}{\partial x} \Delta x + \frac{\partial v}{\partial y} \Delta y \end{cases} \quad (1.1)$$

where:

- x and y are the locations of the point Q in the undeformed image
- x* and y* are the locations of the point Q* in the deformed image
- u and v are the displacement of the subset center in x and y directions, respectively ($u = x_p^* - x_p$, $y = y_p^* - y_p$)
- Δx and Δy are distance between point (x, y) and the subset center (x_p, y_p) [25]–[29].

The idea behind DIC is to compare subsets for two images to obtain values of u , v (displacements) and their derivatives (strains). A correlation function is used to find the unknown values of displacements and strains. The correlation function can be expressed as:

$$C\left(x, y, u, v, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}\right) = 1 - \frac{\sum[F(x, y) * G(x^*, y^*)]}{[\sum(F(x, y)^2) * \sum(G(x^*, y^*)^2)]^{1/2}} \quad (1.2)$$

where:

- $F(x, y)$ and $G(x^*, y^*)$ are the grey scale values of points $Q(x, y)$ in the undeformed image and $Q^*(x^*, y^*)$ in the deformed image, respectively [25]–[29]

Unknown values of displacements and strains can be found by identifying points $Q(x, y)$ and $Q^*(x^*, y^*)$ which minimize the correlation function,. If the subset is small enough, any point inside the subset, such as point Q , is able to express the deformation of the subset. This is due to the fact that deformation of the subset can be assumed homogenous if it is small enough. By finding the deformation of each subset, DIC technique is used for evaluating the full-field displacement and strain of the specimens to further use them to identify some other mechanical properties in several studies [28], [30], [31].

1.4 Stiffness degradation

Several damage modes are involved in the ultimate failure of the composite structures. It is challenging to predict which mode or combination of modes influences the damage the most. However, it is known that mechanical properties of composite structures degrade because of the overall damage of the material. Thus, the properties such as residual strength, stiffness and lifetime can be used as indicators of damage level in composite structures. However, destructive tests need to be performed on the specimens to measure residual strength and lifetime. Thus, it is not possible to track damage development of a single specimen by using residual strength and lifetime. Whereas stiffness of the specimens can be measured without destroying the specimens. Observing stiffness degradation of the composite structures can be a useful and nondestructive method to investigate its current damage.

In [32], the relationship between stiffness degradation and damage was investigated for laminated structures. Both quasi-static and cyclic loadings with $R=0.1$ were

applied to the specimens. Stiffness degradation of the specimens was observed by using an extensometer. Crack density was estimated by using shear lag model. In Figure 1-12, strong correlation between percent stiffness decrease and crack density was shown for a quasi-static test.

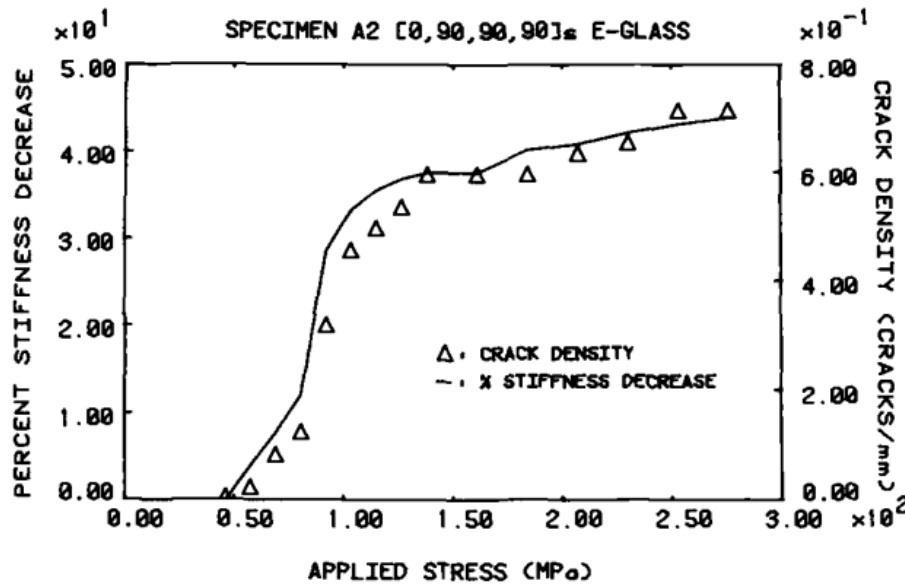


Figure 1-12: Crack density and percent stiffness decrease depending on the applied for a quasi-static test [32]

The same correlation was also observed for fatigue loading. It was reported that stiffness decreased steeply up to a certain level for both quasi-static and fatigue tests in the beginning. The steep decrease of stiffness was correlated to early damaging at micro level. Then, it stabilized and changed gradually until the failure. The same trend was observed for crack density. It is clear that damage development and stiffness degradation are strongly correlated.

As mentioned in Section 1.2, TPM analysis is able to predict the fiber orientation distribution, and so the local stiffness values of the structure. However, stiffness degradation of the material changes over the cycles how stresses are distributed throughout a fatigue test within each layer of an SFRP specimen. Therefore, monitoring stiffness degradation of SFRPs and introducing it to the finite element software could lead to a more accurate evaluation of how stresses evolve throughout a fatigue test.

1.5 Using milled specimens for characterization of SFRPs

It is challenging to accurately estimate the local fatigue strengths of the shell and core layers, i.e., of layers displaying high fiber alignment, by using full specimens. To understand the local fatigue strengths of different layers, 0° and 90° shell layers were machined from the full specimens to investigate their local fatigue strengths and compare them with the full ones [33]. Figure 1-13 shows a graphical representation of a full and milled specimen.

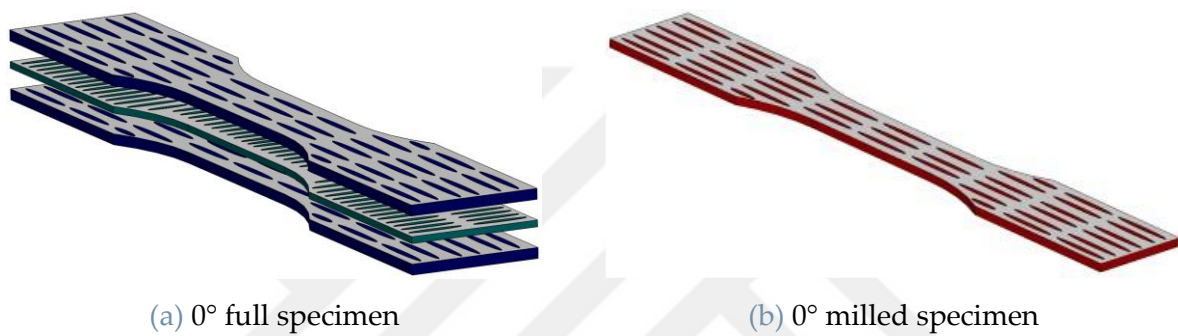


Figure 1-13: Graphical representation of a full and milled specimen

It was observed that 0° shell-only specimens have higher fatigue strength than 0° full specimens [33]. Conversely, 90° shell-only specimens had lower fatigue strength than 90° full specimens. S-N curves obtained in that study was shown in Figure 1-14. This means that the presence of the core layers in the full specimens likely led to an underestimation of the fatigue strength of the 0° orientation and to an overestimation of the fatigue strength of the 90° orientation.

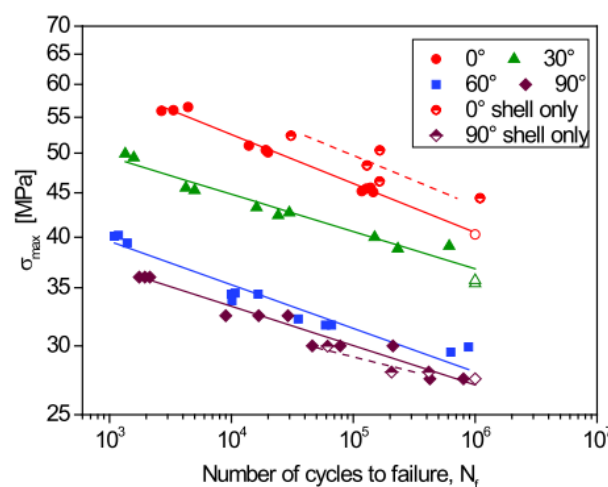


Figure 1-14: Normalized S-N curves of full and milled specimens [33]

However, these studies were preliminary, and the tested specimens were in different moisture content conditions. Thus, both full and shell only PA66GF50 specimens were tested in same conditions to better understand the local fatigue strength of SFRPs [19]. Experimental results in terms of fatigue strength of the milled specimens compared to the full ones agreed with that in [33]. For both full specimens, it was suggested that damage initiation takes place where the fibers are aligned with the specimen and loading direction. This behavior was expected for full 0° specimens but not for full 90° specimens. This is due to the fact that the regions with fibers aligned in the loading direction have higher stiffness, so they withstand a higher share of the applied load. This was verified by a finite element model which showed that the stresses are higher in the layer displaying fibers oriented with the load, as in Figure 1-15 [19]. Hence, fatigue strength of SFRPs, where fibers aligned transversally with respect to loading direction, cannot be accurately evaluated by testing full 90° specimens with a non-negligible core layer. Therefore, testing the milled specimens to evaluate the local fatigue strength seems like a correct method to characterize the true fatigue strength of highly aligned SFRPs and use the obtained properties as an input for a TPM analysis.

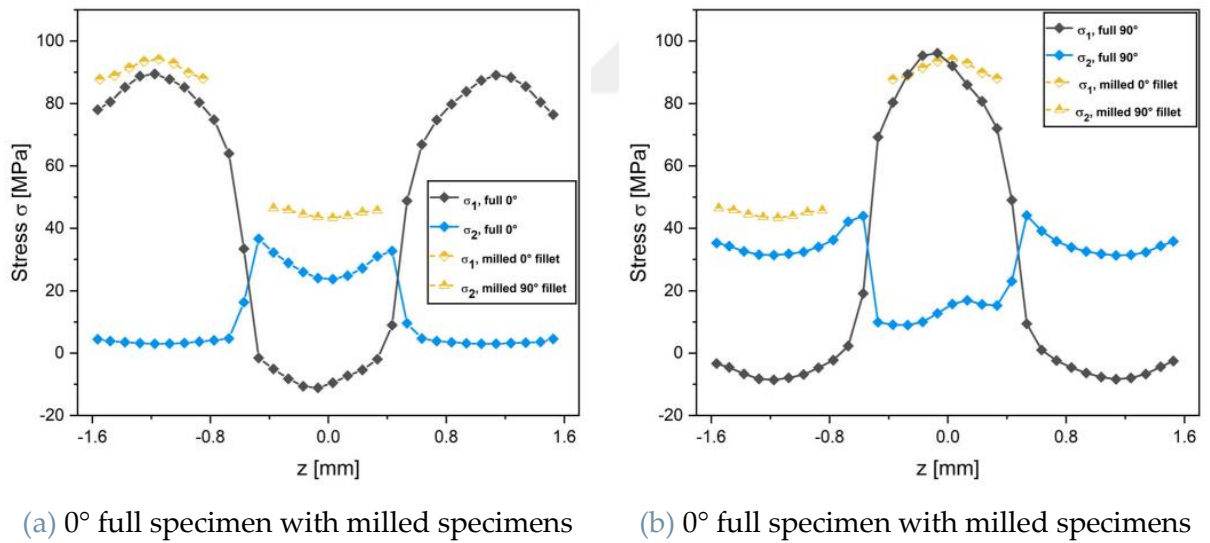


Figure 1-15: Stress distributions through the thickness obtained by using FEA [19]

2. Materials and methods

2.1 Specimen manufacturing

The material investigated in this study was an injected molded short E-glass fiber reinforced polyamide-66 with a fiber weight ratio of 50% (PA66 GF50). Rectangular plates of 120 mm x 80 mm and 3.2 mm thickness were injected molded for the specimens to be extracted out. As it is shown in Figure 2-1, the orientation angles of the specimens were defined as the angle between the axis of the specimen and axis of the plate which corresponds to mold flow direction (MFD).

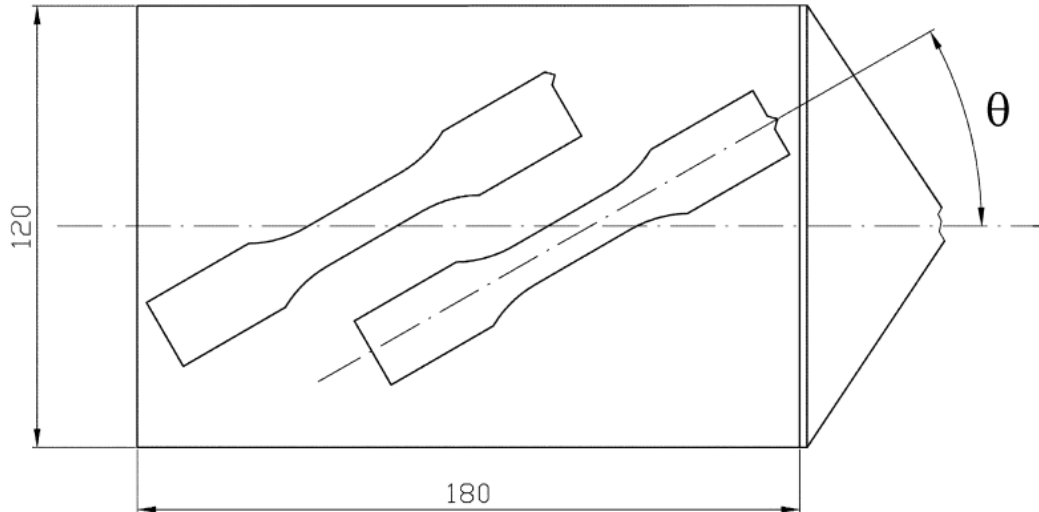


Figure 2-1: Injected molded plates having orientation angle, θ [2]

0° and 90° specimens were extracted from the rectangular plates by using water jet cutting. 0° specimens had a length of 125 mm, whereas 90° specimens had a length of 116 mm. The gauge shape, length and radius were same for both specimen's types. 90° specimens were shortened by reducing the length of the gripped region only. The dimensions of both 0° and 90° specimens were shown in Figure 2-2. From this point on, these specimens will be referred to as full 0° specimens and full 90° specimens.

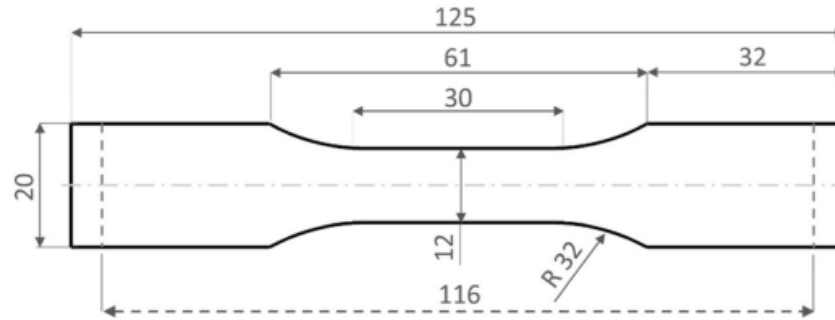


Figure 2-2: Specimen shape and dimensions [19]

The same material with same manufacturing parameters was tested in [19] prior to this study. An analysis was performed in that study to measure fiber orientation distribution (FOD) of the specimens through the thickness. Both micro-computed tomography and ellipsometry methods resulted with similar FOD. The shell layer of the specimens appeared to have a thickness of 0.8 mm as shown in Figure 2-3. Since the same rectangular plates were used in this study, the shell layer of the specimens was 0.8 mm on both sides of the specimen.

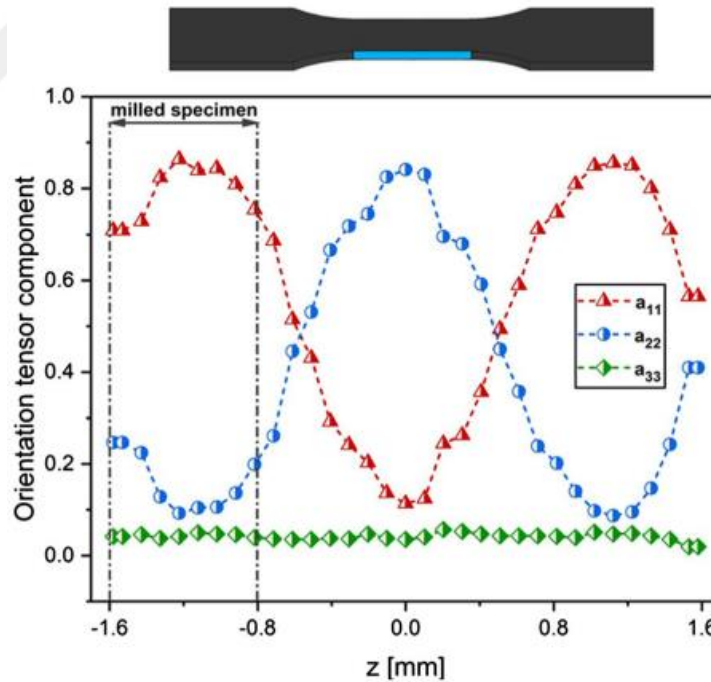


Figure 2-3: Fiber orientation distribution of the specimens through thickness obtained by ellipsometry [19]

As mentioned, the thickness of the full specimens was 3.2 mm. A milling operation to obtain shell-only specimens with a thickness of 0.8 mm was performed according to

what has been reported in [19]. A shank type high-feed milling cutter with a diameter of 32 mm and 4-corner single sided inserts was used for the milling process. The tool was centered in the centerline of the specimen and the thickness was decreased to 0.8 mm in 3 passes. 1 mm of material is removed at the first and second passes, and 0.4 mm of material was removed at the final pass. The spindle speed and feed rate were 1560 rpm and 900 mm/min for all the passes, respectively. Air was blown to the tool-specimen interface for cooling purposes. Due to the size and shape of the tool, the thickness of the specimens at both edges of gripping area could not be milled to exactly 0.8 mm while the tool was centered. Therefore, a single pass for each edge was performed just to obtain a flat surface for all along the gripping region. From this point on, these specimens will be referred to as milled 0° and milled 90° specimens.

Surface roughness measurements have been performed by using a Mahr PGK profilometer with a 2 μm tip radius according to UNI EN ISO 4288:2000 standard. Starting points of the measuring locations was shown in Figure 2-4. The probe moved 5.6 mm upwards for the longitudinal measurements with respect to the specimen orientation and rightwards for the transversal measurements with a same distance. Point 2 was used as the starting point for the measurements performed in the as-molded surfaces. Average surface roughness of the machined surfaces of milled 90° and 0° specimens were 1.25 and 1.19 μm , respectively. Surface roughness of the as-molded surfaces of the full specimens were 0.61 and 0.45 μm , respectively. The average surface roughness for machined surfaces and as-molded surfaces were 2.5 and 0.3 μm , respectively in [19].

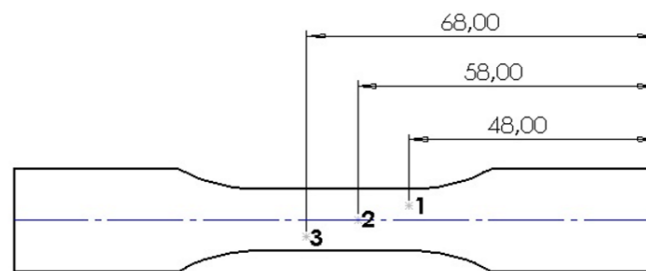


Figure 2-4: Surface roughness measurement locations

The specimens were subjected to accelerated conditioning prior to experimental activities. The specimens were kept at 70°C and 70% relative humidity in a climatic chamber until equilibrium has been reached. The conditions were selected so that the conditions of the tested specimens get closer to real-life conditions. After the conditioning, the specimens were placed inside the air-proof sealed bags so that the moisture content of the specimens did not change until the experiments were performed. The sealed bags were opened just before the tests.

2.2 Testing conditions

2.2.1 Tensile tests

Displacement controlled uniaxial tensile tests were conducted on all specimen types according to the ISO 527-2 standard, [34], using an MTS Alliance RT/100. The displacement rate was 5 mm/min for all the tests. The tests were not performed in a climate-controlled environment since testing duration was short enough to not cause a significant change in the moisture content of the specimens.

For DIC analysis, ARAMIS 3D system was used for the tensile tests [35]. ARAMIS is a measuring system for DIC analysis equipped with two cameras. In addition to the cameras, lights and a control system which is in connection with the testing machine are included in ARAMIS. At least one specimen per kind was tested by using ARAMIS. Pictures for DIC analysis were taken with a frequency of 3 Hz. In addition, an extensometer was used together with ARAMIS for some tests. Set up of the was shown in Figure 2-5.

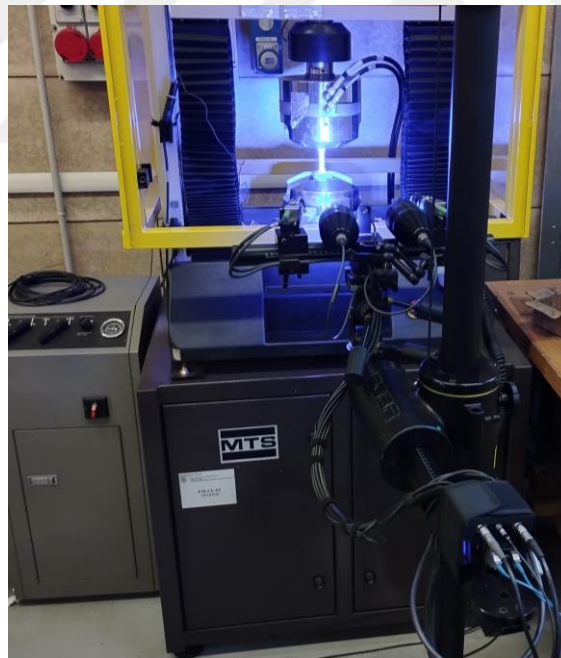


Figure 2-5: Tensile testing setup

2.2.2 Preliminary fatigue tests

Load-controlled tension-tension uniaxial preliminary fatigue tests were performed using an MTS Landmark servo-hydraulic testing machine, with a 25 kN maximum

loading capacity for all specimen types. A sinusoidal load was applied with a load ratio of 0.1 and a frequency of 4 Hz.

Since many parameters had to be decided before starting the fatigue tests, some preliminary trial tests were performed. The trial tests were performed using material coupons extracted from the remaining parts of the injected molded rectangular plates after the specimens were extracted out.

A system consisting of a camera, lights and a control unit which controls the camera and lights was used instead of ARAMIS for fatigue tests. ARAMIS is a closed system for picture acquisition, thus a user defined acquisition during a fatigue test cannot be set. Since this is needed for fatigue tests, ARAMIS could not be used. The testing setup was shown in Figure 2-6.



Figure 2-6: Fatigue testing setup

First, gains of the force controller of the testing machine were adjusted for each specimen. Since the thickness of the milled and full specimens were significantly different, applied loads were also quite different for each specimen. Therefore, force controller gains of each specimen type needed to be adjusted separately in order to ensure that input force given by the controller matches the output force on the specimen.

Then, data acquisition logic was adjusted. Since fatigue tests take a long time, obtaining a reasonable amount of data is necessary. Thus, tests were divided into so-

called blocks in which the data and pictures acquisition frequency varied. The starting and ending cycles of each block was reported in Table 1.

Block number	Starting Cycle	Ending Cycle
Block 1	1	10000
Block 2	10001	125000
Block 3	125001	1000000

Table 1: Starting and ending cycles of each block

The first block, which is the shortest one, was created so that relatively high data and pictures acquisition frequency can be achieved. The reason why a higher frequency was needed is because a rapid damage evolution was expected in the beginning of the test. Then, a second block was created where failure was not expected. Thus, a higher number of cycles can be set between acquisitions. In the third block, where a possible failure was expected, the data acquisition rate was not decreased further. However, acquisition frequencies were adjusted considering that the third block was the longest one.

For peak-valley data acquisition, a single pair data (displacement, force, time and cycle count data) was acquired when the maximum and minimum force was reached within a cycle. For full cycle acquisition, a similar data set of a single full cycle is acquired with a sampling frequency of 512 Hz. The number of cycles between each data set was shown in Figure 2-7 for each acquisition.

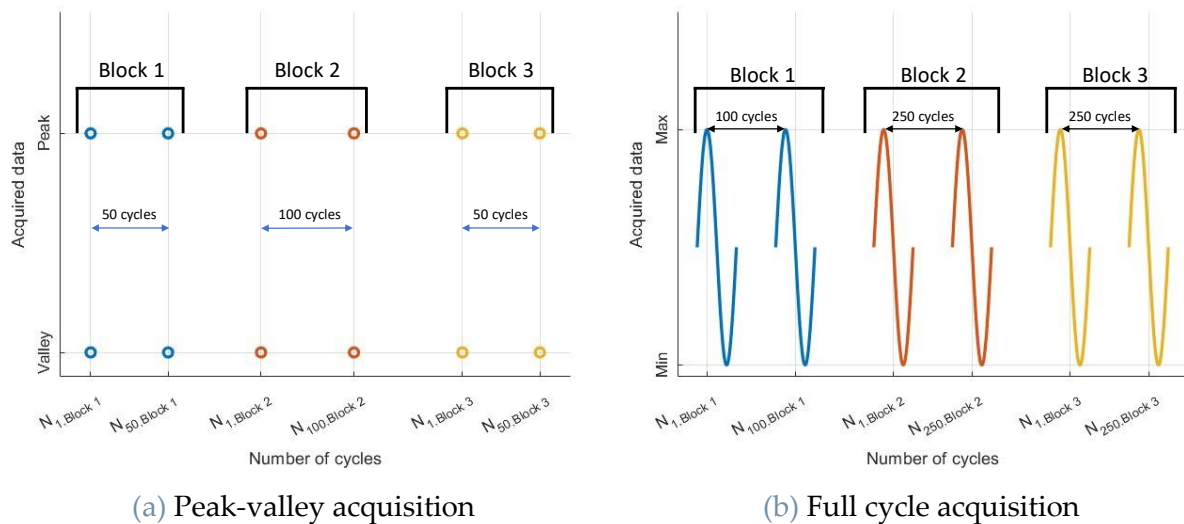


Figure 2-7: Data acquisition sequence

What has been shown in Figure 2-7 was also reported in Table 2. As mentioned, data acquisition frequency for the third block was determined by considering its duration. Thus, peak-valley acquisition frequency was increased although full cycle acquisition frequency could not be increased due to the huge amount of obtained data.

Block number	Number of cycles between peak-valley acquisition	Number of cycles between full cycle acquisition
Block 1	50	100
Block 2	100	250
Block 3	50	250

Table 2: Data acquisition rates for each block

In order to capture the pictures at the same load throughout the fatigue tests, load was holden at a prescribed load throughout the fatigue tests. Relevant data was acquired during every holding period to compare it with the DIC results. The last 100 cycles of the test were also acquired in order to observe the behavior of the specimen just before and during a possible fracture. This acquisition relied on the storing of the latest 100 full cycles data in a circular buffer.

After data acquisition was adjusted, some adjustments were needed for DIC analysis. The images for DIC analysis were taken during the fatigue tests at the priorly defined cycles by using a setup consisting of a camera control unit, with its own logic and an integrated acquisition board. The control unit was connected to both the testing software and the devices it controls (camera and lights). For DIC analysis, load holdings were needed to be performed at the prescribed loads. The reason why holdings were performed was due to the lack of synchronicity between the camera and testing machine. Holdings were performed in order to be sure the pictures were taken at the proper prescribed load. The first thing to do to prevent fatigue tests from being interrupted for a long time was to minimize the holding time.

The restriction on the holding time was that pictures could be taken during that time. As was shown in Figure 2-8, the first trigger signal was created by the testing machine just before the holding. When the control unit detected the first trigger signal through the output channel of the testing machine, it turned on the lights and woke the camera from sleep mode. Then, right after the holding starts, a second trigger signal was created. Then, the control unit commanded the camera to snap the picture. Once the picture was taken, both trigger signals returned to zero. The control unit turned off the lights, and the force started cycling again. By considering any possible delay which may occur in camera and signal detection, the holding time was shortened from an initial guess of 12 seconds to the optimized time of 3.6 seconds.

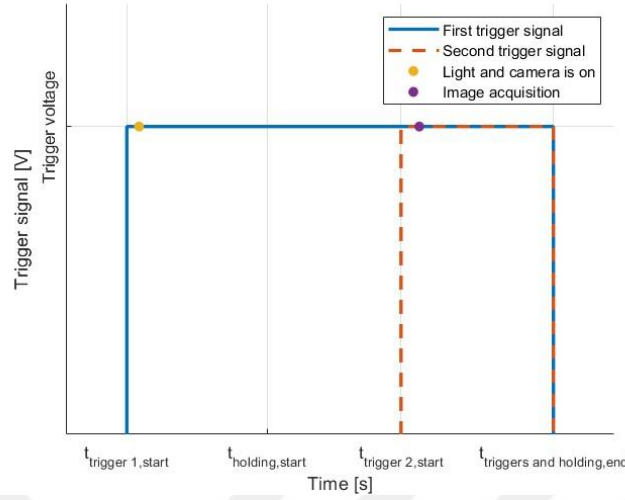
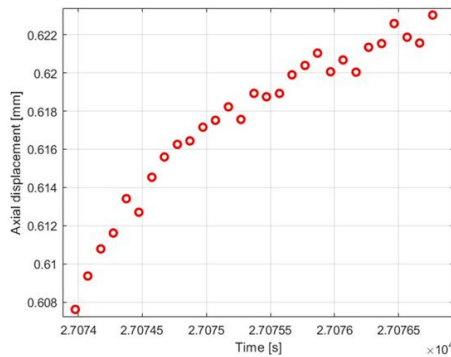
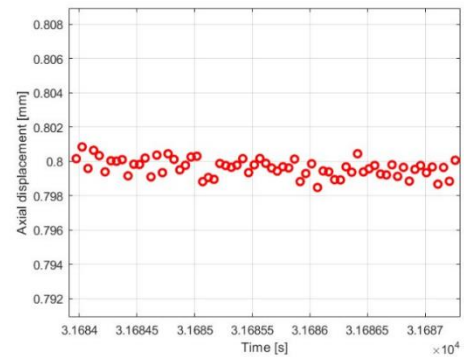


Figure 2-8: Trigger signals for image acquisition

Another concern about the holding time was to further damage the specimen during that time. At the beginning of the trial tests, holdings were performed at the maximum applied load because of the possibility of providing more interesting results. However, it was observed that holding at the maximum force possibly damaged the specimens. Figure 2-9a shows how displacement changed during a holding period at the maximum force. Creep was clearly visible since displacement kept increasing. It can be due to both viscoelastic behavior of the material or damage development. Whatever the reason, a change in the specimen's behavior was introduced during holding at the maximum force. On the other hand, Figure 2-9b shows that displacement stayed the same during a holding period at the mean force. Therefore, the holdings were performed at the mean force in order not to introduce further damage development during holding periods.



(a) Holding at maximum force



(b) Holding at mean force

Figure 2-9: Displacements during holding at maximum and mean force

Another issue to be adjusted is to decide the number of pictures to be taken within each block. The same concern about having a reasonable amount of data, which is now pictures, also holds for this decision. A subblock, called a loop, has been set within each block. Each loop consisted of a certain number of cycles and a single holding. The load kept cycling until the certain prescribed number of cycles was reached. Then, load holding starts to take a picture. Once the picture was taken, the load started cycling again, starting the next loop. This sequence was shown in Figure 2-10. For each block, the number of cycles for loops differed in order to have a reasonable number of pictures.

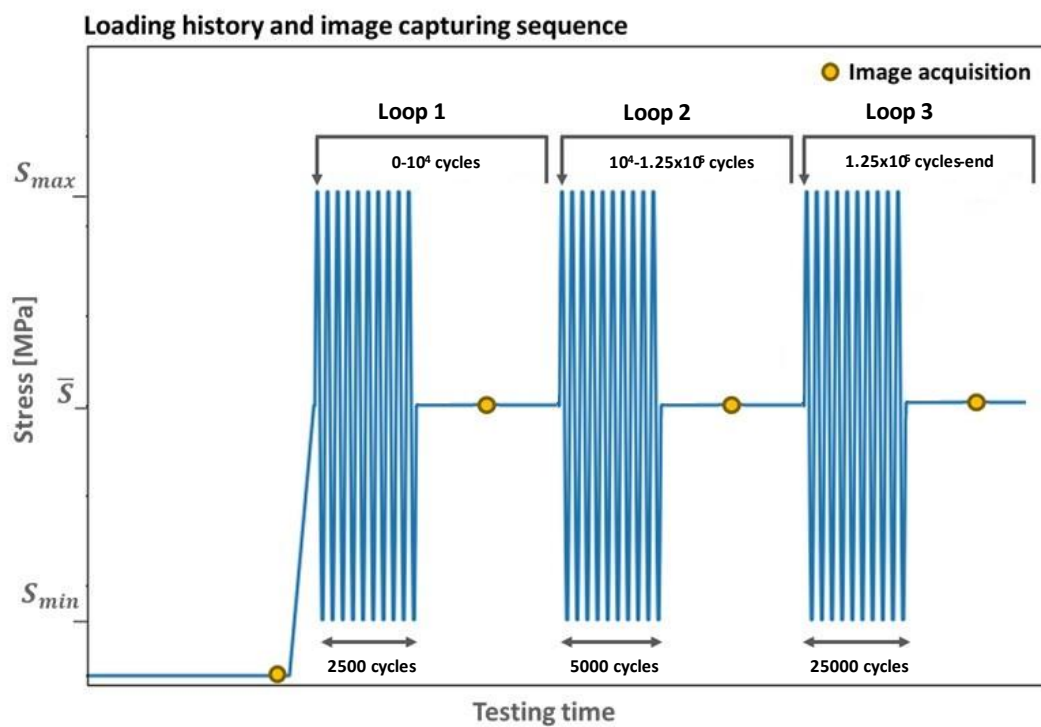


Figure 2-10: Loading history and image capturing sequence

Number of cycles between the pictures for each block and corresponding total number of pictures for each block was reported in Table 3.

Block number	Number of cycles between pictures	Total number of pictures
Block 1	2500	4
Block 2	5000	23
Block 3	25000	35

Table 3: Picture acquisition information for each block

Two different DIC software were used to post process specimen pictures taken during the experiments to evaluate displacement and strain fields: Ncorr and GOM Correlate [35], [36]. For tensile tests, ARAMIS system was used for DIC analysis. GOM Correlate is embedded into ARAMIS. However, the selection of software for fatigue tests and parameters had to be done during the preliminary tests. The definition of parameters of each software was reported in this section.

The first parameters to set in the picture analysis are facet size (FS) and point distance (PD) while creating a surface component in GOM Correlate. In order to perform a DIC analysis, the interested surface has to be divided into smaller regions which are called facets by GOM Correlate. GOM Correlate created square facets as was shown in Figure 2-11. The inserted facet size value is used as the edge length of the facets. Then, the point distance between the facets has to be set. The facets should be overlapped for a more accurate calculation; thus, the point distance should be smaller than facet size.

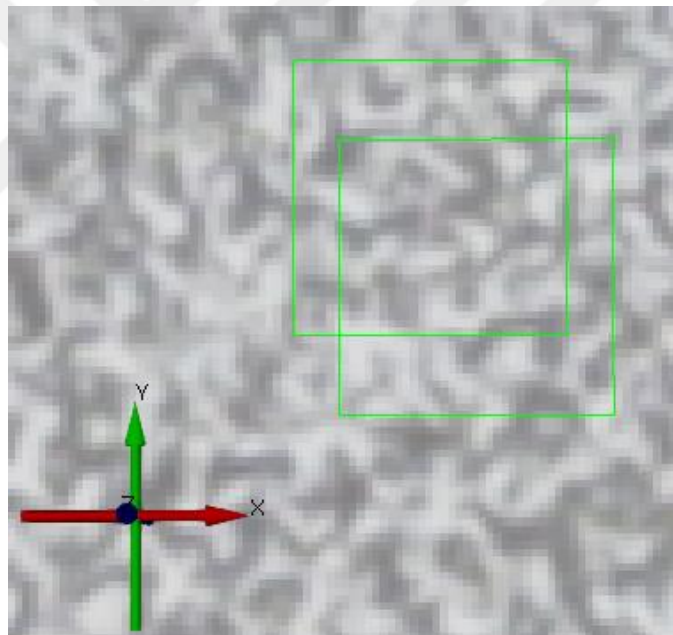


Figure 2-11: Preview of two subsequent facets (in green) created by GOM Correlate

By setting only facet size and point distance, displacements and strains can be calculated. However, the results can be filtered by applying the optional spatial filtering parameter.

The terminology of Ncorr is different than GOM Correlate. Subset, subset radius and subset spacing are used instead of facet, facet size and point distance, respectively. Subsets are circular in Ncorr unlike in GOM Correlate, which were rectangular.

Thus, obtaining the same subset pattern is not possible. The subsets resulting from Ncorr was shown in Figure 2-12.

For strain calculation, a parameter called strain radius exists in Ncorr. It is used to interpolate the calculated strain data to make it smoother. The user selects the size of the data to be interpolated by inserting a strain radius.

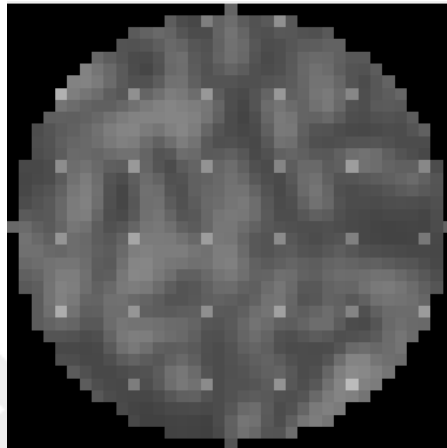


Figure 2-12: Subset centers placed by Ncorr (Each light pixel inside the circle represents a subset center)

The effect of all the abovementioned parameters was investigated and reported in the results section.

2.2.3 Fatigue tests

The same testing setup shown in the previous section was used with all the parameters selected according to the results of the preliminary tests, reported in section 2.2.2. The tests were conducted in a temperature and humidity-controlled room. The temperature and the relative humidity were set at $23\text{ }^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and $50\% \pm 5\%$, respectively. The tests were continued until 10^6 cycles (run-out) are reached if the specimens did not fail before.

The system for taking the pictures described in the previous section was used for the fatigue tests. Before the tests were started, a picture was taken to be used as the reference picture when the load was zero. Then, pictures were taken at the prescribed cycles defined in the previous section.

Modulus for fatigue tests was calculated by using stress and strain data obtained from full cycle acquisitions in order to track stiffness degradation of the specimens.

3. Results

3.1 Results of tensile tests

3.1.1 Overview of the tests

Stress-strain curves of the tensile tests were plotted in Figure 3-1 together with their fatigue strength at around 200000 cycles. The reason for specifying the fatigue strength in that cycle is reported in the following sections.

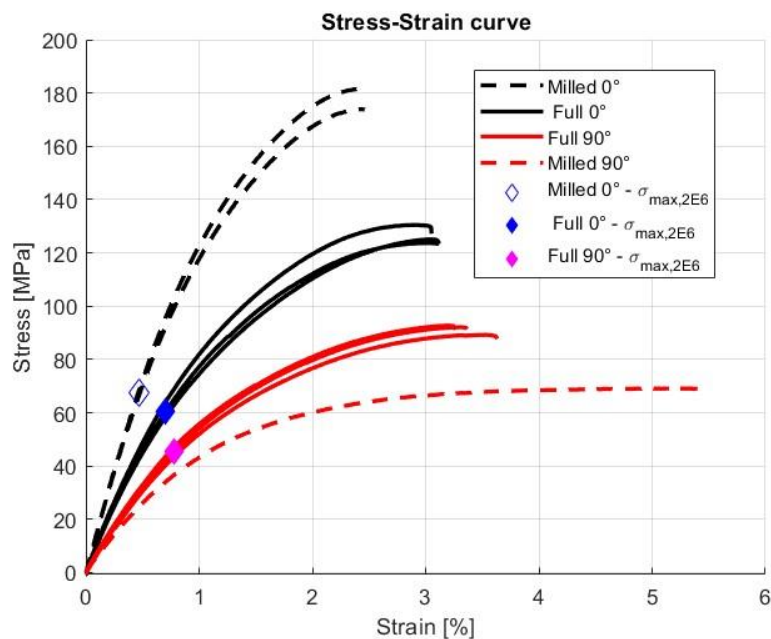


Figure 3-1: Stress-strain curves of the tensile tests

The elastic modulus, tensile strength, and strain at failure of each specimen type obtained from the tensile tests were reported in Table 4. The tensile strength and tensile modulus of the specimens decrease in order of milled 0°, full 0°, full 90° and milled 90°, as expected. The opposite trend was observed for the strain-at-break.

Fibers are highly oriented along the loading direction for milled 0° specimens. Therefore, fibers, which have a much higher load bearing capacity than the matrix material, carry a high portion of the applied load for these specimens. On the other hand, fibers are highly oriented perpendicular to the loading direction for milled 90° specimens. Thus, it is not the fibers which carry the higher portion of the load, but the matrix material. As a result, the milled 0° specimens had the highest tensile strength, whereas the milled 90° specimens had the lowest one. The full specimens had intermediate tensile strength values between the strengths of the milled specimens. The tensile strength of full 0° was higher than tensile strength of the full 90° specimen since 0° layers occupy a higher volume fraction for full 0° specimens.

Specimen Type	Tensile Strength [MPa]	Tensile Modulus [GPa]	Strain-at-break [%]
Milled 0°	177.8	15.4	2.45
Full 0°	126.5	10.0	3.10
Full 90°	91.4	6.7	3.42
Milled 90°	69.2	5.7	5.48

Table 4: Mechanical properties of full and milled specimens

It was observed that tensile modulus and strain-at-break respectively followed the same and the opposite trend as tensile strength for the same reason. Since fibers are much stiffer than the matrix material, highly oriented fibers along the loading direction prevent large deformation of the specimens. This was why milled 0° specimens had the highest tensile modulus and the lowest strain-at-break. Milled 90° specimens showed the opposite behavior to the milled 0° specimens, as expected. Full specimens had the intermediate values of tensile modulus and strain-at-break between milled specimens, again.

An analytical model to estimate elastic modulus of unidirectional discontinuous laminae was developed by Halpin and Tsai as shown in Equation (3.1) [37].

$$\left\{ \begin{array}{l} E_x = E_m \frac{1 + \xi \eta v_f}{1 - \eta v_f}, x = 1, 2 \\ \eta = \left[\frac{E_f}{E_m} - 1 \right] / \left[\frac{E_f}{E_m} + \xi \right] \\ \text{For } x = 1, \xi = \frac{2L_f}{d_f} \\ \text{For } x = 2, \xi = 2 \end{array} \right. \quad (3.1)$$

E_x is elastic modulus in two main material directions (1 parallel and 2 transverse to main fiber orientation, respectively), E_m is elastic modulus of matrix material, E_f is elastic modulus of reinforcing fibers, v_f is fiber volume fraction, L_f/d_f is aspect ratio and ξ is reinforcement parameter. The data required for the calculations was presented in Table 5.

Mechanical Properties	Matrix	Fibers
Elastic modulus [GPa]	2.35	72
Volume fraction	0.69	0.31
Aspect ratio	-	20

Table 5: Mechanical properties of fiber and matrix [19]

Estimation of modulus for milled specimens using Halpin-Tsai model was shown in Figure 3-2.

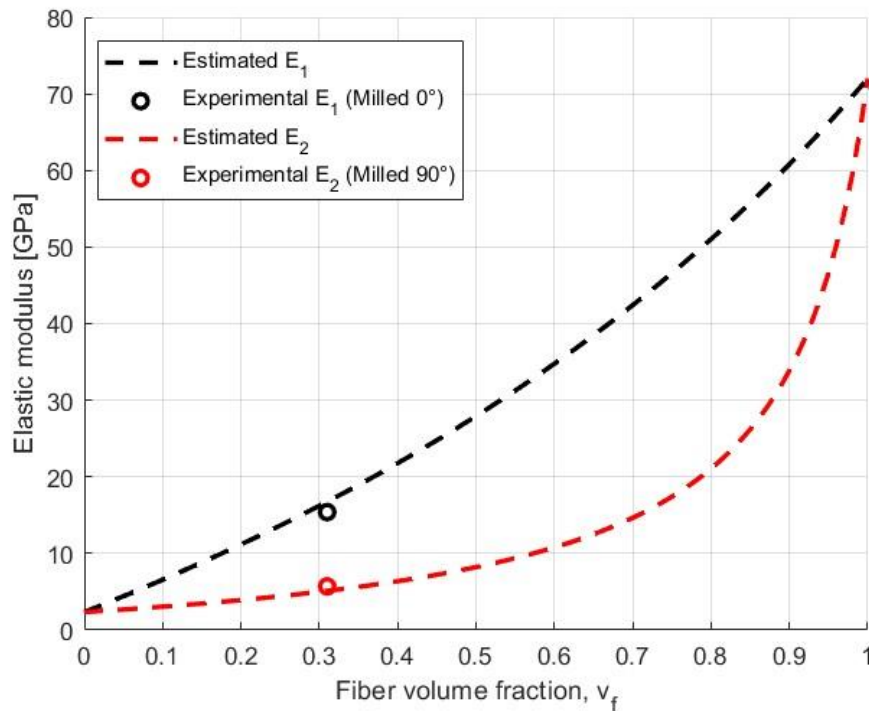


Figure 3-2: Modulus estimation of milled specimens

The modulus of milled 0° specimen was overestimated by Halpin-Tsai model, whereas modulus of milled 90° specimen was underestimated. Equation (3.1) is valid for perfectly aligned SFRPs. Even though milled specimens have a high degree of alignment, they are not perfectly aligned. There exists a certain degree of misaligned fibers as shown in Figure 2-3 where components of fiber orientation tensor were

reported. Both overestimation of the milled 0° specimens and underestimation of the milled 90° specimens can be explained by the fact that the milled layers did not preserve perfectly aligned fiber along its axis.

3.1.2 Comparison of displacement and strain obtained by testing machine and DIC

A portion of the specimens could not be seen by the camera due to the geometry of the grips on both upper and lower sides as shown in Figure 3-3. There were non-gripped regions on both sides which were blocked by the grips. Thus, maximum displacement obtained by the testing machine and zero displacement cannot not be captured in DIC.

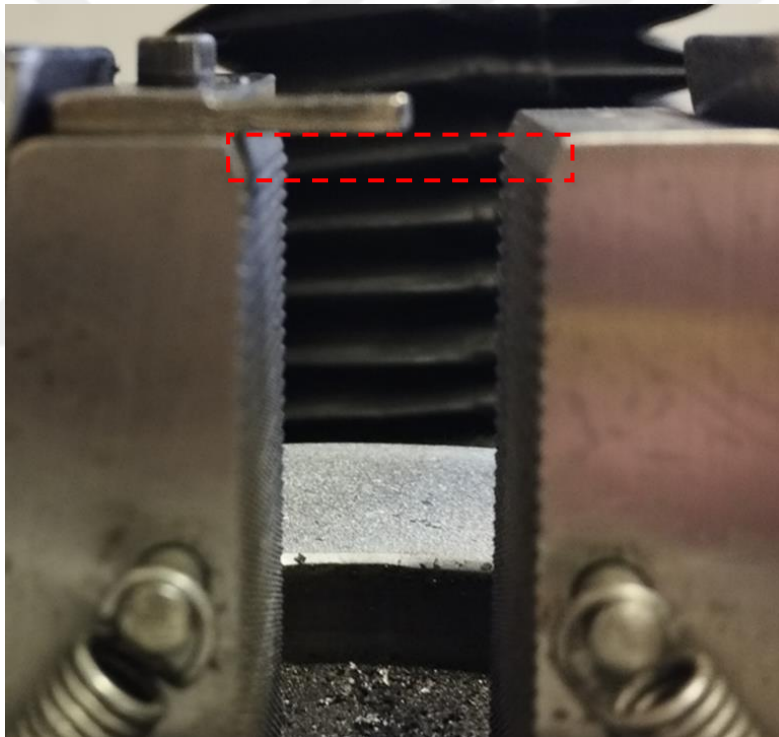


Figure 3-3: Grip and region not visible to camera (regions inside red box)

As mentioned, GOM Correlate software is embedded into ARAMIS. Thus, reported image correlation analysis was performed by using GOM. The software parameters used in this analysis were reported in the following results of preliminary fatigue tests section. For comparing displacements and strains, displacements and strains obtained from DIC analysis were plotted along a straight curve coincident with specimen's axis as shown in Figure 3-4.

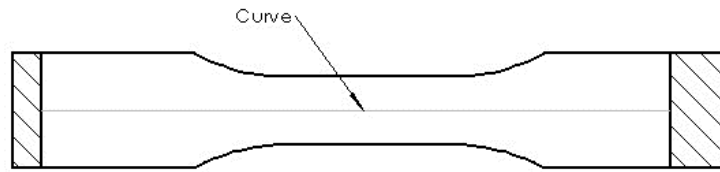
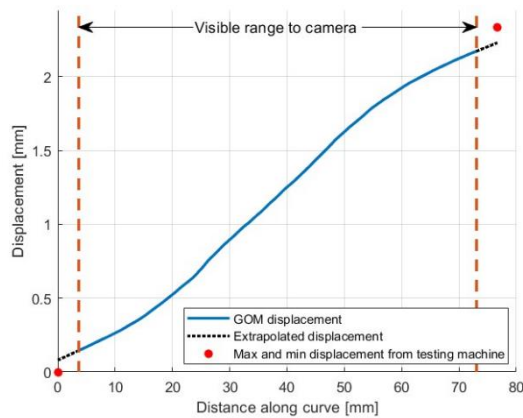
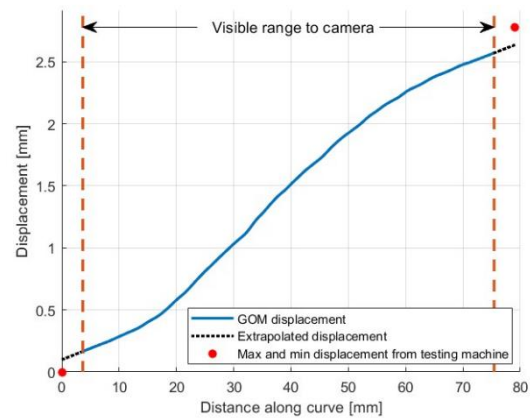


Figure 3-4: The straight curve coincident with specimen's axis used for comparisons

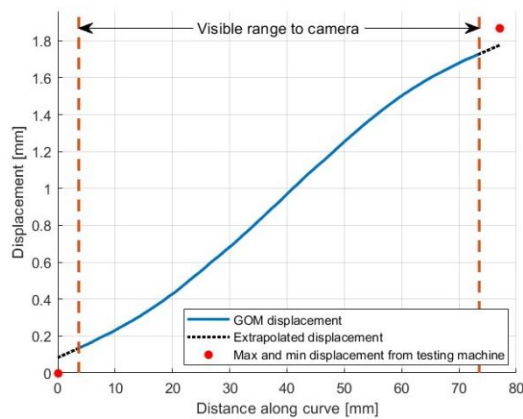
Plots for the displacement comparison was shown in Figure 3-5. Plots in Figure 3-5 showed that even after extrapolation of the displacement obtained by DIC diverged from maximum and zero displacement.



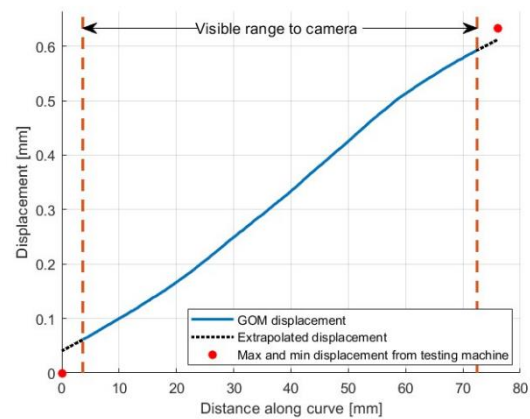
(a) Full 0°



(b) Full 90°



(c) Milled 0°



(d) Milled 90°

Figure 3-5: Comparison of displacements obtained by DIC and testing machine

curve between the arms of the extensometer. For comparison, strain obtained by the testing machine was also plotted along the full length of the specimen. As it is clear in Figure 3-8, DIC was able to capture well the strain obtained by the extensometer.

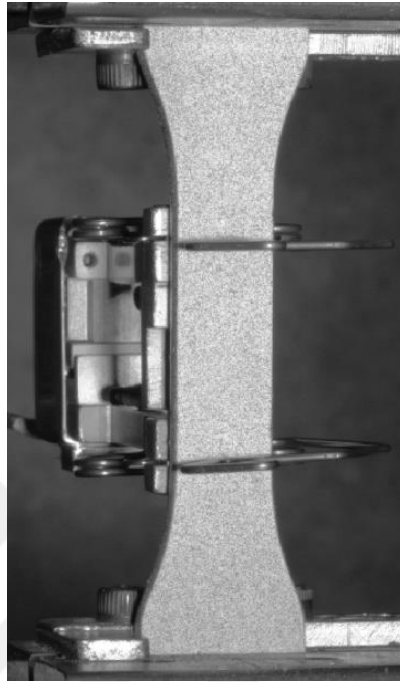


Figure 3-7: Specimen with the extensometer placed on

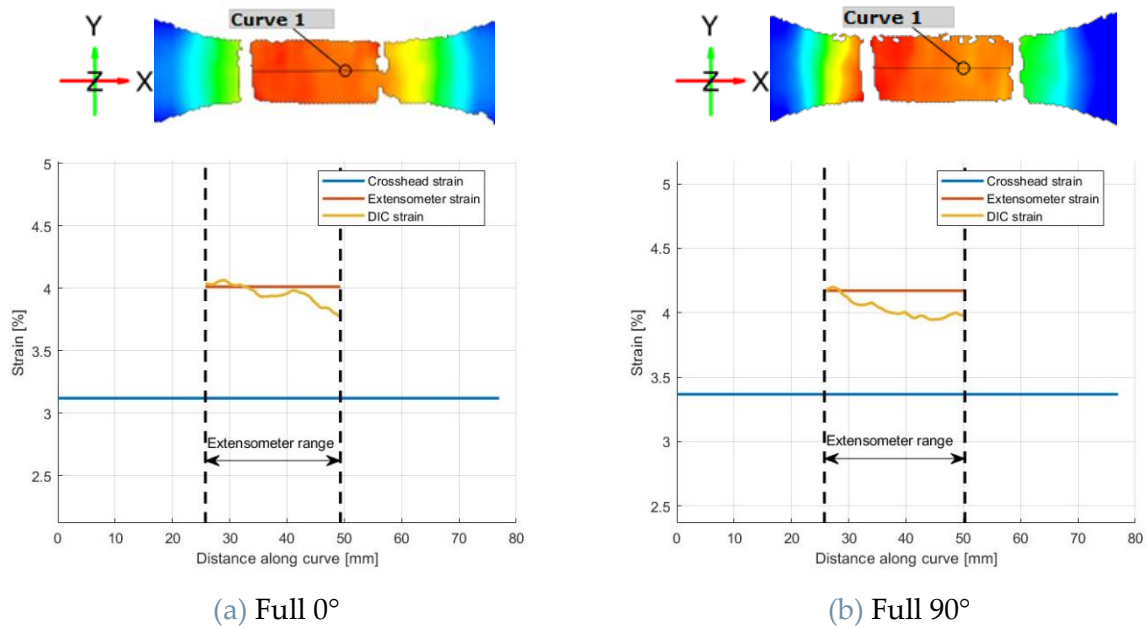


Figure 3-8: Comparison of strains obtained by DIC and extensometer for full specimens

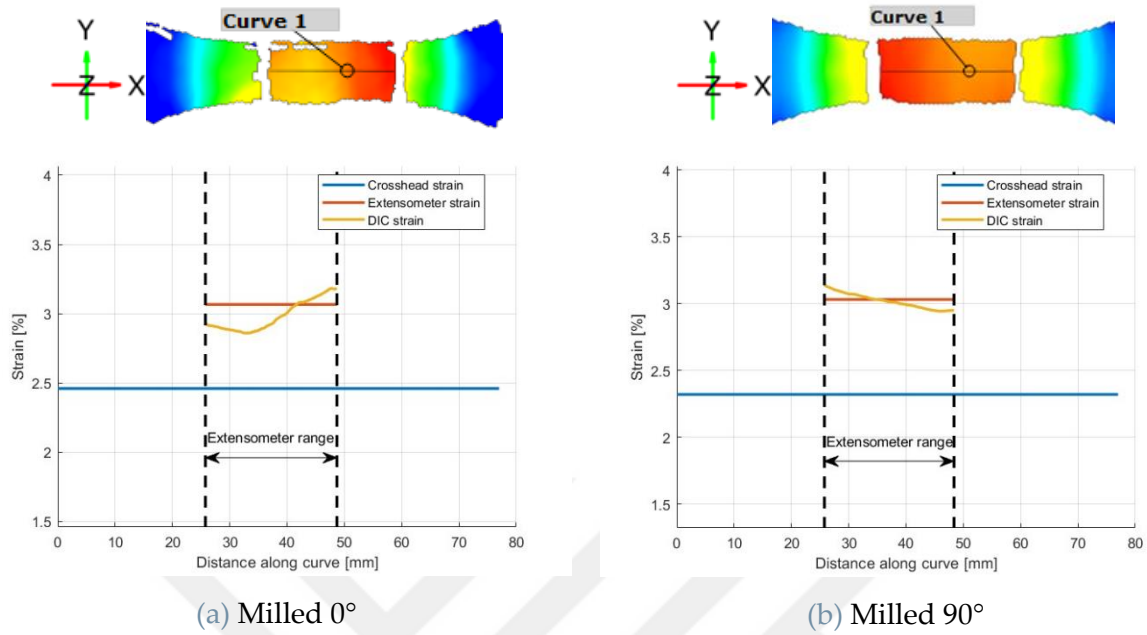


Figure 3-9: Comparison of strains obtained by DIC and extensometer for milled specimens

In order to further compare strains of the extensometer and DIC, strains were plotted over the entire testing period in Figure 3-10 and Figure 3-11. DIC strain was plotted for a single point in the middle of the specimen within its gauge length. Good agreement between the two curves exists, therefore, DIC was able to accurately evaluate strain all over the test.

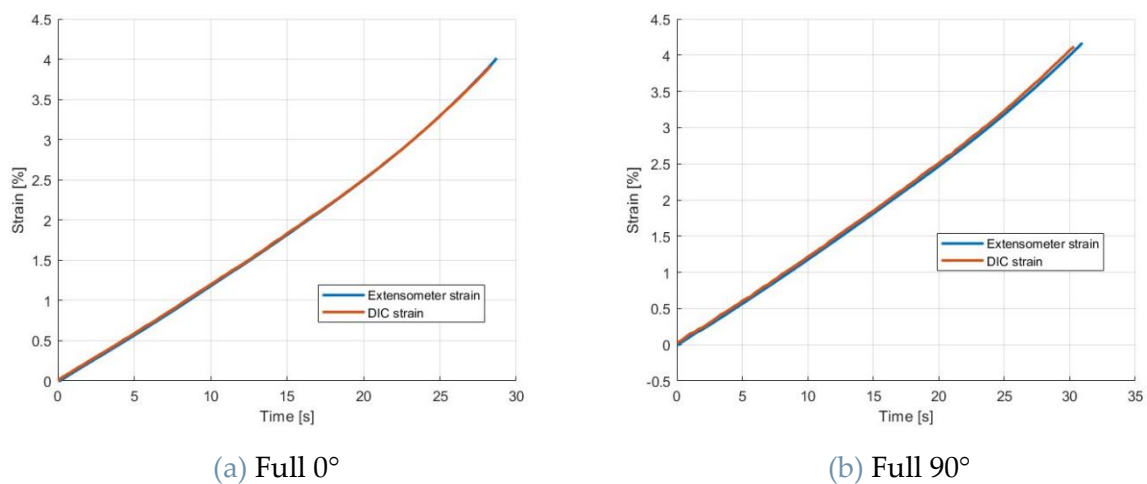


Figure 3-10: Strains over the entire testing period for full specimens

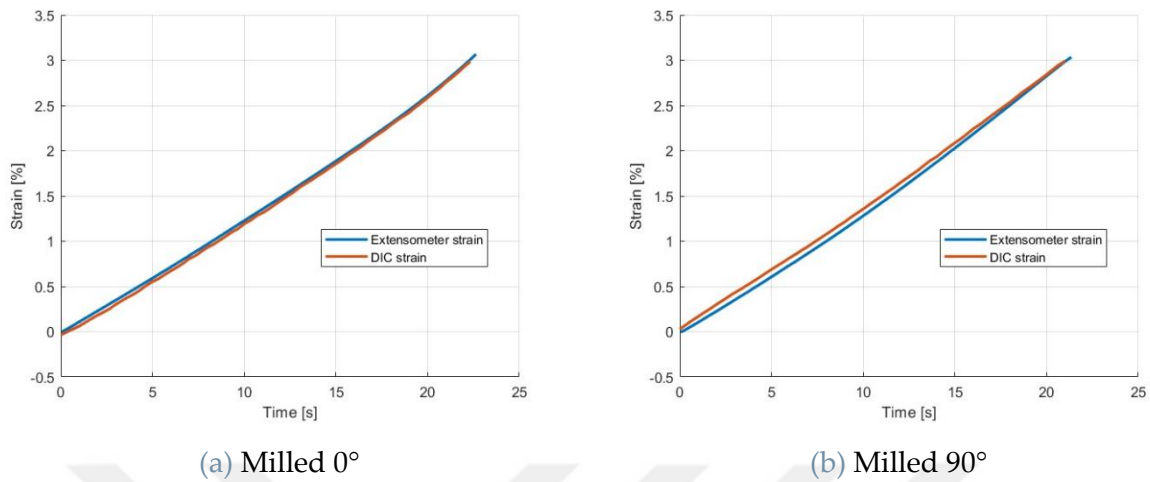


Figure 3-11: Strains over the entire testing period for milled specimens

Displacements of the extensometer and DIC were also compared over the entire test. DIC displacement was obtained as the relative displacement between Point C and D in Figure 3-12.

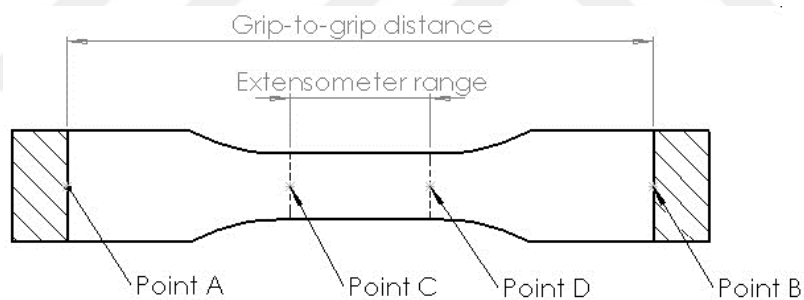


Figure 3-12: Extensometer range

Comparison of displacements of the extensometer and DIC was shown in Figure 3-13. Displacements of the extensometer and DIC were quite similar all over the test. However, a small deviation can be seen after a while towards the end of the test. All the results presented in this section showed that ARAMIS correctly estimated displacement and strains all over the tests.

In [38], it was reported that crosshead displacement and strain calculated by using it were found as the least uncertain measurements when compared to extensometer and strain gauge. Moreover, crosshead resulted in overestimating the displacement and strain compared to extensometer and strain gauge results. This fact can explain why maximum displacement could not be captured by DIC. However, it does not explain why zero displacement could not be captured. It was also reported that

extensometer provides the most accurate results compared to crosshead and strain gauge data [38]. Compatibility of DIC analysis results to the extensometer data showed that DIC results were reliable although zero and maximum displacement could not be captured.

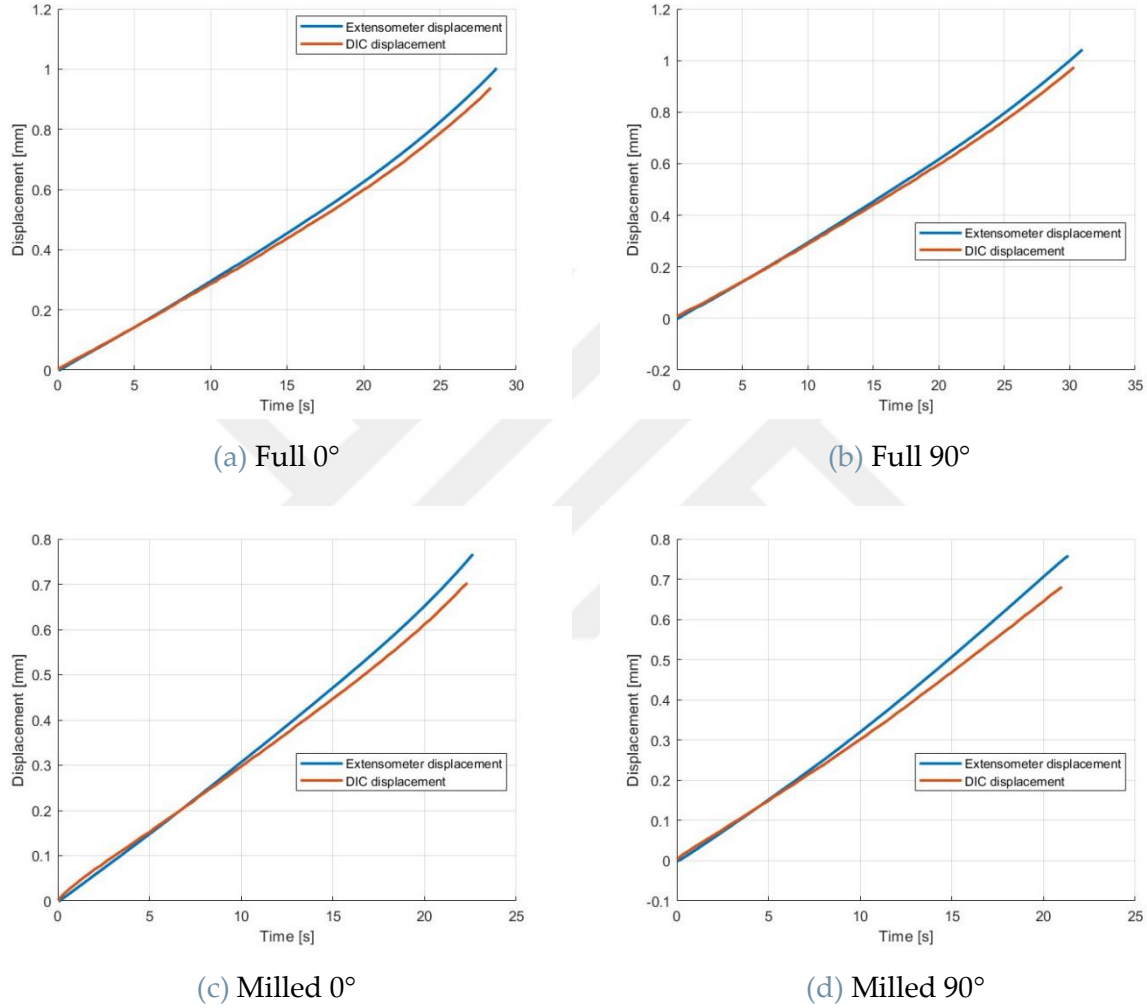


Figure 3-13: Displacements over the entire testing period

3.1.4 Stress concentration around fillet radii

In [19], it was observed that milled specimens were likely to fail around to fillet radii. Therefore, a possible strain concentration around the fillet radii was investigated by using full-field strain distribution obtained using DIC-Aramis. Figure 3-14 and Figure 3-15 shows where maximum strains were located on the specimen surfaces. However, no strain concentration due to specimen geometry was observed for both milled and full specimens around the fillet radii in tensile tests. Highly strained

regions were observed in some tests, most likely due to the higher density of defects in those regions. However, those measures are superficial. Hence, if failure in the fillet occurs, stress concentration may still occur in the inner layers, and thus may not be detected by DIC.

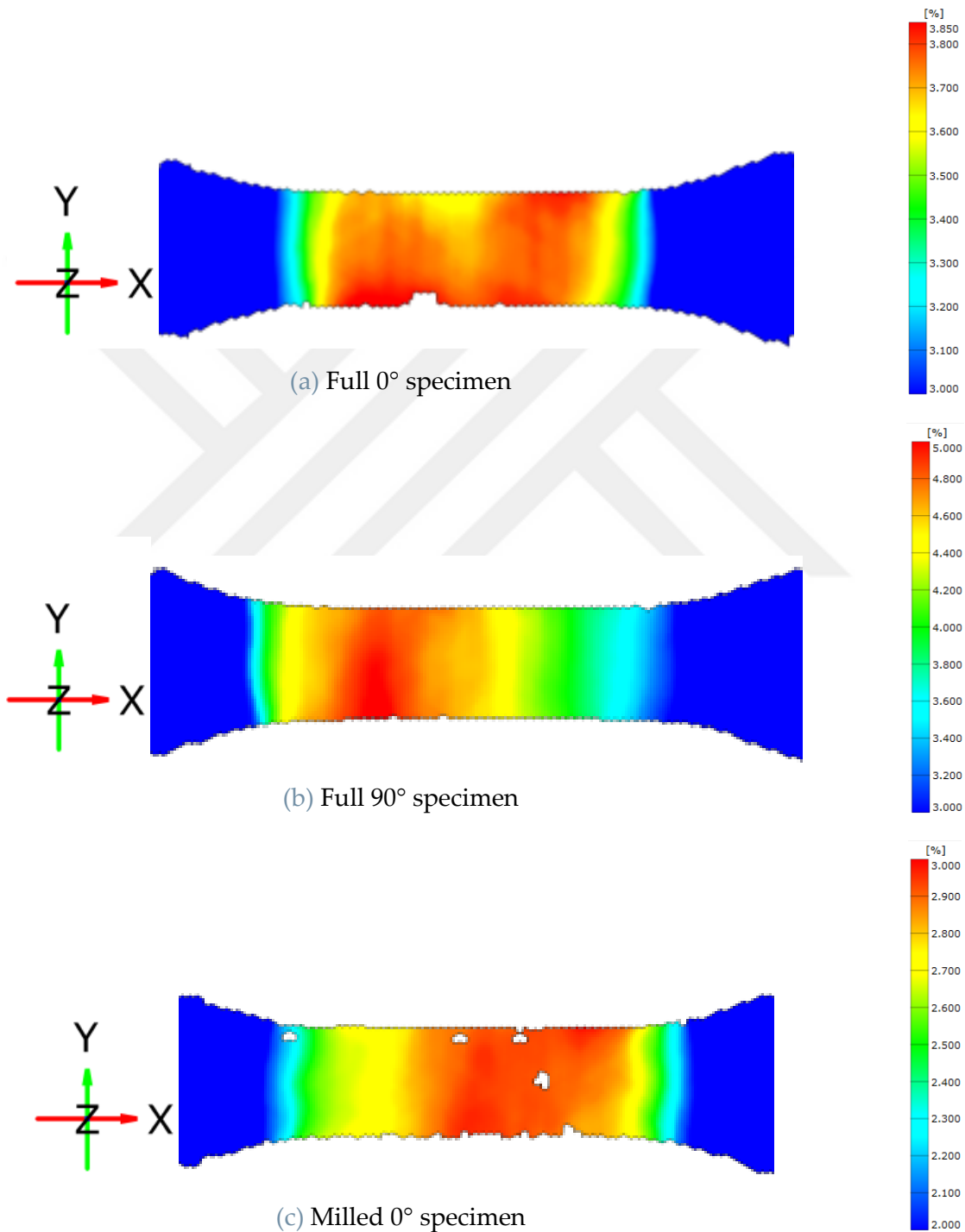


Figure 3-14: Full-field strain in x-direction

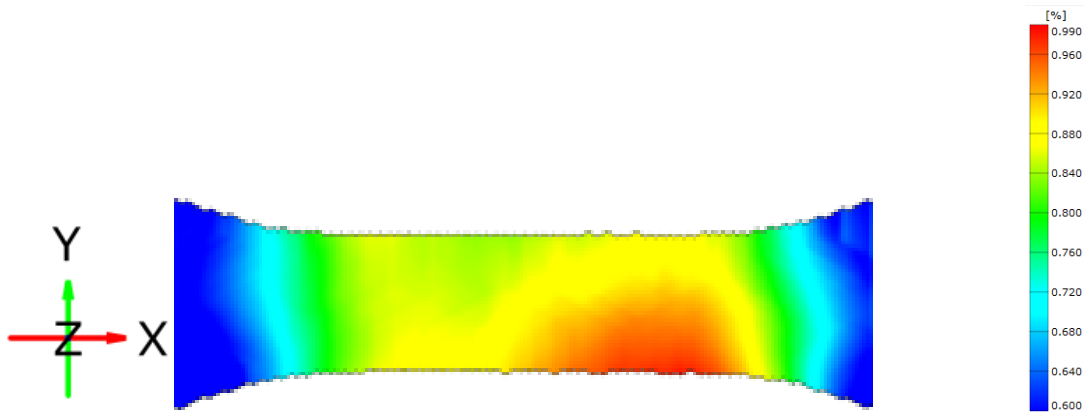


Figure 3-15: Full-field strain of milled 90° in x-direction

3.1.5 Evolution of strains

Longitudinal strains along the loading direction were plotted along the curve in Figure 3-16.

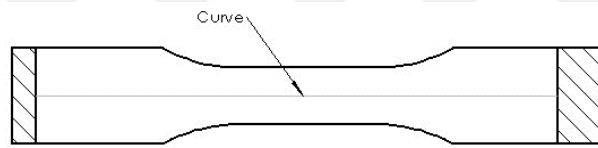


Figure 3-16: Location of the curve used for the plots

Strains were plotted at prescribed levels of stresses in Figure 3-17 and Figure 3-18. For all the specimens, it was observed that strains were localized within the gauge length as stress increased.

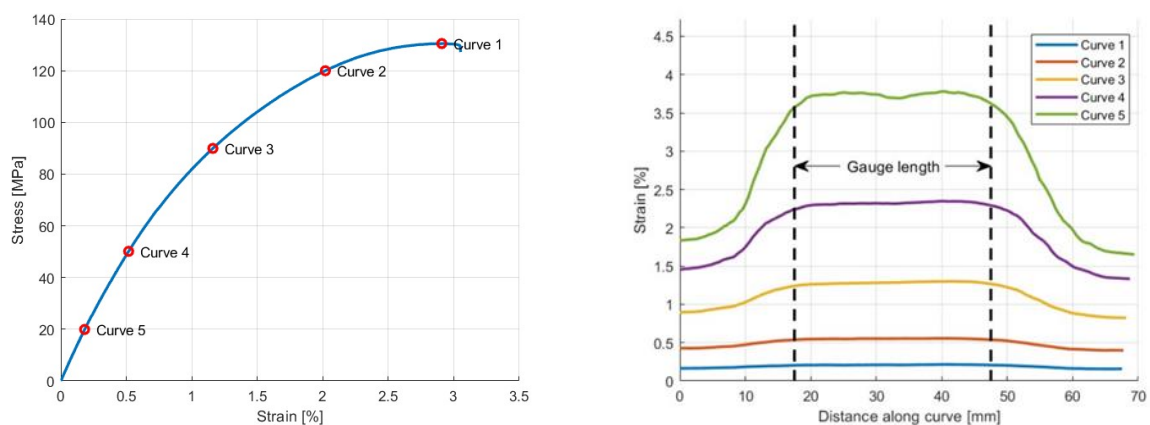


Figure 3-17: Evolution of strains of full 0° specimen (picture on the right) with the information at which stress level they were plotted (picture on the left)

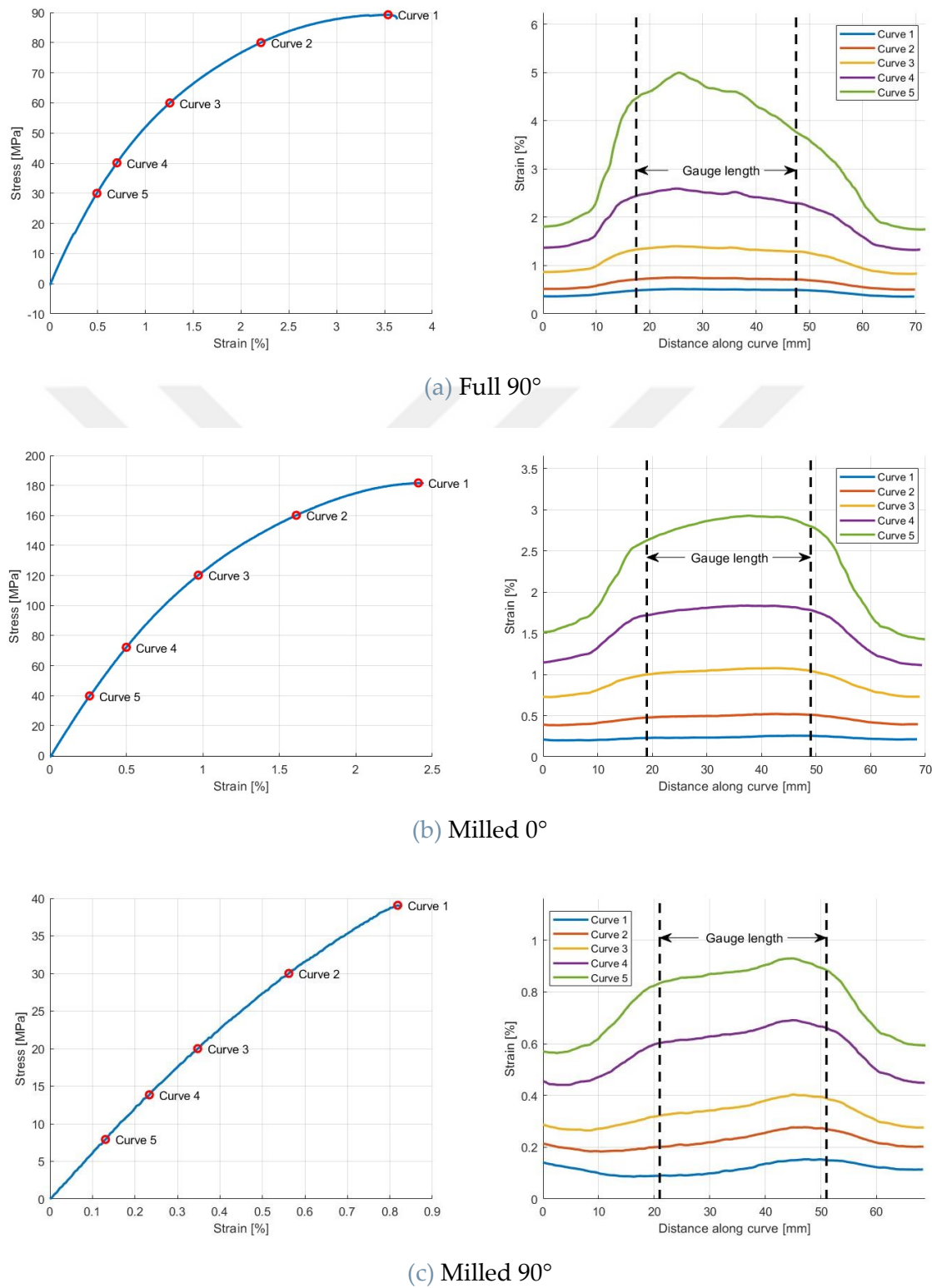


Figure 3-18: Evolution of strains (picture on the right) with the information at which stress level they were plotted (picture on the left)

3.1.6 Failure locations

Strain distribution of specimens obtained by DIC analysis together with failure surface and failed specimens was shown in Figure 3-19 and Figure 3-20. Failure surfaces coincide with regions of maximum strain or vicinity of maximum strain. It may indicate that the true strength of each specimen could be higher than the nominal one.

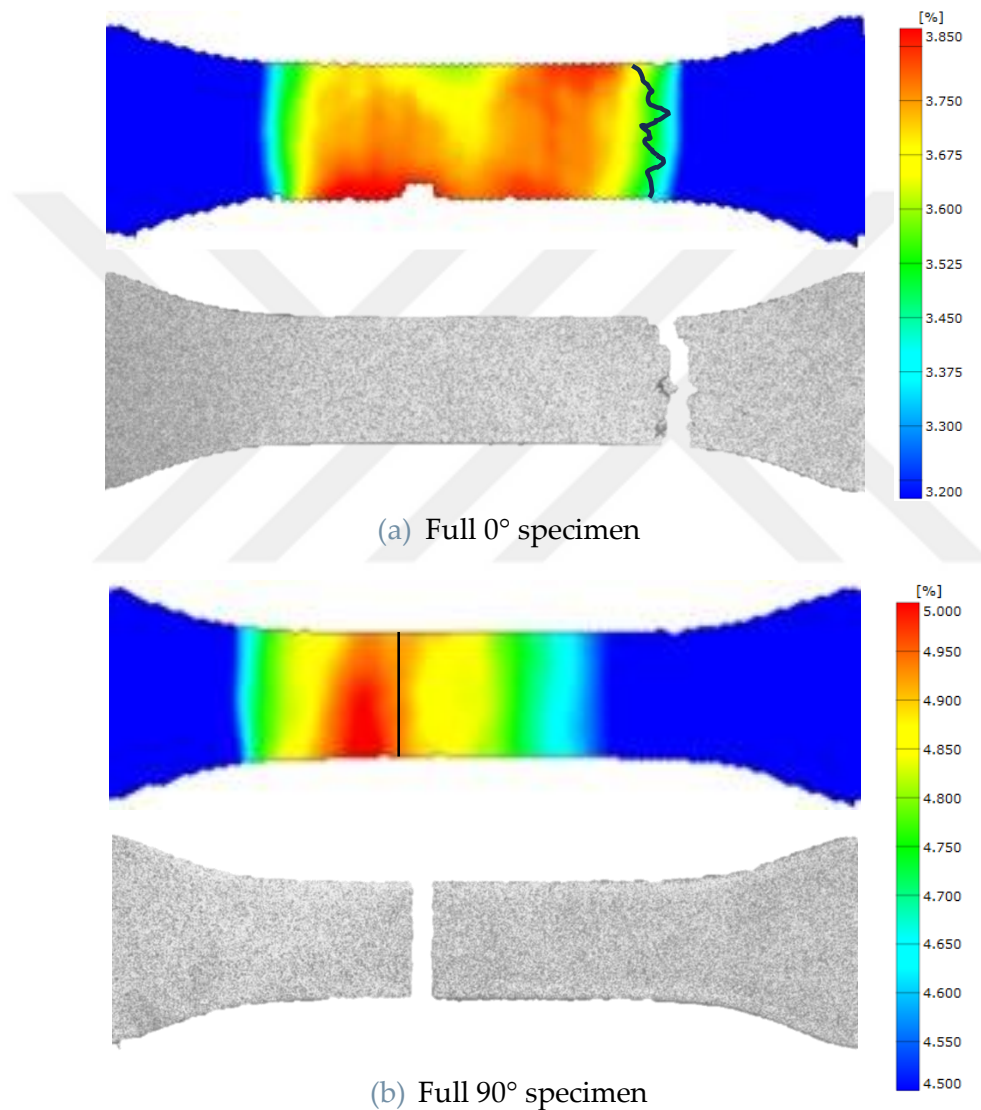


Figure 3-19: Strain distribution of the specimens just before failure (upper pictures) with crack surface (black lines in the upper pictures), failed specimens (lower pictures)

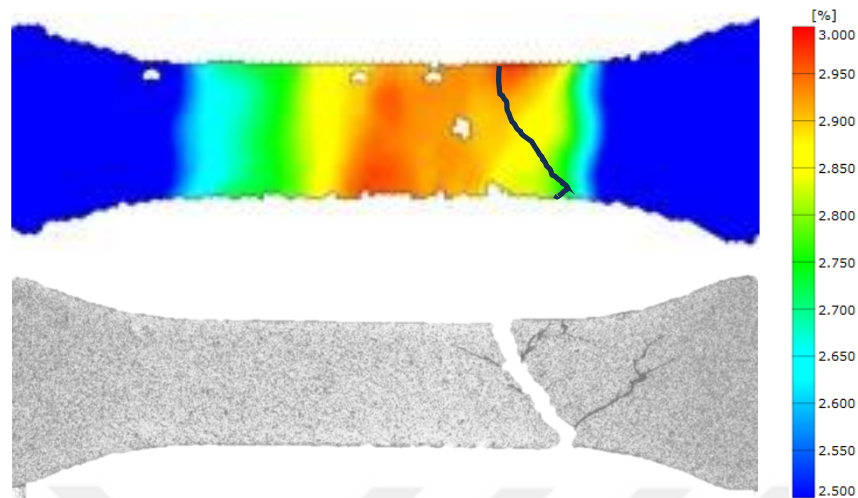


Figure 3-20: Strain distribution of the milled 0° specimen just before failure (upper picture) with crack surface (black line in the upper picture), failed specimen (lower picture)

3.2 Results of preliminary fatigue tests

The selection of software for DIC analysis of the fatigue tests and DIC parameters were reported in this section. The pictures of several tests were used to set the parameters. The pictures reported in this chapter for setting the parameters and comparison belong to a full 0° specimen at 10^6 cycles just for exemplificative purposes.

3.2.1 Investigating the effect of parameters for the calculation of displacement field by using GOM Correlate

First, the effect of changing point distance by keeping the same facet size was investigated. The facet size was fixed to 36 pixels (for comparison, 1 pixel $\approx$ 0.020 mm). Point distance was varied between 6 and 15 pixels in 3-pixel steps. The displacement field was calculated on the surface component for different pairs of facet size and point distance and a straight curve coincident with specimen's axis was created for data evaluation, as shown in Figure 3-21.

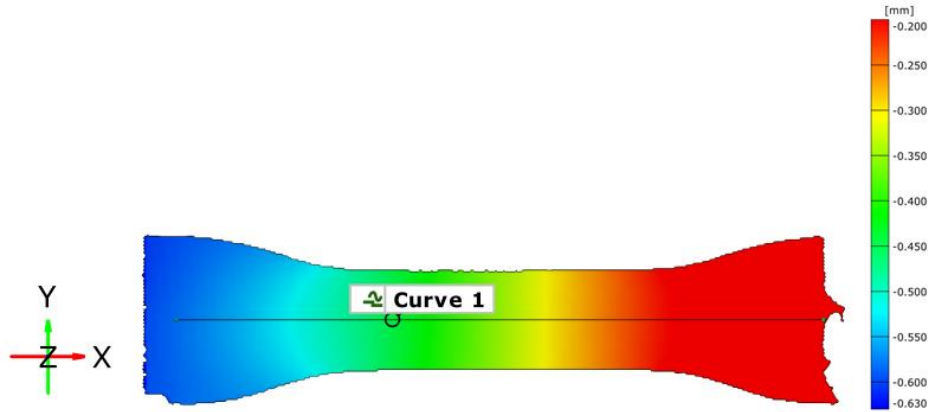


Figure 3-21: Displacement field and curve

Then, displacement through the curve was plotted to investigate the effect of point distance. Figure 3-22 shows that changing the point distance had a slight effect on the displacement calculation since all the plots almost overlapped.

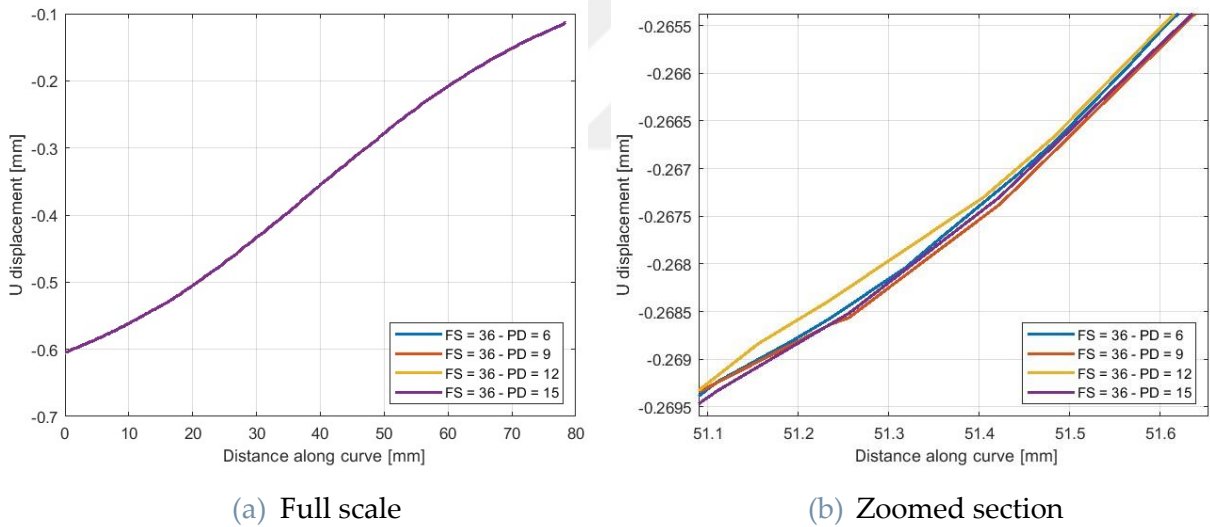


Figure 3-22: Effect of point distance on longitudinal displacement calculated by GOM Correlate (FS: Facet size, PD: Point distance) along the curve defined on the specimen's axis

Second, the effect of changing facet size by keeping the same point distance was investigated. The point distance was fixed to 12 pixels. Facet size varied between 30 and 42 pixels in 6-pixel steps. Displacement through the curve was plotted to investigate the effect of facet size. Same as before, Figure 3-23 shows that changing the facet size had almost no effect on the displacement calculation since all the plots almost overlapped.

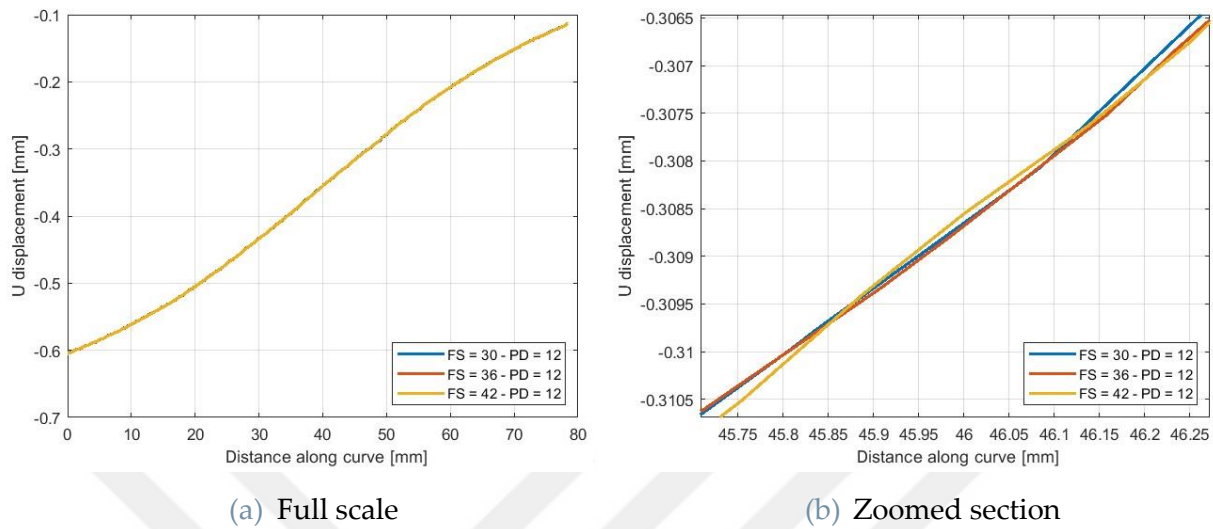


Figure 3-23: Effect of facet size on longitudinal displacement calculated by GOM Correlate (FS: Facet size, PD: Point distance) along the curve defined on the specimen's axis

3.2.2 Investigating the effect of parameters for the calculation of strain field by using GOM Correlate

As done for displacement in the previous section, related to GOM software, the effect of changing the point distance on the strain calculation was examined first. For a fixed value of facet size, which is 36 pixels, point distance was varied between 6 and 15 pixels in 3-pixel steps. Longitudinal strain was calculated and plotted along the same curve in the previous section defined on the specimen's axis without setting any other parameter. The results in Figure 3-24 shows that strain data was quite noisy for all point distance values. Increasing the point distance decreased the peaks of the strain data, but overall, the trend appeared to be similar.

Then, the effect of changing the facet size between 30 and 42 pixels in 6-pixel steps on the strain calculation was examined. Point distance was fixed to 12 pixels. Strain was calculated and plotted through the curve without setting any other parameter, again. The effect of increasing the facet size was the same as increasing the point distance. The peaks of the strain data decreased as the facet size increases as was shown in Figure 3-25.

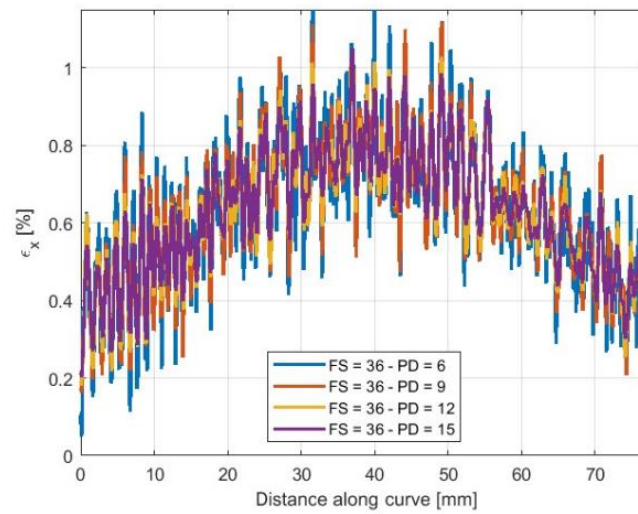


Figure 3-24: Effect of point distance on strain calculated by GOM Correlate (FS: Facet size, PD: Point distance) along the curve defined on the specimen's axis

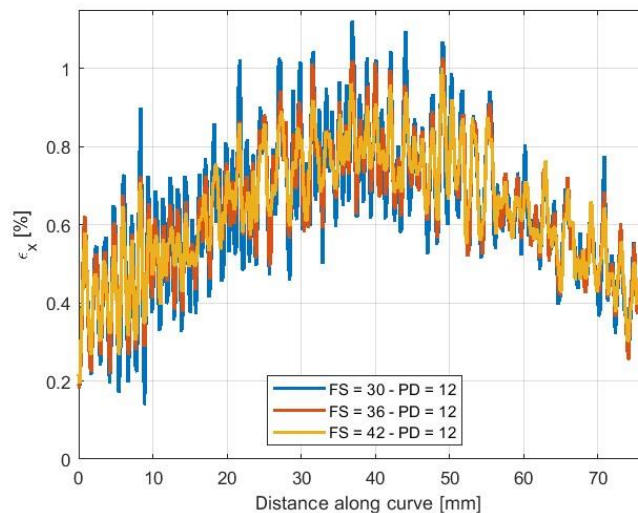


Figure 3-25: Effect of facet size on strain calculated by GOM Correlate (FS: Facet size, PD: Point distance) along the curve defined on the specimen's axis

Calculated strains were noisy as mentioned before and affected by facet size and point size parameters. This was because strain is a derivative quantity, so it was much more sensitive to small displacement oscillations. Thus, the spatial filtering option provided by GOM Correlate was used for strain calculation. The results were plotted in Figure 3-26. For a fixed facet size, the required average filter value to fully filter out the data decreased as point distance was increased. Same was valid for increasing facet size for a fixed point distance. Almost the same results could be

obtained by using proper average filter value as was shown in Figure 3-26b. The used filtering value has to be set individually for each test until a smooth trend of noisy strain is obtained.

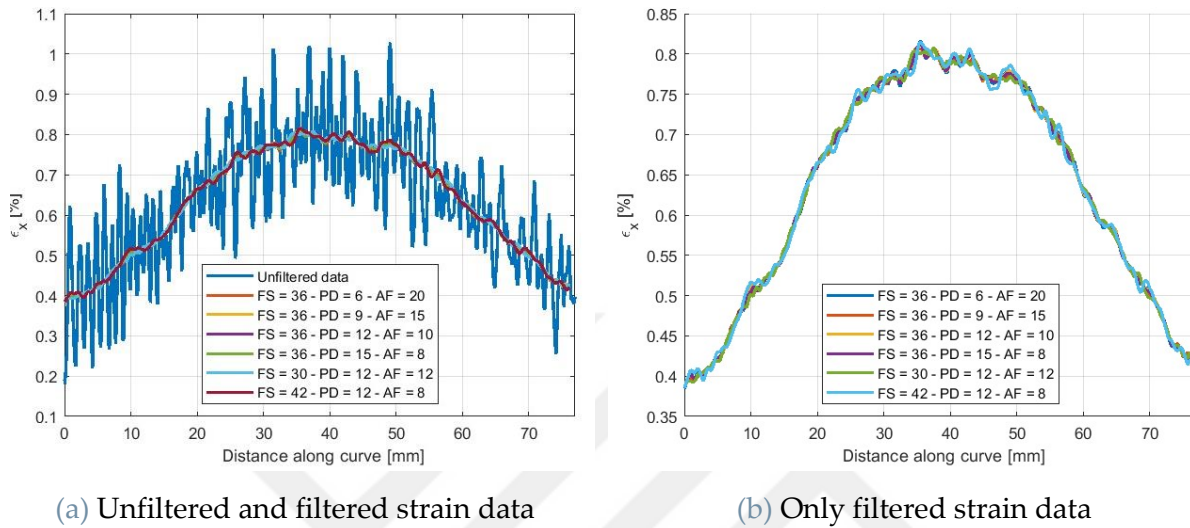


Figure 3-26: Effect of spatial filtering on strain calculated by GOM Correlate (FS: Facet size, PD: Point distance, AF: Average filter) along the curve defined on the specimen's axis

Full-field strain maps was shown in Figure 3-27 and Figure 3-28. In Figure 3-27, the noise was clearly visible as the bands of different colors are sequentially lined up since no filter was applied. A smoother strain field was achieved by applying spatial filtering as in Figure 3-28.

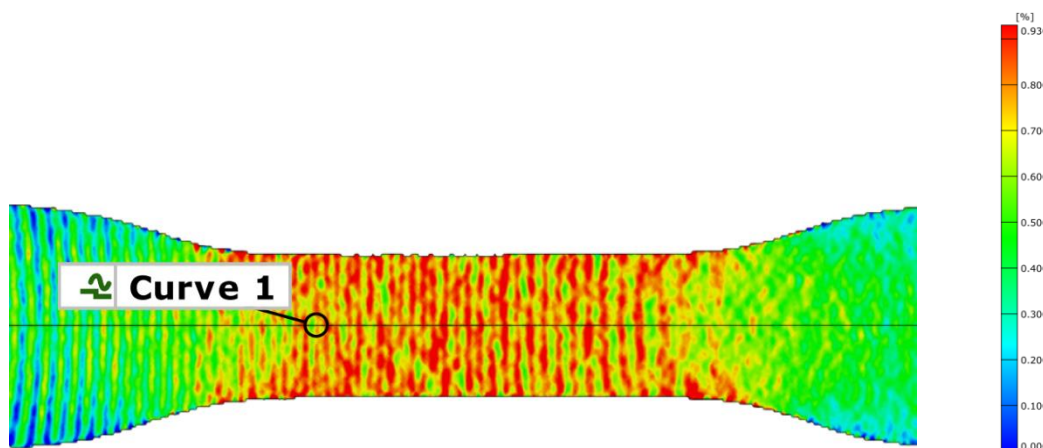


Figure 3-27: Full-field strain maps calculated by GOM Correlate (FS = 36 px / PD = 12 px / No filter)

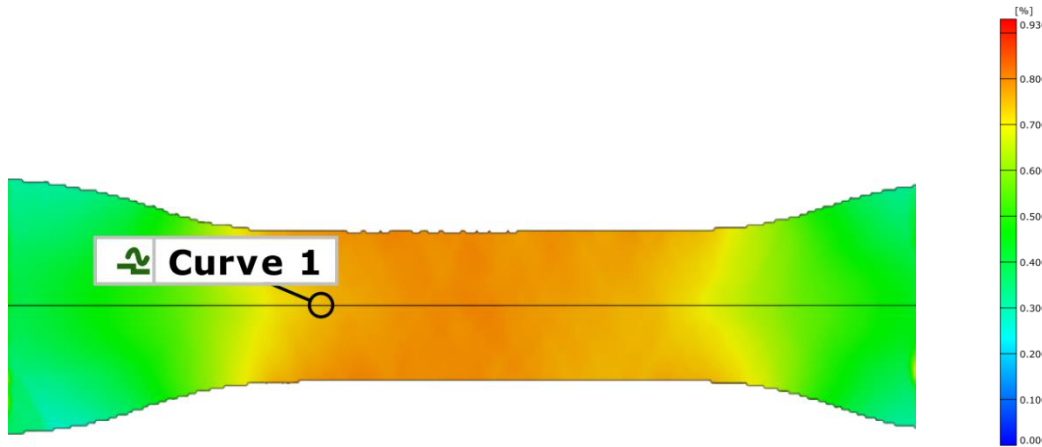


Figure 3-28: Full-field strain maps calculated by GOM Correlate (FS = 36 px / PD = 12 px / Average filter = 10)

Since almost the same strain field could be reached by choosing different facet size and point distance, 36 pixels of facet size and 12 pixels of point distance was chosen in order to decrease the computation time and size of the GOM Correlate project file.

3.2.3 Investigating the effect of parameters for the calculation of displacement and strain fields by using Ncorr

The subset radius was set as 18 pixels to obtain a subset with a diameter of 36 pixels which is the edge length of a facet in GOM Correlate. Subset spacing was set as 5 to obtain at least a similar pattern with GOM Correlate.

Then, the displacement field was calculated for the same specimen and the results were plotted along the curve defined on the specimen's axis in Figure 3-29.

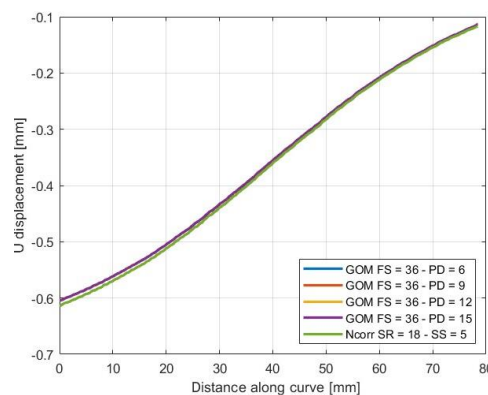


Figure 3-29: Longitudinal displacement along the curve, defined on the specimen's axis, calculated by Ncorr and GOM Correlate

Quite similar displacement patterns to the ones of GOM Correlate were obtained by using Ncorr.

For strain calculation, 1 pixel of strain radius, which is the minimum value allowed, was selected initially to compare the results with unfiltered GOM Correlate data. It followed the same trend with the strain calculated by GOM Correlate although the noise level may differ along the curve as shown in Figure 3-30.

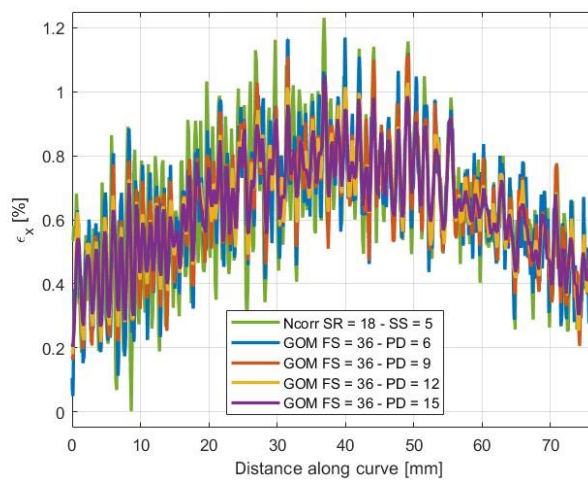


Figure 3-30: Longitudinal strain calculated by Ncorr and GOM Correlate along the curve defined on the specimen's axis

Then, a strain radius of 20 pixels was selected to filter out the noise. The results were compared with the filtered GOM Correlate data in Figure 3-31. Almost the same trend can be achieved by both software. Both displacement and strain field obtained from both software were quite comparable with each other.

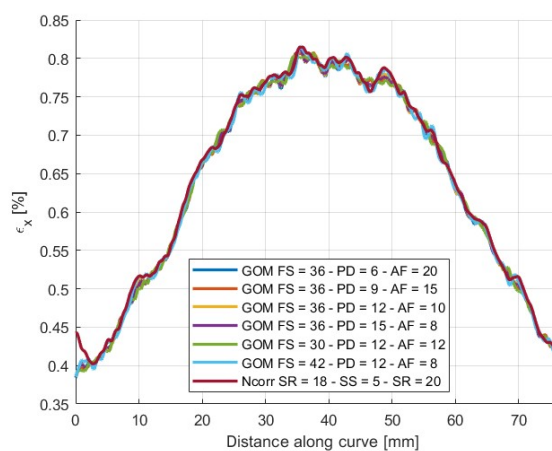


Figure 3-31: Comparison of filtered longitudinal strain calculated by Ncorr and GOM Correlate along the curve defined on the specimen's axis

3.2.4 Comparison of GOM Correlate and Ncorr

As discussed above, comparable displacement and strain fields can be obtained by using both the software. Therefore, both software provide almost the same accuracy of the results. However, calculation time differed significantly for the two software. A maximum of 62 pictures were taken during a run-out test. The calculation of displacement and strain field for all the pictures took more than an hour in Ncorr for a run-out test. However, it only took a few minutes in GOM Correlate. Therefore, GOM Correlate software was chosen to be used for DIC analysis of the fatigue tests since it was much more efficient in terms of computational time. The parameters used were summarized in Table 6. Both for tensile and fatigue tests, same parameters were used.

DIC parameters	
Software	GOM Correlate
Area of specimen surface	1872 mm ² for 0° specimens 1692 mm ² for 90° specimens
Pixels per millimeter	≈ 50 pixels/mm
Facet size	36 pixels
Point distance	12 pixels
Average filter	15-25 pixels

Table 6: Chosen DIC parameters

3.3 Results of fatigue tests

3.3.1 Overview of the tests

Fatigue tests were performed for all specimen types. Some tests were interrupted due to power loss of the testing machine. Since the specimens were made of polymeric matrix, (viscoelastic), the tests cannot be continued once the tests were interrupted. Otherwise, the effect of cyclic creep would be misevaluated.

Initially, the aim was to investigate specimens which failed at approximately 10^6 cycles. Therefore, the loads were selected from the resulting S-N curves of the same specimens in the previous study, [19]. The mechanical properties of the specimens in this study and the previous one was expected to be the same since they were manufactured within the same batch and supposed to have some moisture content. The S-N curves of full specimens obtained in the previous study, the expected and actual location of the failure of the first two tests of the current study are in the chart in Figure 3-32.

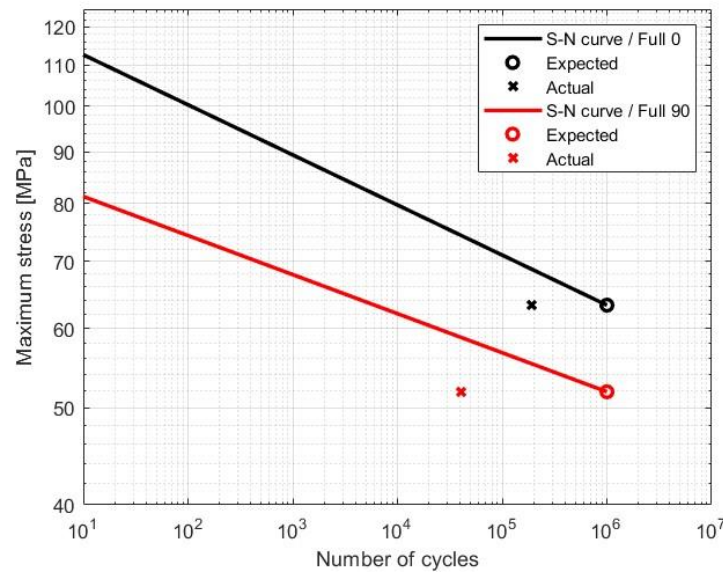


Figure 3-32: S-N curves of full specimens from previous study, [19], together with expected and actual locations of the first two tests in the chart

S-N curves provide 50% probability of failure, thus some sort of deviation can be always observed. However, this one was much more than 50% probability. Therefore, tensile tests of full specimens of the previous and this study were used to normalize S-N curves. Stress-strain curves of previously tested full specimens and specimens tested in this study were shown in Figure 3-33.

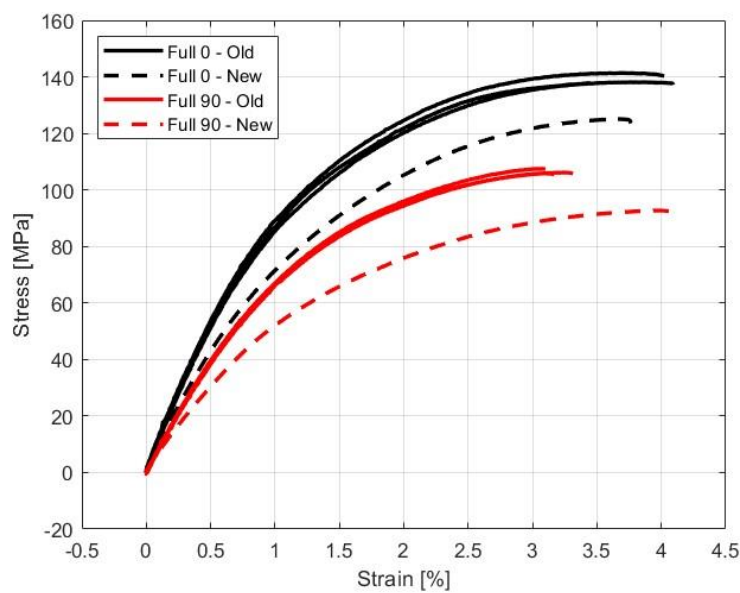


Figure 3-33: Stress-strain curves of previously tested full specimens in [19] and specimens tested in this study

However, even after normalization of S-N curves, failures at desired number of cycles, which was around 10^6 cycles, could not be obtained. S-N chart of the tests other than the interrupted ones were plotted in Figure 3-34 where maximum applied stress was plotted against number of cycles to failure. The tests went to run-out were indicated with an arrow. All the failed specimens were failed between 200000 and 300000 cycles except for Test 1 (T01). The tests failed within the mentioned region were indicated inside the orange box in Figure 3-34. Result and discussion sections about fatigue data mainly focus on these results. The 90° milled specimen was the only one whose failure did not fall within the mentioned cycles range.

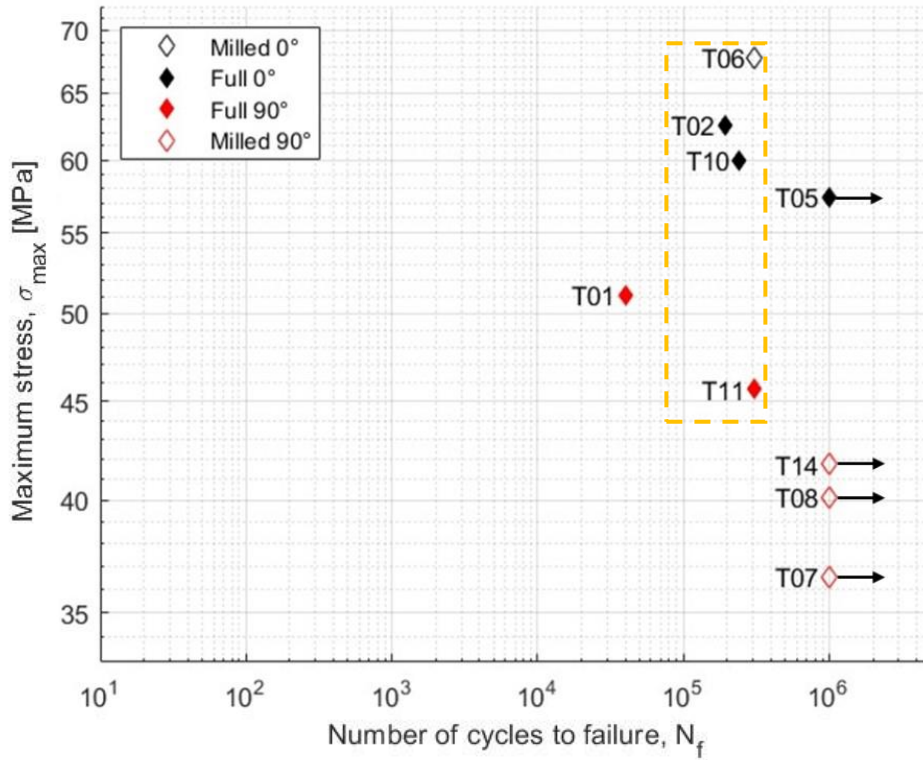


Figure 3-34: S-N chart of the tests

The tests were also reported in Table 7 with information on the maximum applied stress, number of cycles to failure and specimen ID. From this point onwards, each specimen will be referred to by its specimen IDs.

As expected, milled 0° specimen was the one with the highest fatigue strength inside the interested region due to its higher degree of fiber orientation along the loading direction. Then, full specimens were ranked depending on the volume or thickness fraction of the 0° layers they contain. Thus, full 0° and full 90° specimens followed milled 0° specimen, respectively. If a milled 90° specimen was obtained within the

region, it was expected to be the one with the lowest fatigue strength due to its higher degree of fiber orientation perpendicular to the loading direction and potentially no fiber oriented along the loading direction.

Specimen ID	Specimen Type	$\sigma_{\max}$ [MPa]	Number of cycles to failure
T06	Milled 0°	67.7	307146
T02	Full 0°	62.5	192389
T10	Full 0°	59.9	243282
T05	Full 0°	57.3	Run-out
T01	Full 90°	51.0	40193
T11	Full 90°	45.6	307159
T14	Milled 90°	41.7	Run-out
T08	Milled 90°	40.1	Run-out
T07	Milled 90°	36.5	Run-out

Table 7: Summary of fatigue tests

3.3.2 Normalized S-N chart

The maximum applied stress in fatigue tests was normalized with respect to ultimate tensile strength of each specimen type in Figure 3-35. Full specimens within the orange box in Figure 3-35 coincided. This means that the normalized strength parameter does not depend on the fiber orientation for full specimens. This behavior was also reported for SFRPs in some previous studies [2], [7], [39]–[41]. However, milled 0° specimens within the same region laid up at a lower normalized fatigue strength value than the full specimens. Furthermore, even though there is no information about milled 90° specimen within the mentioned region, normalized strength of the milled 90° specimen have to place at a higher value of normalized strength than the full specimens. This fact is clear by looking at the normalized strength of the milled 90° specimens went to run-out. Thus, normalized fatigue strength of the milled specimens did not collapse with that of the full specimens and each other. Normalized fatigue strength values of all tested specimens at a certain fatigue life decreased in the order of milled 90° specimen, full specimens and milled 0° specimen. It was reported that normalized fatigue strengths of a unidirectional continuous fiber reinforced polymers diverged for 0° and 90° specimens [42]. It was lower for the unidirectional 0° specimens than the unidirectional 90° specimens as it was observed in this work.

The difference between normalized fatigue strengths of milled 0° and milled 90° specimens means that quite different damage mechanisms take place for each

specimen type in fatigue and tensile loading conditions. It was reported that damage mechanisms for 90° specimens are matrix dominated [20], [42]. The ability of the specimens to absorb energy may become more pronounced in fatigue life of milled specimens. On the contrary, it may become less pronounced in tensile strengths. If this is the case, it explains that the normalized fatigue strengths of the milled 90° specimen is the highest and that of the milled 0° specimen is the lowest. However, these results depend on a few experimental data. The observed behavior may simply be a scatter of data. Therefore, as future development of the work, further fatigue tests should be performed at different loads to verify this behavior.

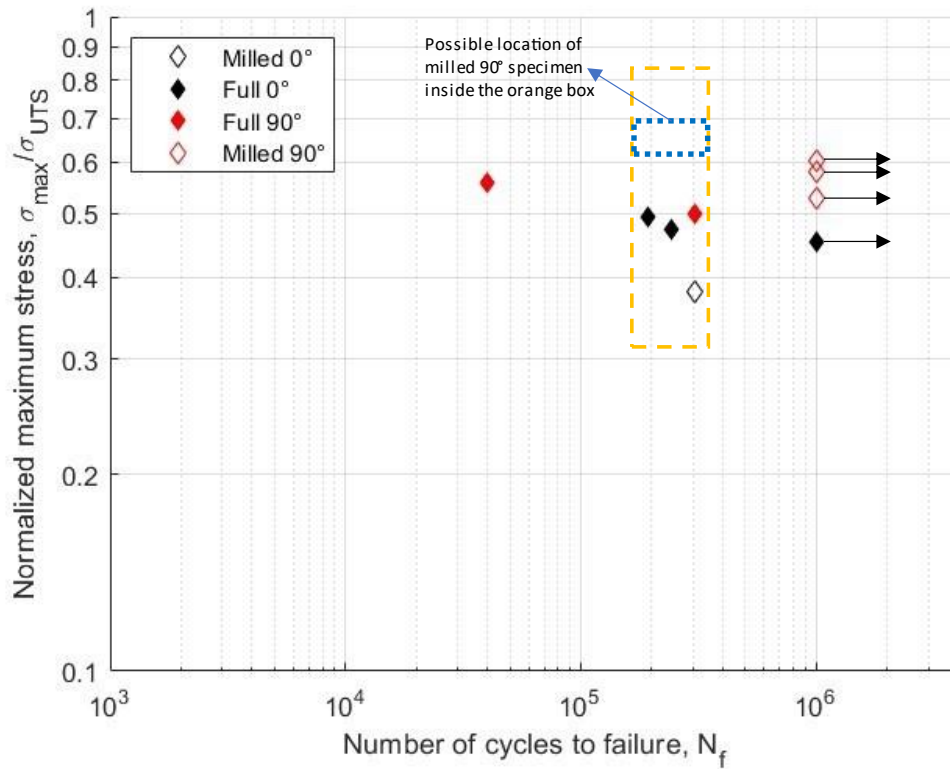


Figure 3-35: Normalized fatigue strength with respect to tensile strength vs number of cycles to failure

3.3.3 Comparison of displacement obtained by testing machine and DIC

Due to the geometry of the grips and the specimen holder as was shown in Figure 3-36, a portion of the specimen cannot be viewed by the camera.

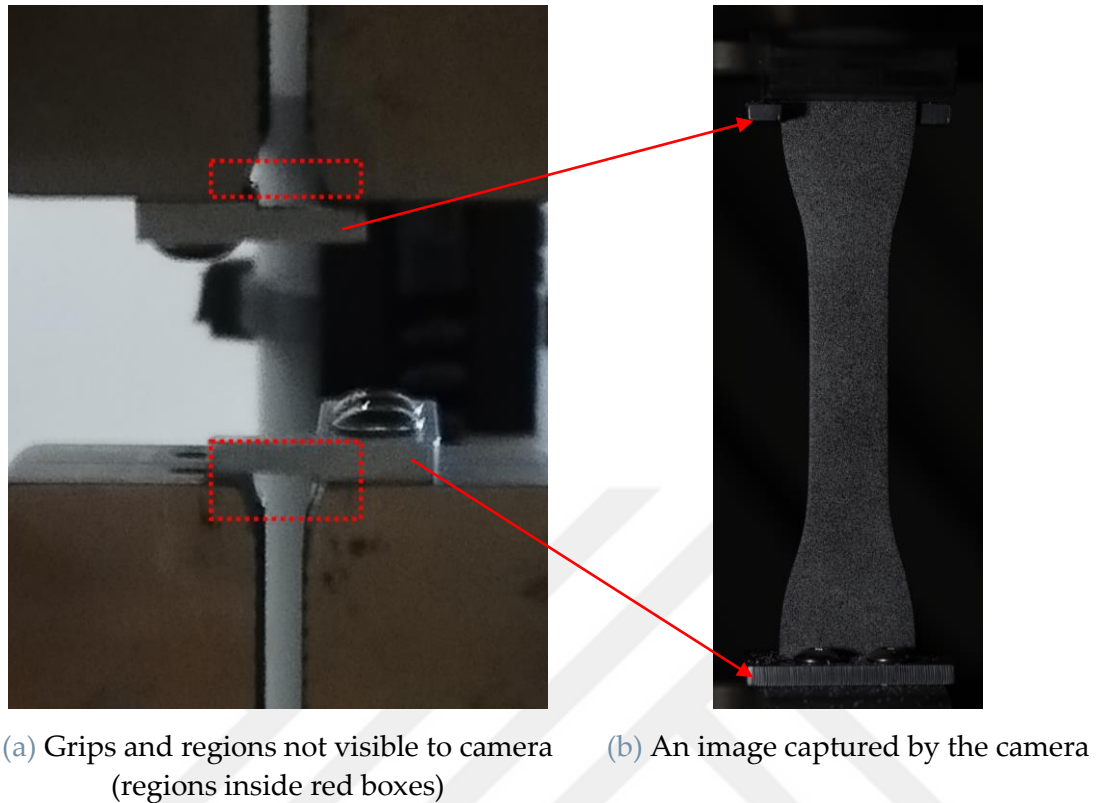


Figure 3-36: Grips of the testing machine and a sample image

Thus, the surface of the specimen, in which DIC analysis can be performed, can be schematized as in Figure 3-37. This means that maximum displacement acquired by the testing machine and the region where zero displacement occurs cannot be evaluated by DIC analysis. 7.35 mm of the specimens cannot be viewed by the camera on the left-hand side of the specimen in Figure 3-37, where the fixed part of the testing machine is located. 3.65 mm of the specimens cannot be viewed by the camera on the right-hand side of the specimen (see Figure 3-37), where the moving part of the testing machine is located.

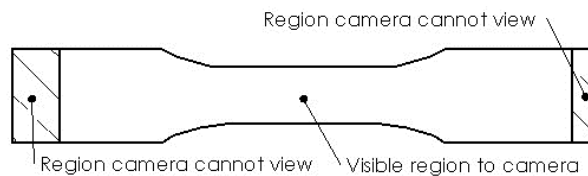


Figure 3-37: Visualization of the specimen with regions visible and not visible to the camera

In Figure 3-38 and Figure 3-39, displacements were plotted to show the comparison between displacements obtained by the testing machine and DIC analysis.

Displacements obtained by DIC analysis were extrapolated by preserving the initial and final trend of data for the region not visible to camera.

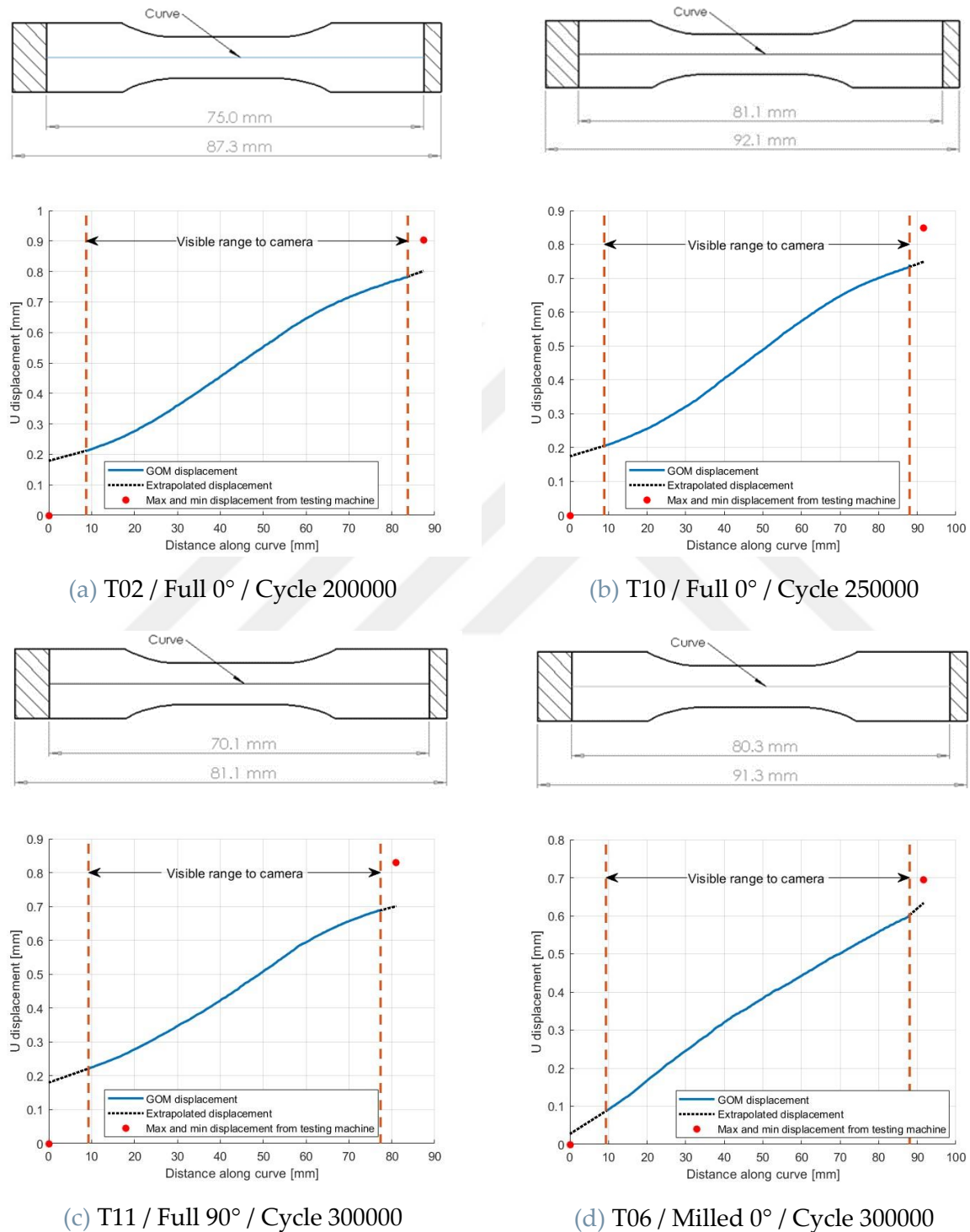


Figure 3-38: Displacement comparison obtained from testing machine and DIC for the last pictures of the specimens

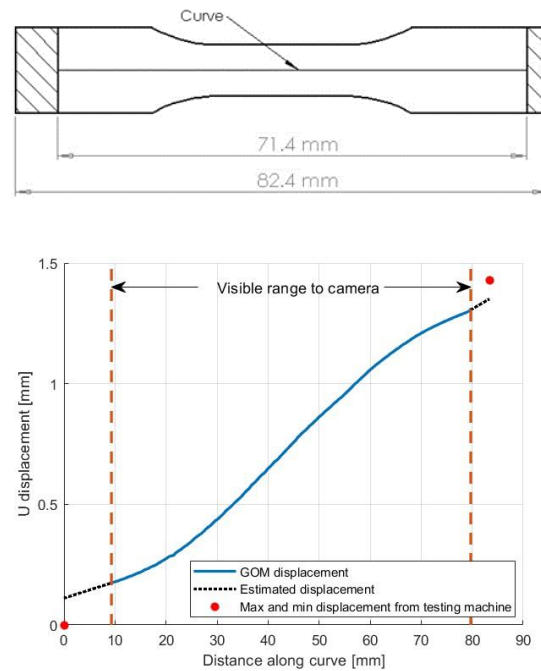


Figure 3-39: Displacement comparison obtained from testing machine and DIC for the last pictures of the specimens (T14 / Milled 90° / Cycle 1000000)

Similar to what found from the DIC analysis of the tensile tests, DIC analysis of fatigue tests cannot capture the zero displacement and maximum displacement measured by the testing machine even after extrapolation. However, the difference is more than the tensile tests in terms of percentage. It could be due to the fact that ARAMIS has double cameras, so a better assessment of displacement became possible. Although maximum and minimum displacements could not be captured by DIC, S-shaped displacement profile was coherent with the specimen geometry.

Some possible reasons for inaccuracy of the displacement were considered to understand why DIC cannot capture displacement. The first one was considering a possible movement of the camera. However, when the taken pictures were investigated, no movement of the camera could be found. Another consideration was about the accuracy of the crosshead displacement. In [38], it was reported that crosshead displacement and strain calculated by using it were found as the least uncertain measurements when compared to extensometer and strain gauge. Moreover, crosshead resulted in overestimating the displacement and strain compared to extensometer and strain gauge results. This fact can explain why maximum displacement could not be captured by DIC. However, it does not explain why zero displacement could not be captured.

The inaccuracy may be related to the fact that one camera cannot perfectly project the surface into a 2D image at its actual size. The use of two cameras at different angles like in ARAMIS can overcome this problem and thus enable a better evaluation.

3.3.4 Comparison of strains obtained from the testing machine and DIC

Strain obtained from crosshead displacement should be close to average strain obtained from DIC analysis theoretically. However, maximum and zero displacement cannot be captured by DIC analysis for the abovementioned reasons as discussed in the previous section. Strains obtained from the testing machine and average strains from GOM were different from each other. Comparison between those strains was shown in Figure 3-40 and Figure 3-41. The testing machine strain was calculated by dividing measured displacement data by the initial grip-to-grip distance. As expected, strain from the testing machine was higher than the average strain from DIC analysis due to the inability of DIC to capture zero and maximum displacement even after extrapolating the displacement. The average strain obtained by DIC was more diverged from the strain obtained by the testing machine than by the tensile tests. All the results provided in the previous and this chapter showed that using ARAMIS with double cameras provides better assessment of displacements and strains.

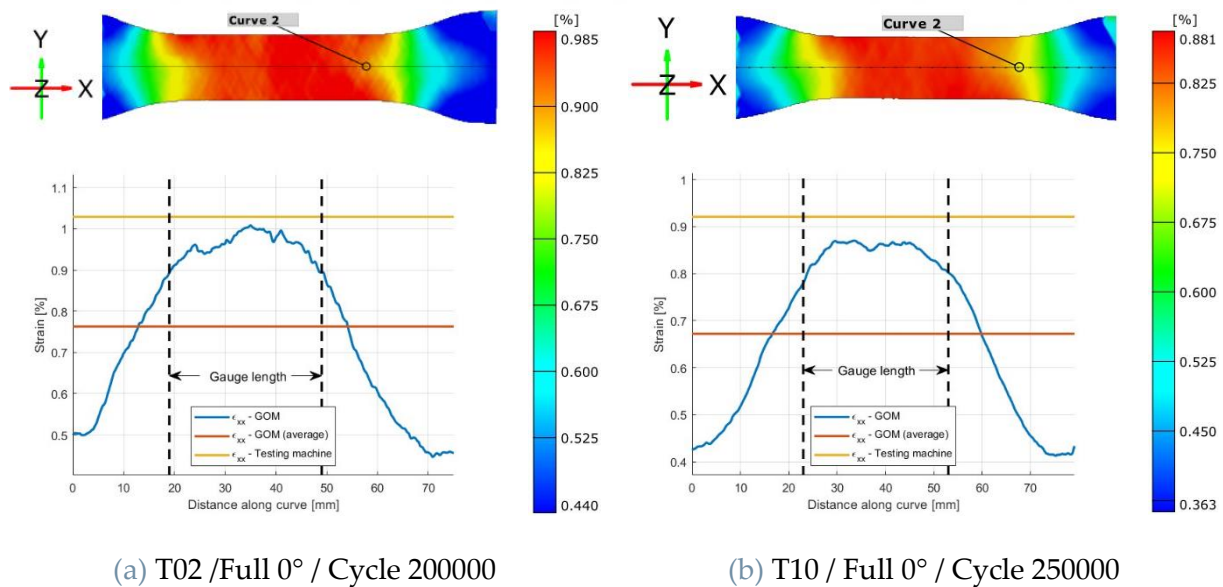


Figure 3-40: Strain comparison obtained from testing machine and DIC for the last pictures of the specimens

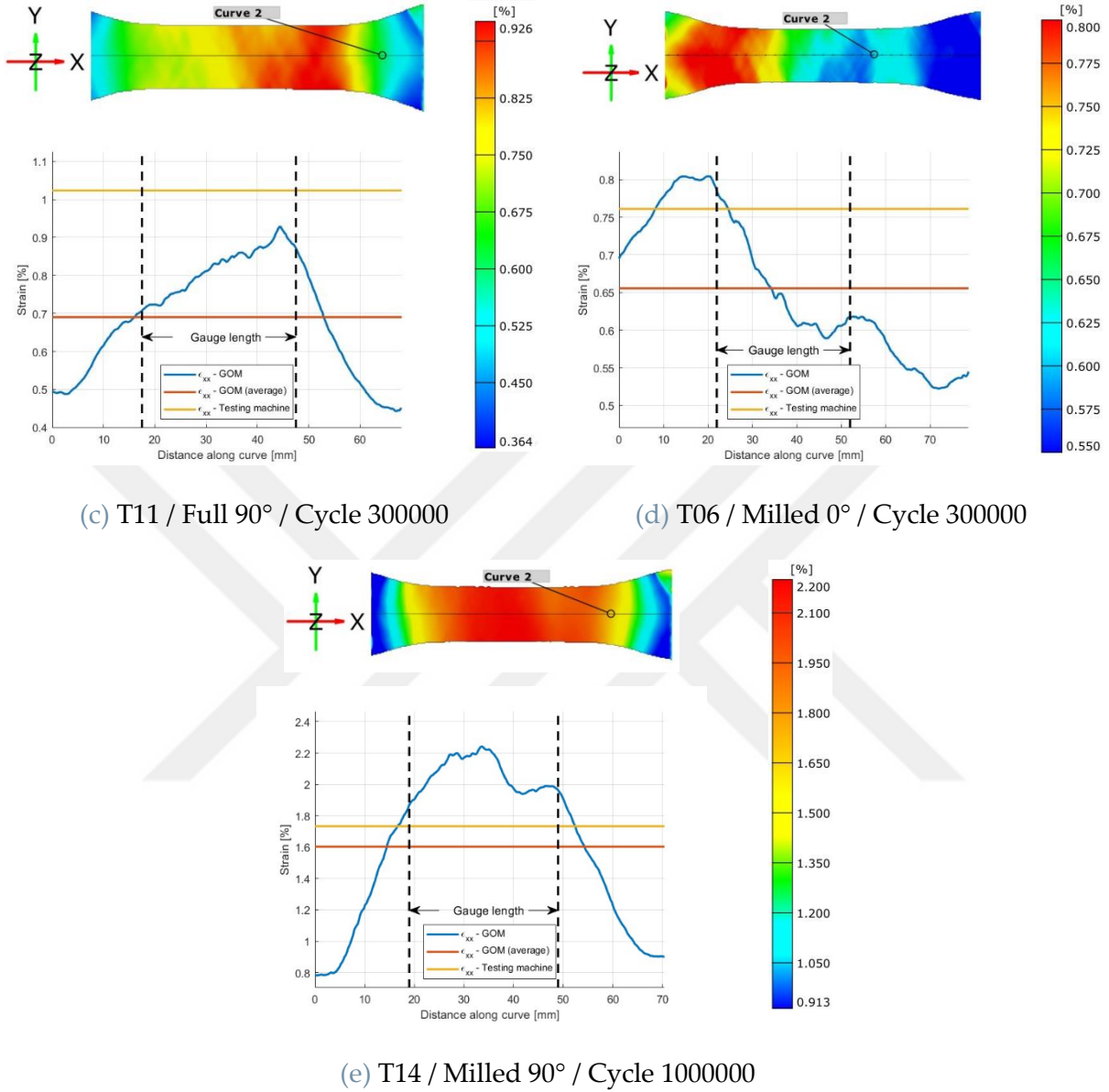


Figure 3-41: Strain comparison obtained from testing machine and DIC for the last pictures of the specimens

3.3.5 Stress concentration around fillet radii

An observation in the previous work, [19], was related to the failure locations of the milled and full specimens. It was seen that full specimens were likely to fail in the middle of the gauge length. However, milled specimens tended to fail around the fillet radii. It could be an indication of higher sensitivity on the stress concentration around the fillet radii for the milled specimens, thus reducing their fatigue strength. Thus, one of the objectives of this study was to investigate the stress distribution of

the full and milled specimens by using DIC method. The images of both full and milled specimens were analyzed to investigate a possible stress concentration around the fillet radii and how strains were distributed on the specimen surface.

3.3.5.1 Investigation of stress concentration on full specimens

Figure 3-42a shows the longitudinal strain distribution of the specimen T02 (full 0°). No evidence of stress (or strain) concentration has been found for this specimen. To further investigate the strain distribution, strains are plotted along the curves which was shown in Figure 3-42a. As Figure 3-42b shows clearly, the development of strain can be divided into three regions.

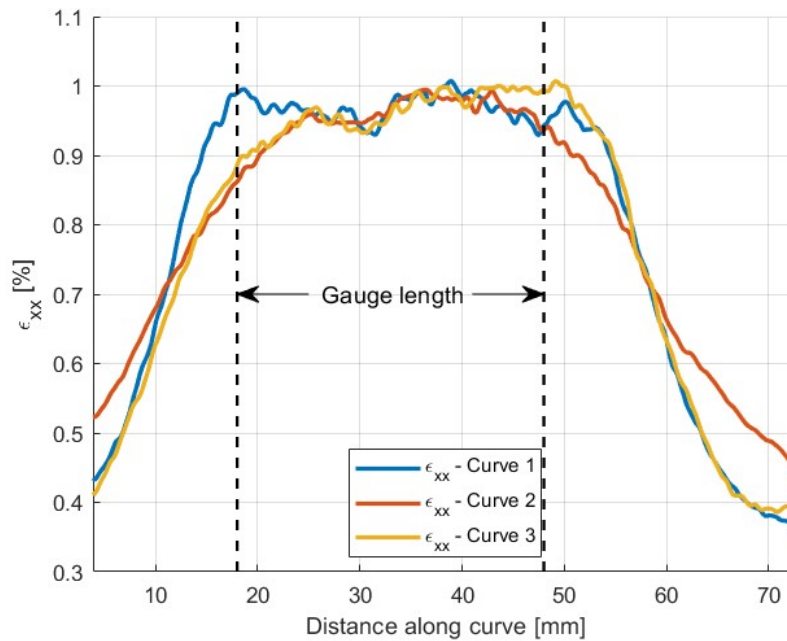
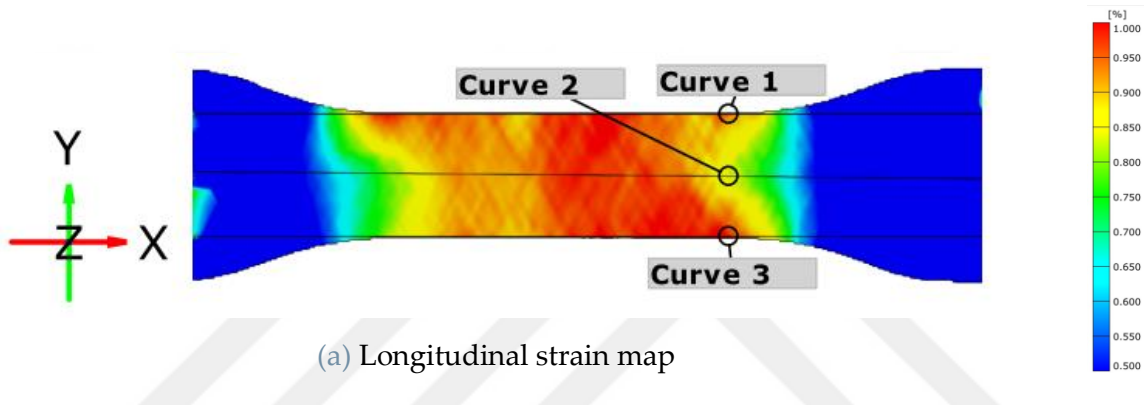


Figure 3-42: Investigation of stress concentration on a full specimen (T02, Full 0° specimen, $\sigma_{\max} = 62.5$ MPa, Cycle = 200000)

First, strain increases as the cross section of the specimen decreases due to the fillet radii. Second, strain stabilizes at the gauge length. Then, the opposite trend to the first one is observed as expected. No strain concentration is evident around the fillet radii.

Strain map and strain along the curves of the specimen T10 (full 0°) was shown in Figure 3-43. The same results were obtained as the previous one. There is no evidence of stress concentration around the fillet radii, again.

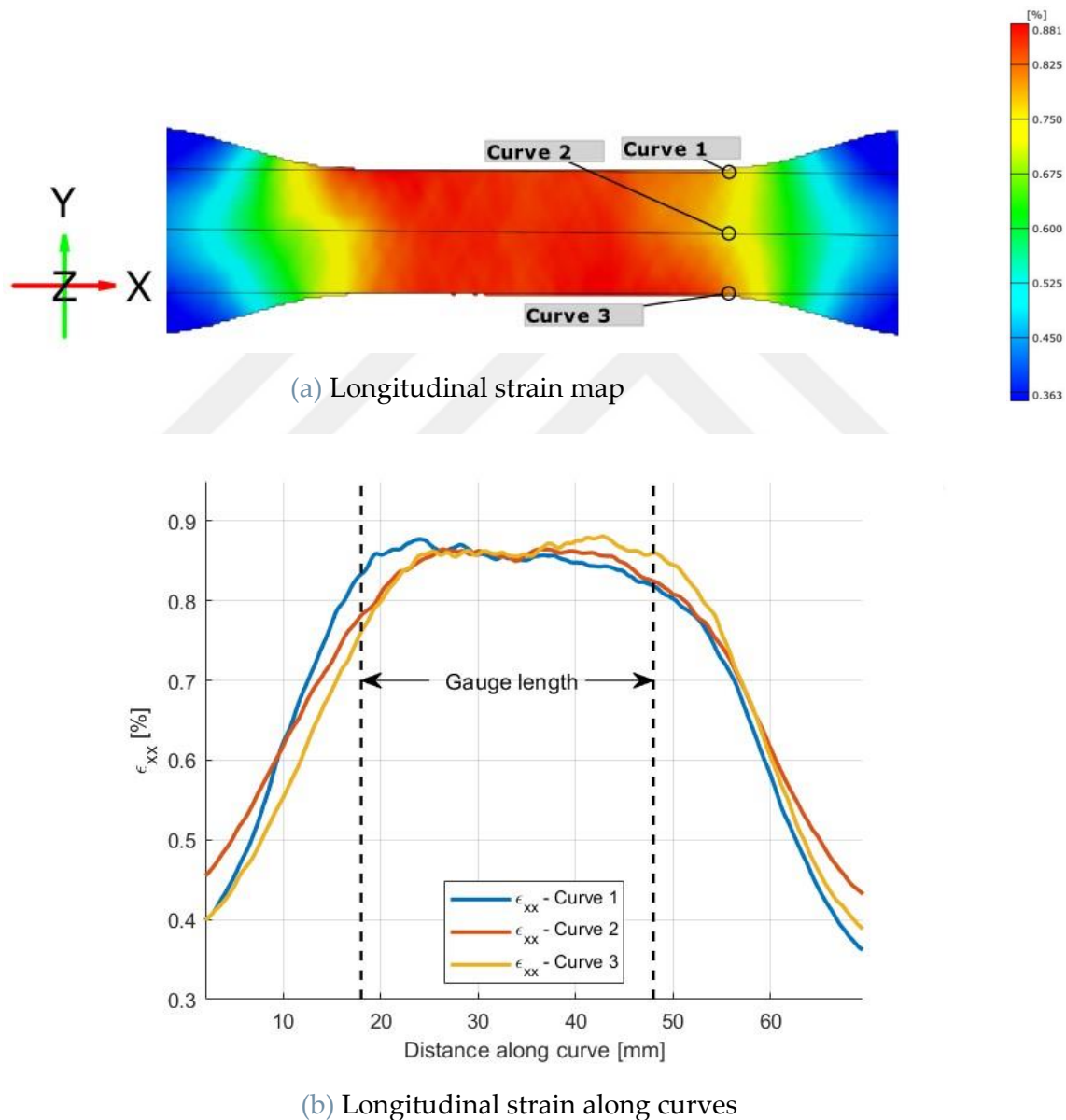


Figure 3-43: Investigation of stress concentration on a full specimen (T10, Full 0° specimen, $\sigma_{\max} = 59.9$ MPa, Cycle = 240000)

Figure 3-44 shows strain map and strain along the curves for specimen T11 (full 90°). A different distribution of strain on gauge length than the previous full specimens was observed. Strain tended to localize on the right-hand side of the specimen. However, localized strains were observed within the gauge length and no evidence of stress concentration due to fillet radii was found.

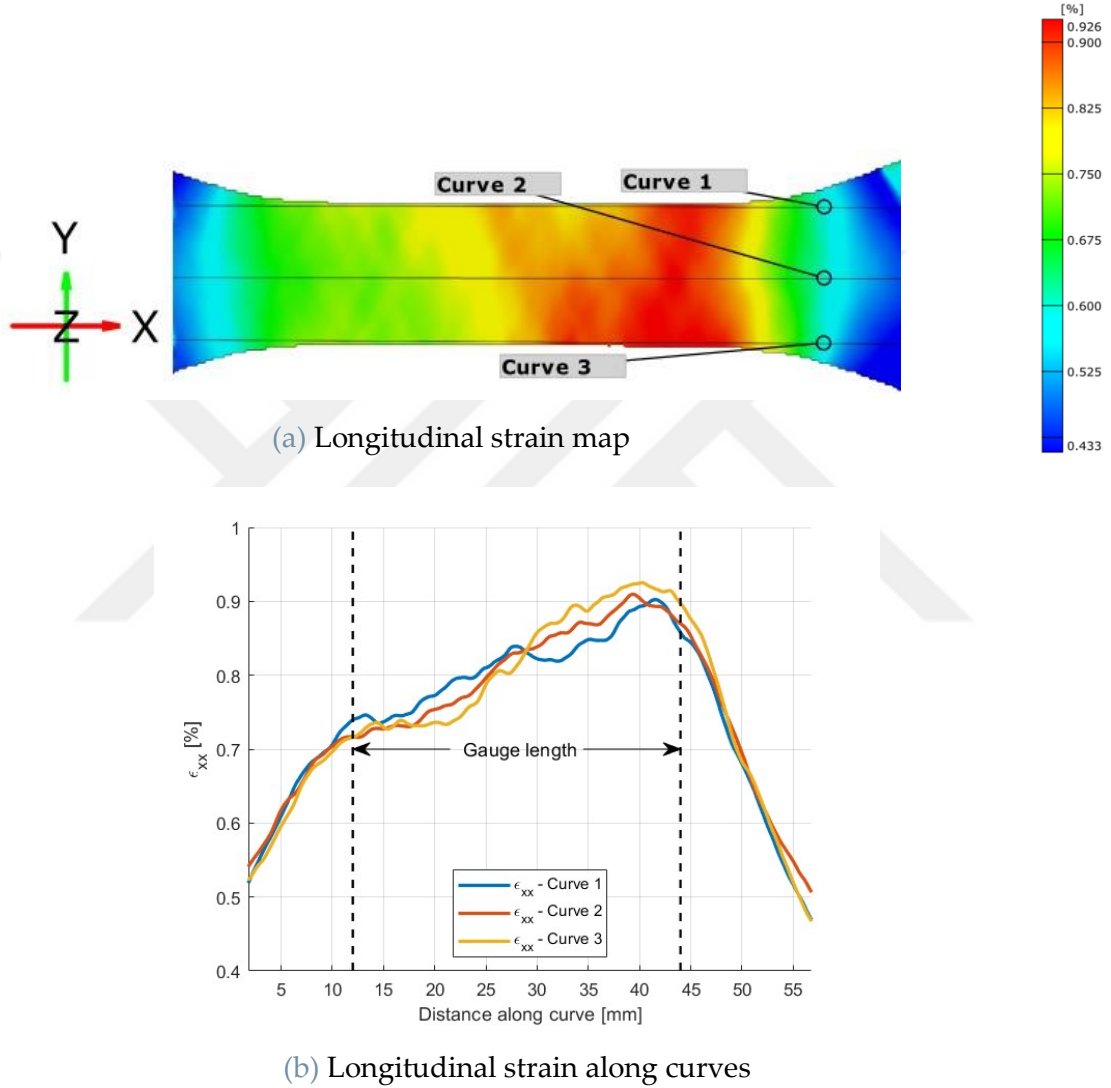


Figure 3-44: Investigation of stress concentration on a full specimen (T11, Full 90° specimen, $\sigma_{\max} = 45.6$ MPa, Cycle = 300000)

3.3.5.2 Investigation of stress concentration on milled specimens

Full field strain map of specimen T06 (milled 0°) in Figure 3-45a shows that strain was localized on both sides of the specimen. Double peak of the strain distribution on both sides can be clearly observed in Figure 3-45b.

The locations of the maximum strains are outside of the gauge length and right at the end of gauge length for left-hand and right-hand side of the specimen, respectively as was shown in Figure 3-45b.

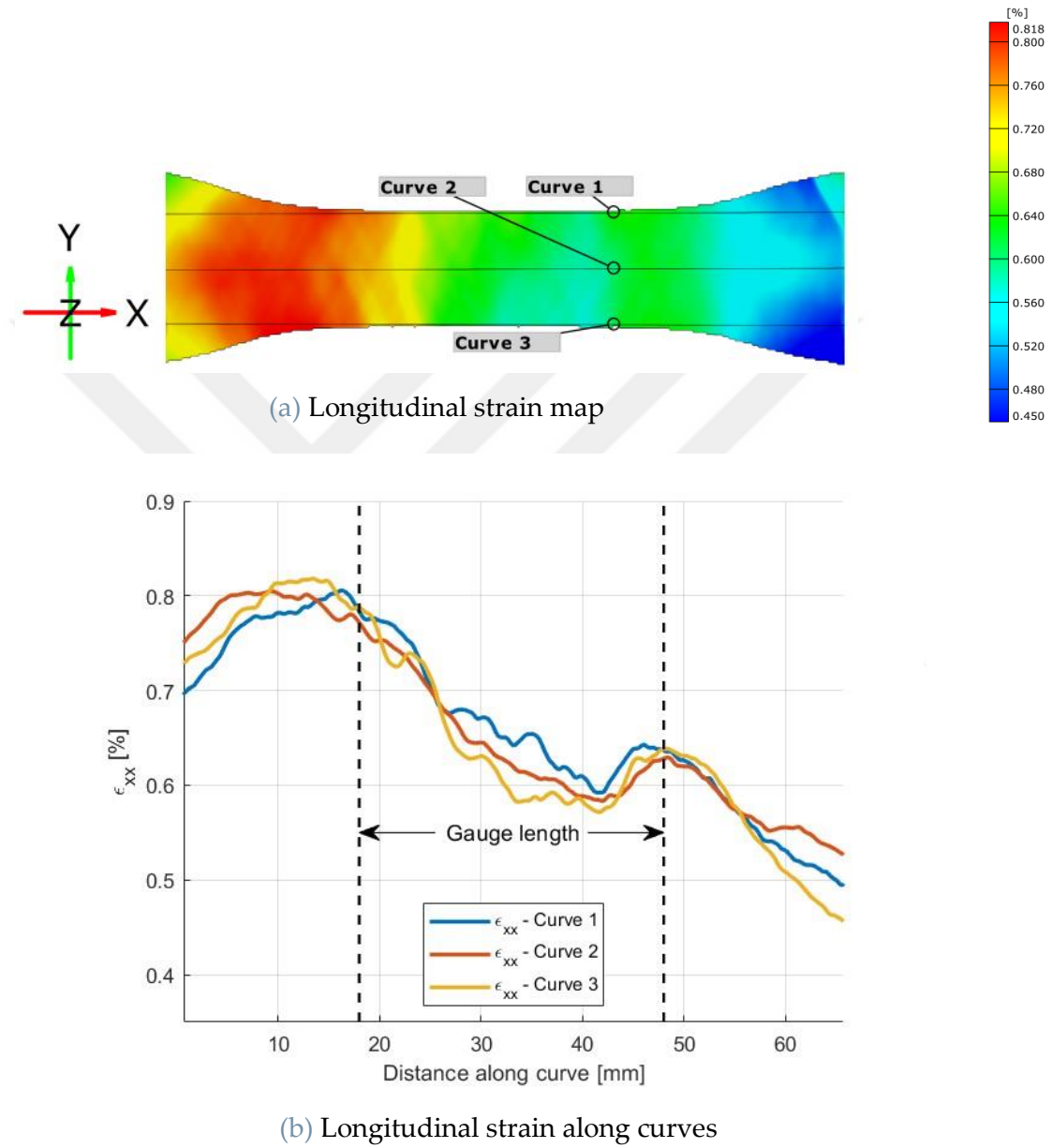


Figure 3-45: Investigation of stress concentration on a full specimen (T06, Milled 0° specimen, $\sigma_{\max} = 67.7$ MPa, Cycle = 300000)

Figure 3-46 shows how strains were distributed on the surface of specimen T14 (milled 90°). A constant strain field could be obtained inside the gauge length.

However, variation of strain inside the gauge length was not caused by a stress concentration around the fillet radii.

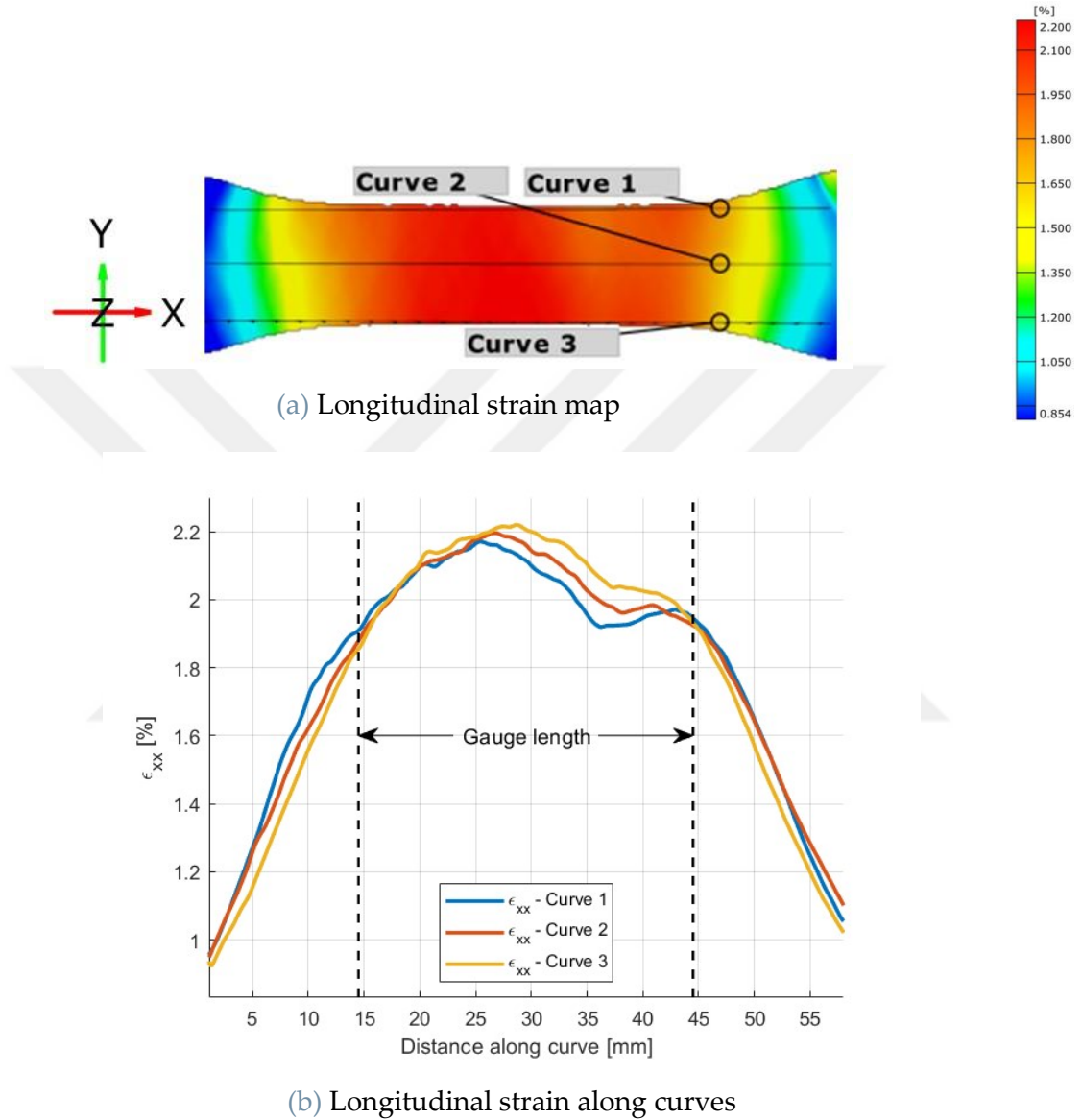


Figure 3-46: Investigation of stress concentration on a milled specimen (T14, Milled 90° specimen, $\sigma_{\max} = 41.7$ MPa, Cycle = 1000000)

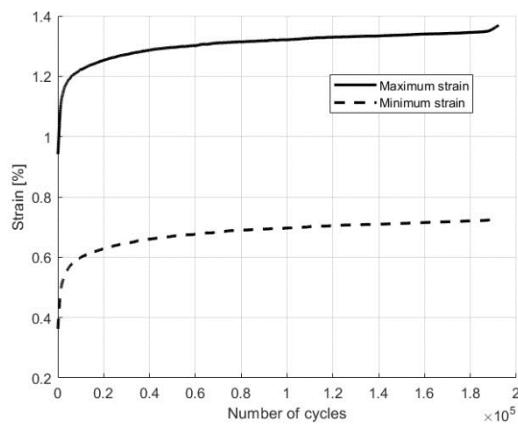
In conclusion, DIC analysis of the full and milled specimens showed that there is no proof of strain or stress concentration for full specimens due to fillet radii. For milled specimens, it was observed that higher local strains around the fillet radii could be observed for multiple number of tests (only one of them is reported in the text). However, some cases where no evidence of strain concentration due to fillet radii

was also observed. Therefore, it could be concluded that there exists a probability distribution whether strain concentration occurs or not for milled specimens.

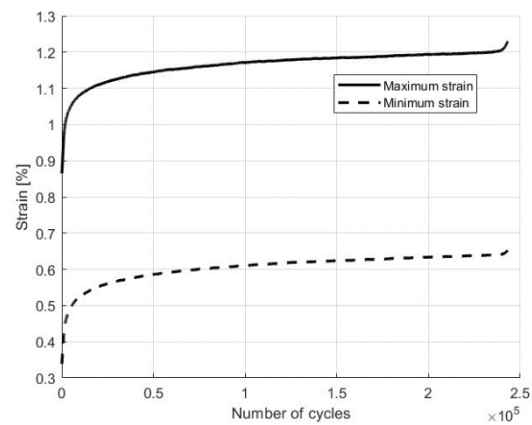
3.3.6 Evolution of strains

3.3.6.1 Testing machine data

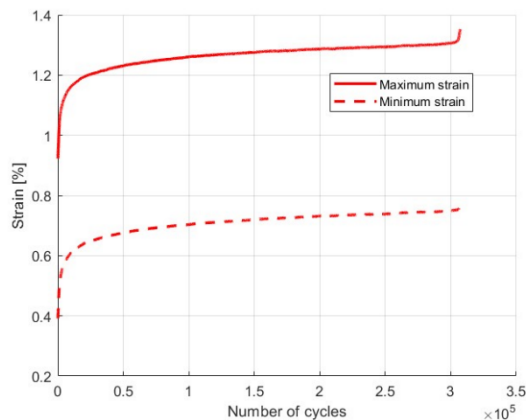
The fatigue tests were load controlled. This means that strain should increase as the number of cycles increases due to cyclic creep and damage development. Figure 3-47 and Figure 3-48 shows the evolution of strains throughout the tests. The trend of maximum and minimum strain for all tests can be divided into three regions. In the first region, a rapid increase of strain was observed. Then, a linear increasing trend was obtained for the second region. Finally, a third region was visible just before the failure. The trend was again a rapid increase as in the first region.



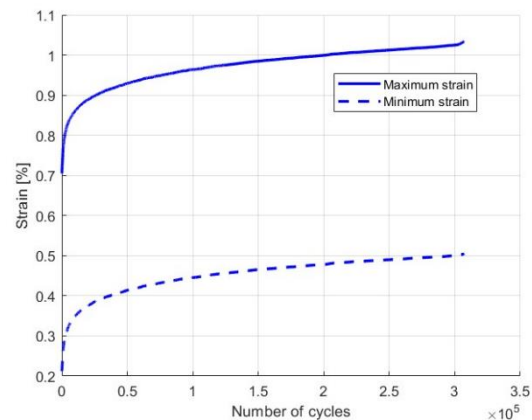
(a) Full 0° / T02



(b) Full 0° / T10



(c) Full 90° / T11



(d) Milled 0° / T06

Figure 3-47: Evolution of maximum and minimum strains

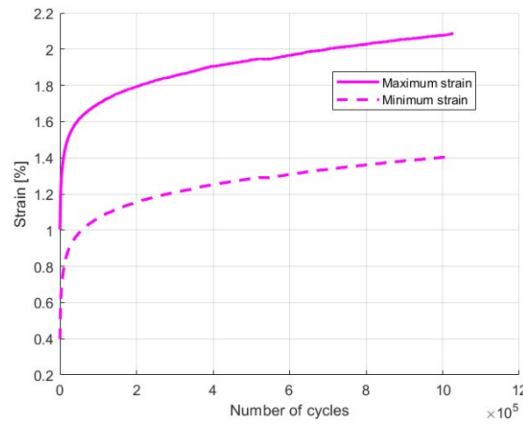


Figure 3-48: Evolution of maximum and minimum strains (Milled 90° / T14)

3.3.6.2 DIC analysis

3.3.6.2.1 Full 0° specimens

Constant strain region was observed within the gauge length for full 0° specimens. The strain evolution along the test was plotted in Figure 3-49 and Figure 3-50. Strain evenly increased as the number of cycles increased within the gauge length.

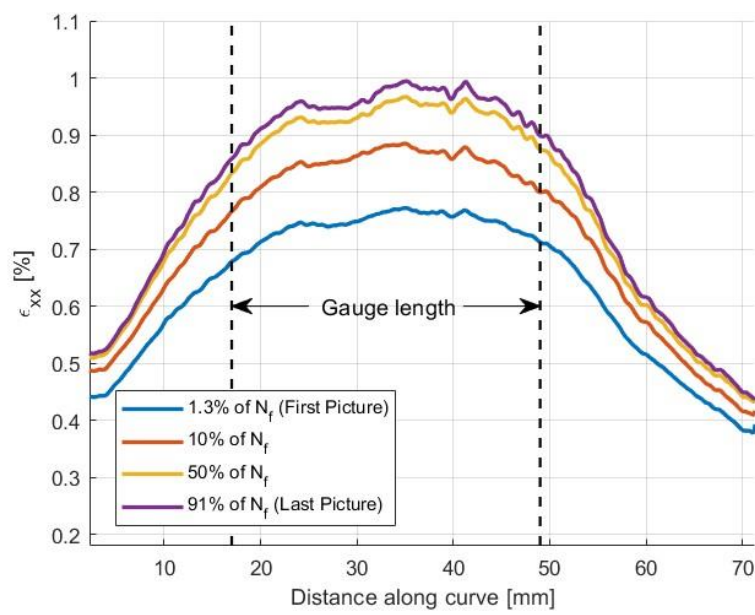
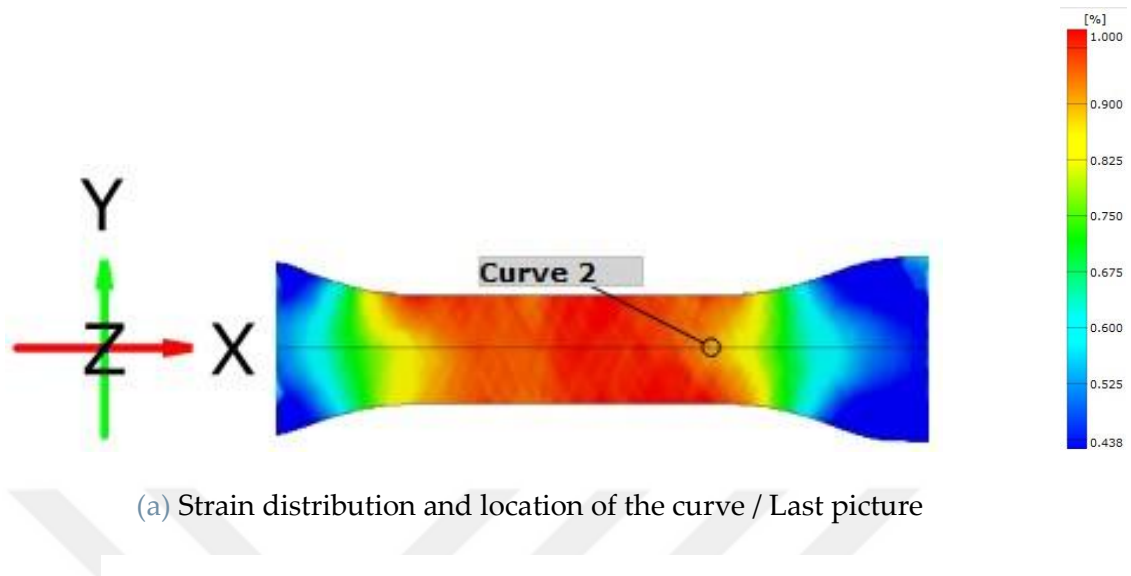


Figure 3-49: Evolution of strains along the curve (specimen T02)

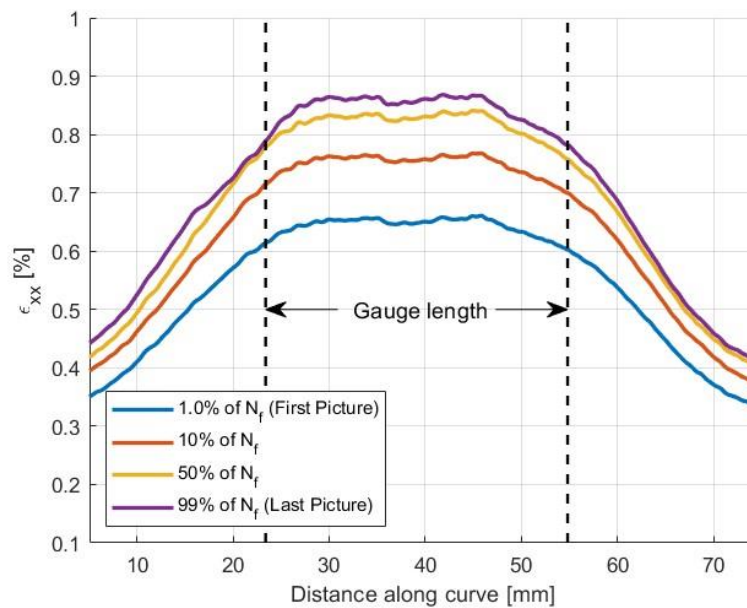
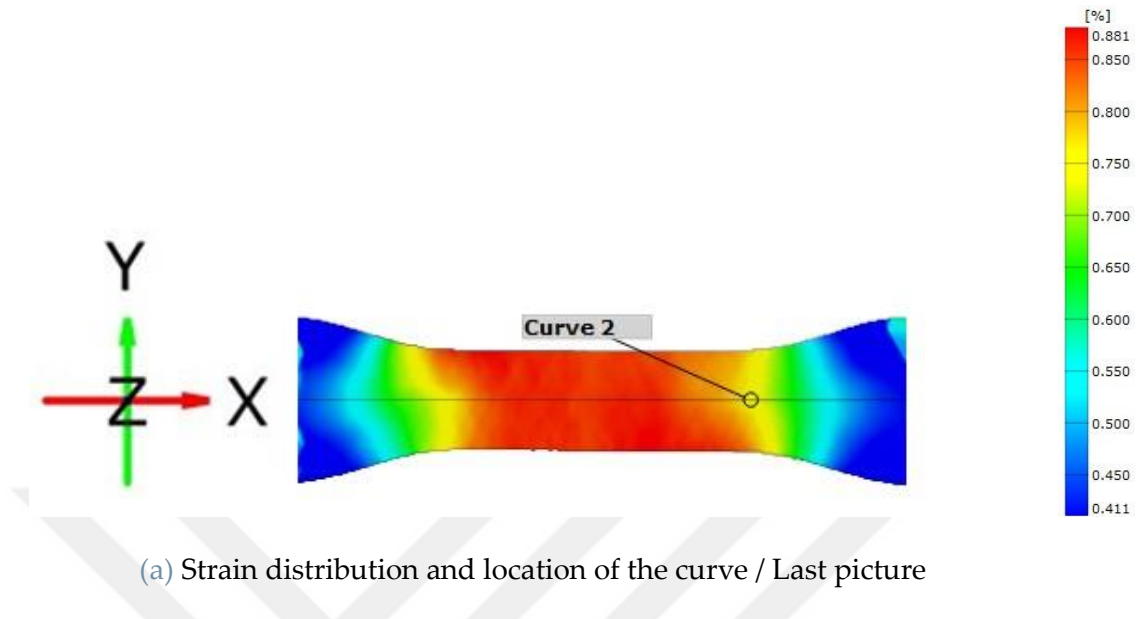


Figure 3-50: Evolution of strains along the curve (specimen T10)

3.3.6.2.2 Full 90° specimen

The strain evolution along the test was plotted in Figure 3-51b along the curve in Figure 3-51a, where maximum strain was detected. The percentage increase of the maximum strain within the gauge length from first picture to last picture was lower

than percent increase of minimum strain within the gauge length. This means that localization of strains became less pronounced throughout the test.

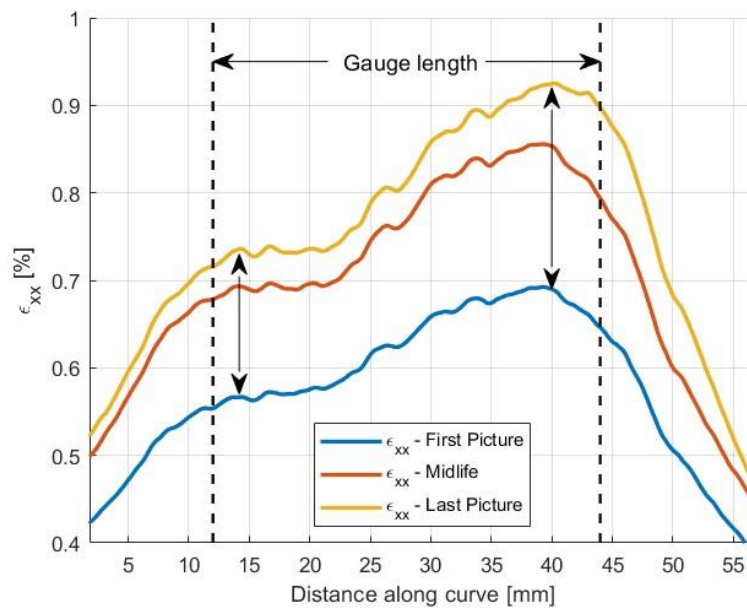
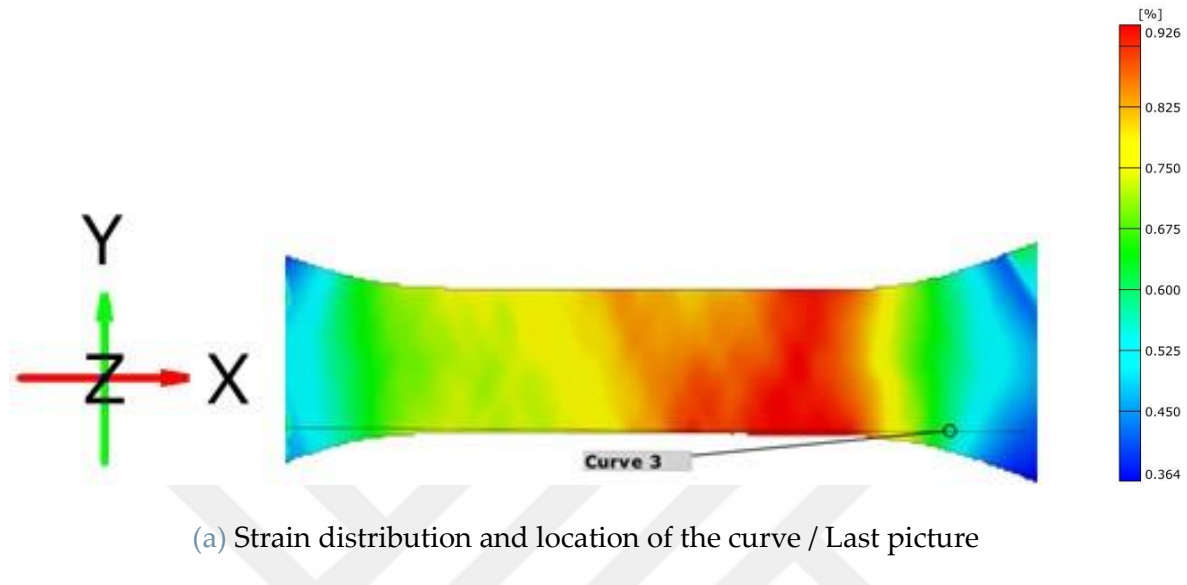


Figure 3-51: Evolution of strains along the curve (specimen T11)

3.3.6.2.3 Milled 0° specimen

Strain along the curve in Figure 3-52a, where maximum strain was detected, was plotted in Figure 3-52b at some selected number of cycles. The percentage increase of

the maximum strain from first picture to last picture was lower than percent increase of minimum strain within the gauge length. This means that localization of strains became less pronounced throughout the test as for the full 90° specimen.

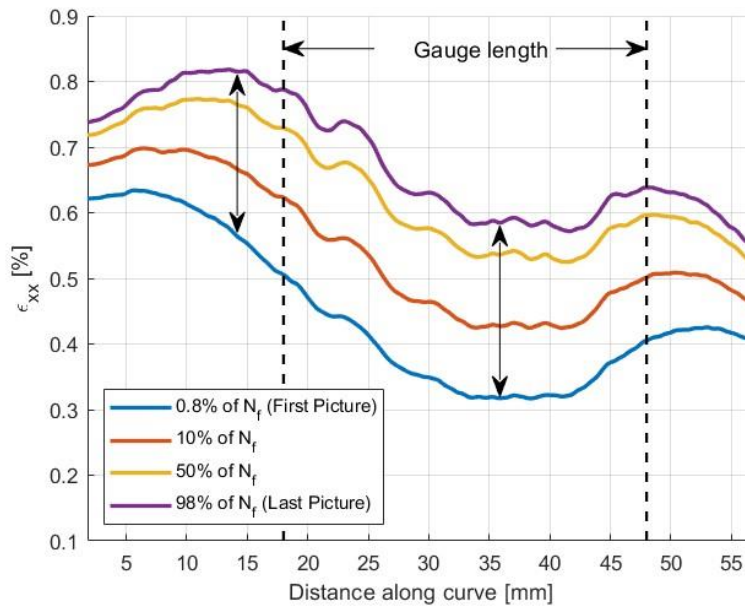
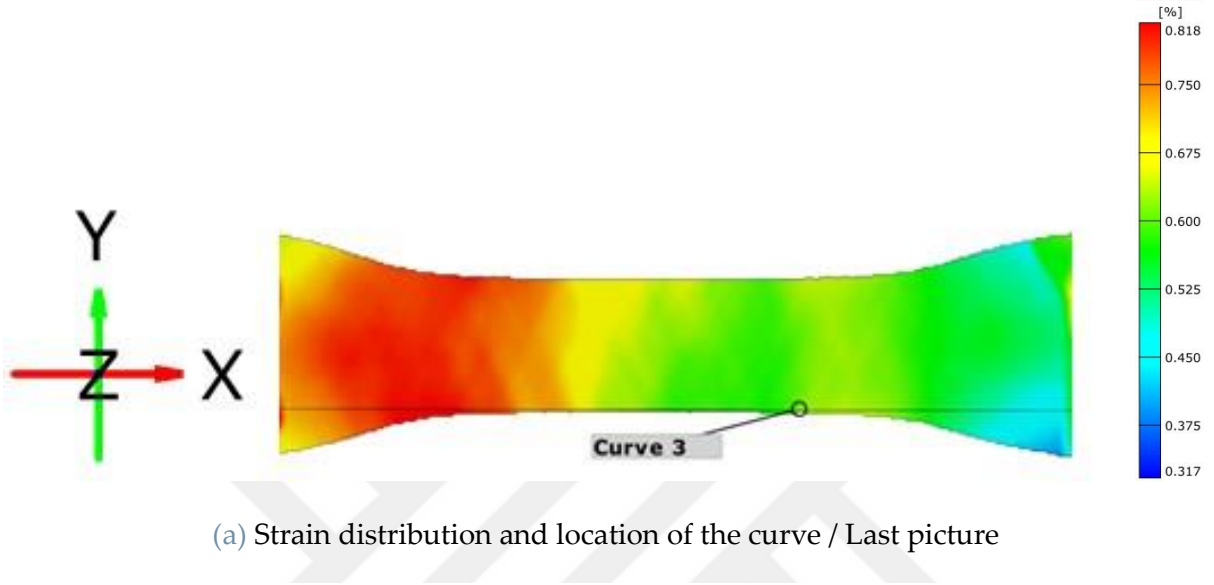


Figure 3-52: Evolution of strains along the curve (specimen T06)

A shift of the locations, where the maximum strain occurred, was observed for both sides of the specimen in Figure 3-52b. Thus, strain distribution around fillet radii at the first and last holding was shown in Figure 3-53. Maximum strain for the first

holding was detected in the middle of the specimens for both sides as was shown Figure 3-53a and Figure 3-53b. Instead, maximum strain for the last holding was located around the fillet radii as was shown Figure 3-53c and Figure 3-53d.

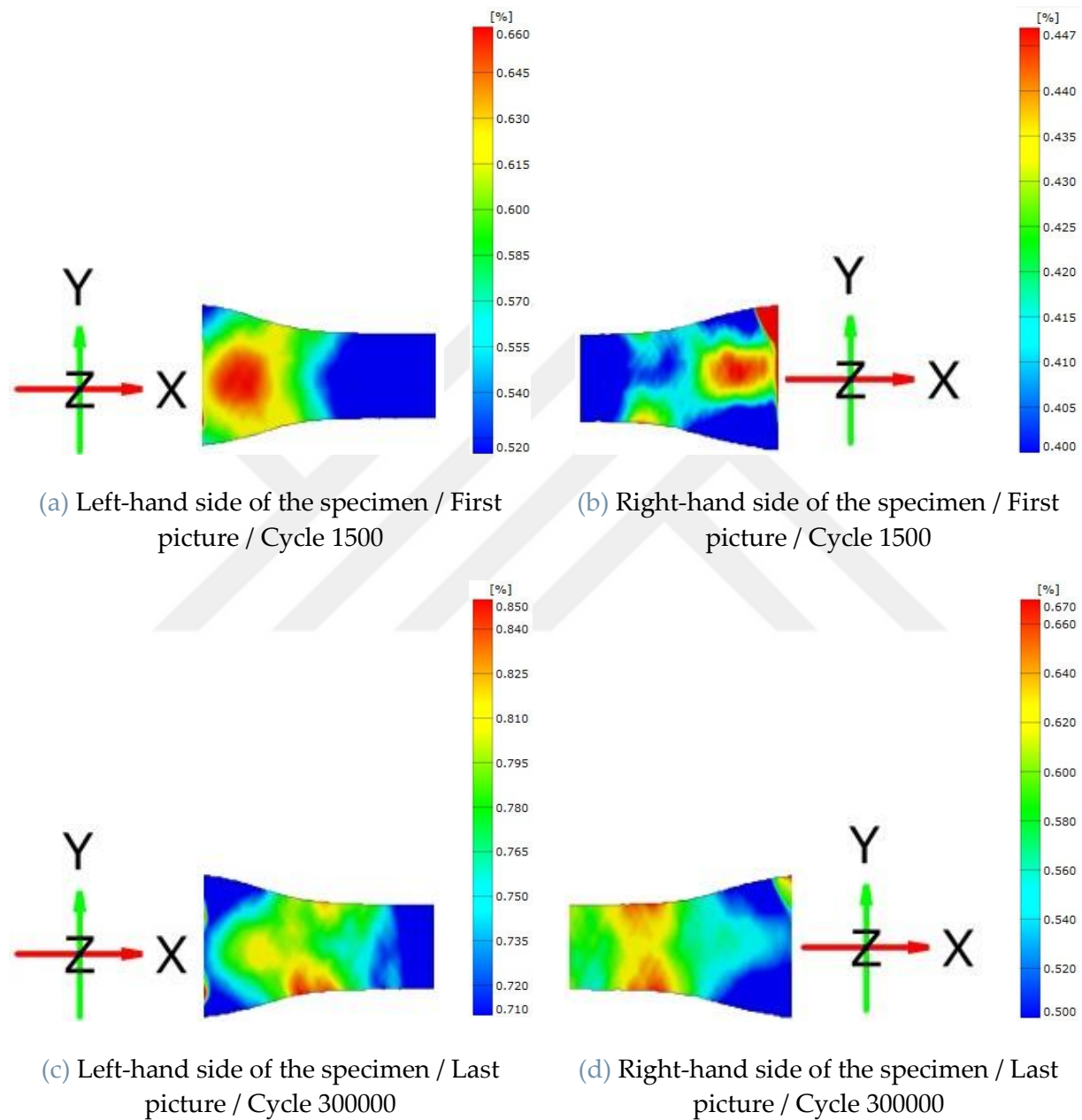
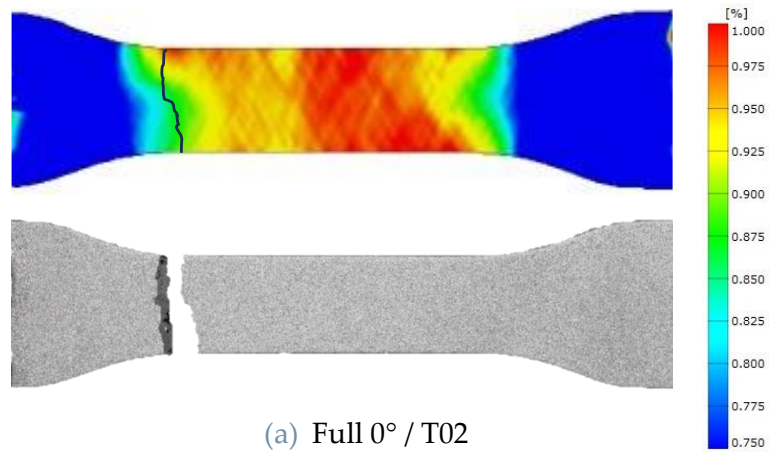


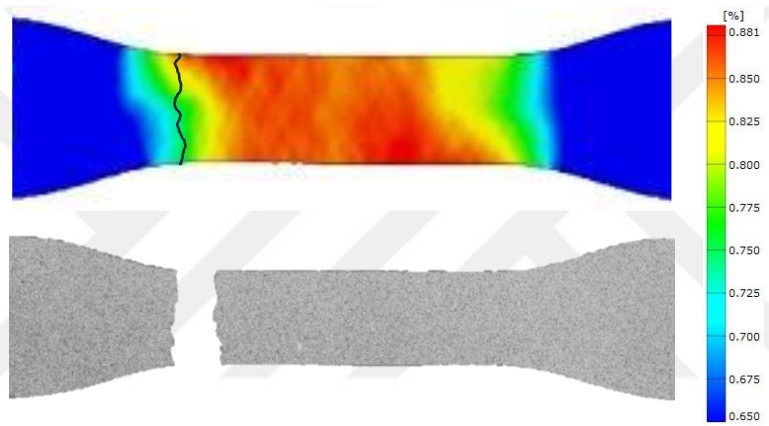
Figure 3-53: Strain distribution of milled 0° specimen (T06) at first and last holding

3.3.7 Failure locations

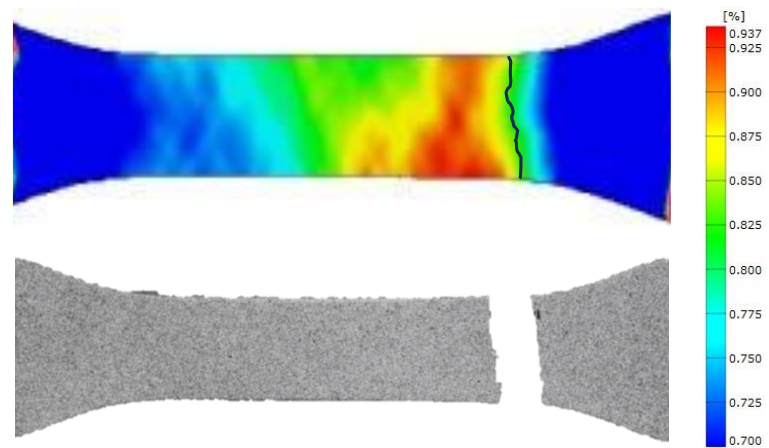
Strain distribution of specimens obtained by DIC analysis together with failure surface and failed specimens was shown in Figure 3-54 and Figure 3-55.



(a) Full 0° / T02



(b) Full 0° / T10



(c) Full 90° / T11

Figure 3-54: Strain distribution of the specimens just before failure (upper pictures) with crack surface (black lines in the upper pictures), and failed specimens (bottom pictures)

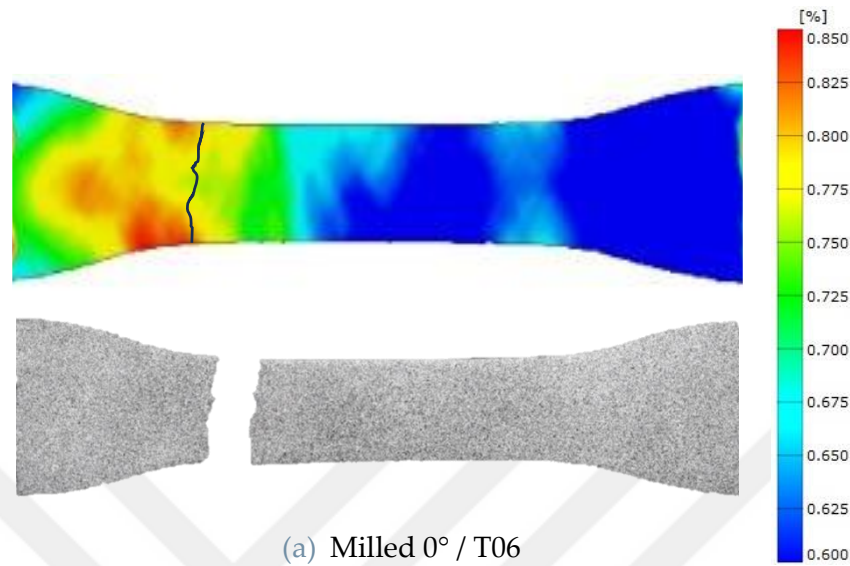


Figure 3-55: Strain distribution of the Milled 0° / T06 specimen just before failure (upper picture) with crack surface (black line in the upper picture), and failed specimen (bottom picture)

Failure surfaces coincide with regions of maximum strain or vicinity of maximum strain as in the tensile tests. Full 0° specimens showed a more uniform strain distribution within the gauge length as mentioned before. Thus, the fatigue strength of that specimen was probably accurately estimated. For T11 (full 90°) and T06 (milled 0°), a localized region of strains was observed. It may indicate that the true strength of each specimen could be higher than the nominal one.

3.3.8 Hysteresis area

Stress obtained by full cycle acquisition was plotted against strain of the same acquired data in Figure 3-56. Since fatigue loading consists of many repeated loading and unloading cycles, the resulting plot becomes closed curves for each loading-unloading cycle which are so called hysteresis loops. Hysteresis loops tended to shift rightwards and grow throughout the fatigue tests due to damage accumulation and viscoelastic effects. In this section, the areas of the hysteresis loops were calculated as a possible indication of failure.

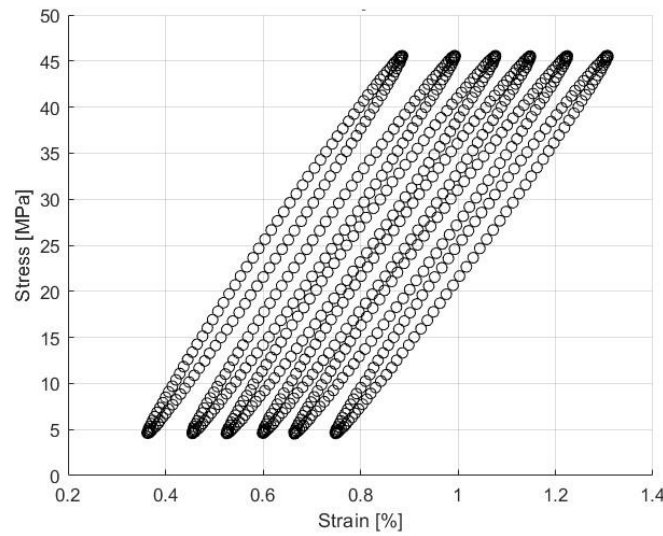


Figure 3-56: Some selection of the hysteresis loops

The areas of the hysteresis loops were calculated using the data obtained during the tests. Stress and strain data obtained from full cycle acquisitions were integrated to calculate the hysteresis areas. Hysteresis area per cycle was plotted against the number of cycles in Figure 3-57. Only the tests failed between 200000-300000 cycles were plotted with addition of a milled 90° specimen goes to run-out since a failed specimen could not be obtained during fatigue tests. The evolution of hysteresis area can be divided into three regions, again. First, a rapid increase is observed up to more or less 1000 or 2000 cycles. Then, a gradual region is evident until the few cycles before the failure. Finally, a quick increase happens up to failure within a few cycles. The difference between the full and milled specimen was apparent in the second region. For the full specimens, a quite gradual decrease of the hysteresis area per cycle was observed in the second region. However, energy kept increasing for the milled specimens. This trend was more noticeable for the milled 90° specimen.

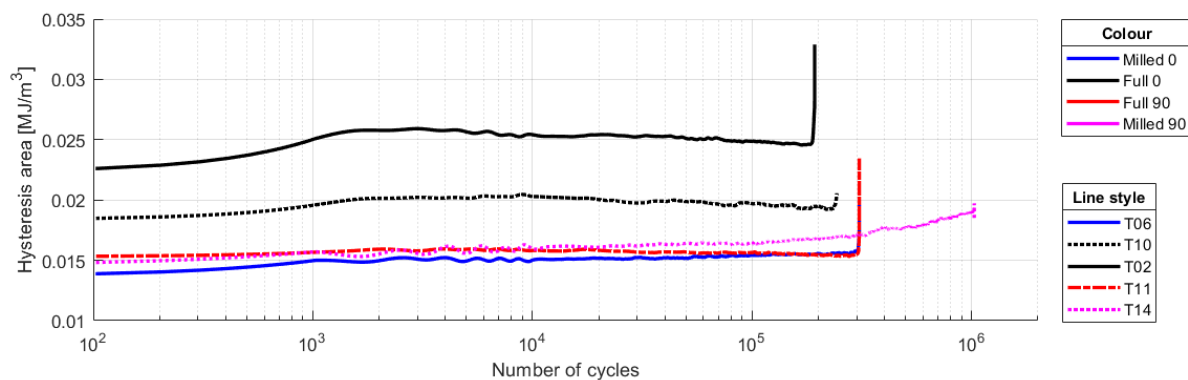


Figure 3-57: Cyclic hysteresis energy per cycle

4. Discussion

In Chapter 3.1.5, the evolution of maximum and minimum strains throughout the fatigue tests were reported. In literature, cyclic mean strain rate or combination of cyclic mean strain rate with other parameters is used as indicator for assessing fatigue life of full specimens extracted from injected molded plates [20], [39], [43]. This parameter has never been applied to assess the role of each individual layer of a shell-core-shell micro-structured specimen. In order to calculate cyclic mean strain rate, mean strain throughout the tests were calculated by averaging the maximum and minimum strains as was shown in Figure 4-1.

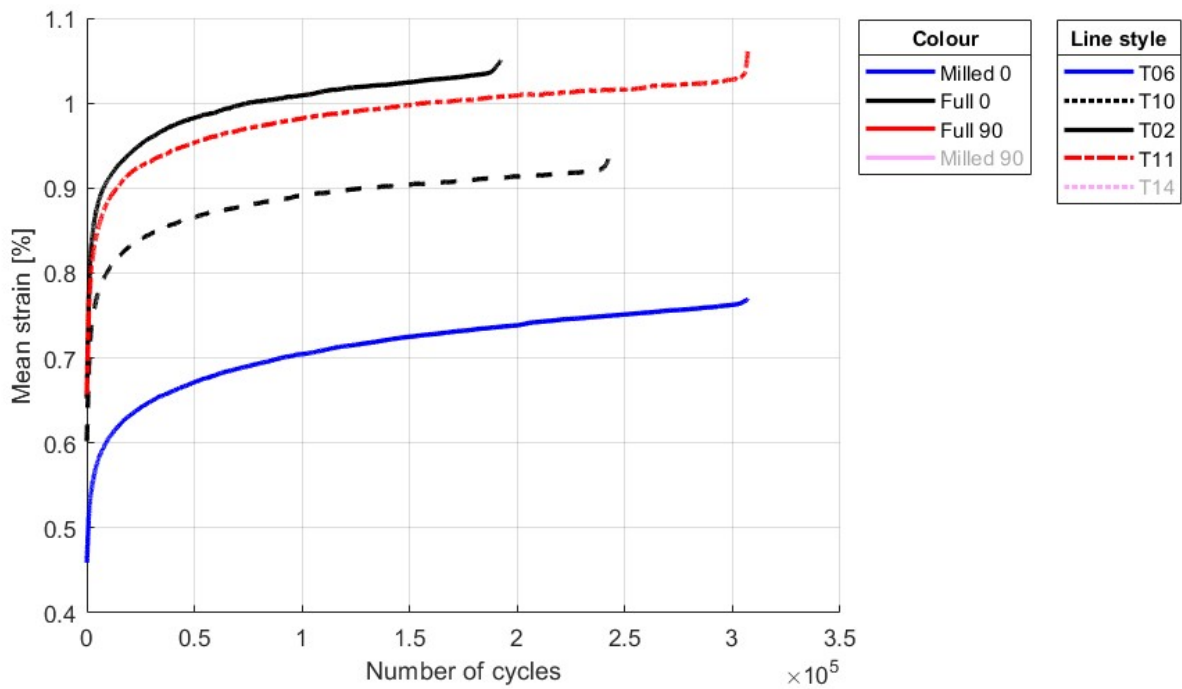


Figure 4-1: Evolution of mean strains

Then, cyclic mean strain rate was calculated by using Equation (4.1) as suggested in [43]. It is the slope of the mean strain curves in Figure 4-1 between 45% and 55% of fatigue lifetime times the testing frequency.

$$\dot{\epsilon}_{mean} = \frac{\epsilon_{mean55\%} - \epsilon_{mean45\%}}{N_{55\%} - N_{45\%}} frequency \quad (4.1)$$

According to literature [20], [39], [43]–[45], the cyclic mean strain rate is a parameter which does not depend on the fiber orientation. Thus, similar values of cyclic mean strain rate should be obtained for specimens at different fiber orientations. In Figure 4-2, the calculated cyclic mean strain rates were plotted against number of cycles to failure for each specimen type. The y-axis scale of the graph was set the same as the mentioned works [20], [39], [43]–[45]. Since all the tests were laid on the same region, it could be concluded that cyclic mean strain rate parameter also does not depend on whether the specimen is full or milled. If mean strain rate can be modeled using more experimental data, it may be used to predict fatigue life of SFRPs as a future development. However, data concerning the failure of milled 90° specimen and a statistical analysis are required to assess whether the cyclic mean strain rate parameter can be a failure indicator for both milled and full SFRPs. In order to model cyclic mean strain rate, a material model describing cyclic behavior of SFRPs is needed.

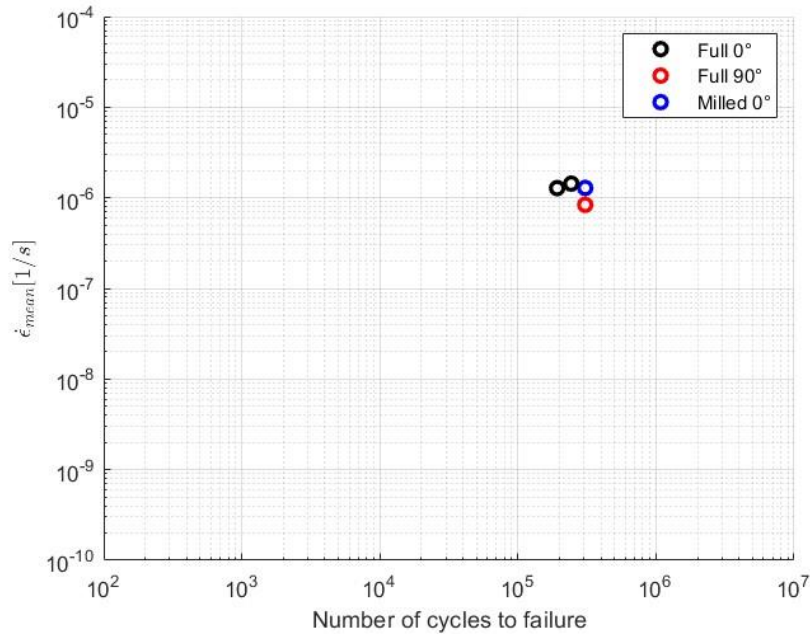


Figure 4-2: Cyclic mean strain rate

Then, the hysteresis area per cycle, reported in Chapter 3.3.8, was integrated through the number of cycles to find the total cyclic hysteresis energy. To investigate energy dependency of the failure of SFRPs, understand the role of layers and to be used as a

possible failure indicator, total hysteresis energy was plotted against the number of cycles in Figure 4-3. All the tests failed between 200000-300000 cycles resulted in same total energy at the end of their fatigue life. Both full specimen types and milled 0° specimen failed when total hysteresis energy reached around 4700 MJ/m^3 . It was reported that hysteresis energy does not depend on the fiber orientation for full specimens [39]. However, it has not been reported in literature that total hysteresis energy of the full specimens is the same as that of the layer highly oriented in the loading direction. Thus, similar conditions have to be met for fatigue failure of milled 0° and full specimens. Data concerning the failure of milled 90° specimen and a statistical analysis are required to assess whether the total hysteresis energy parameter can be a failure indicator for both milled and full SFRPs.

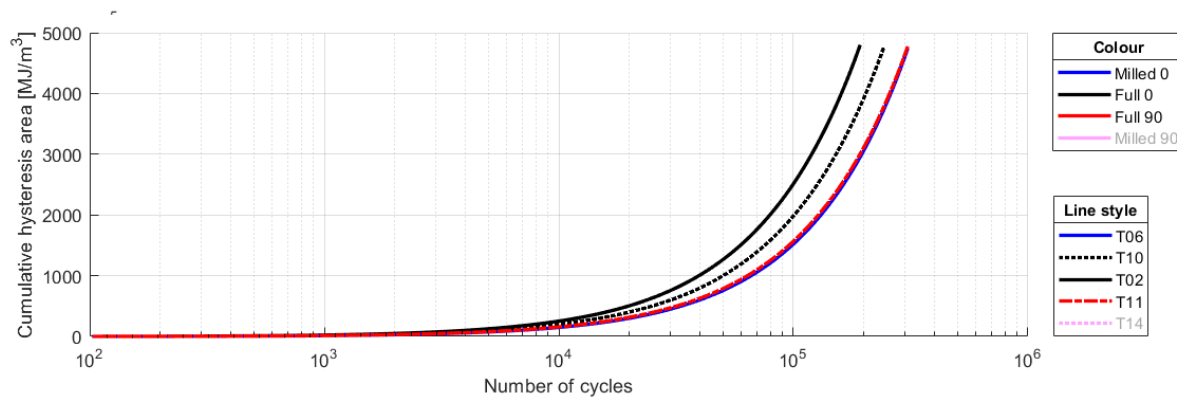


Figure 4-3: Total cyclic hysteresis energy

In [46], total cyclic energy was reported to be correlated to the number of cycles to failure of the unidirectional laminates, regardless of fiber orientation. Using an analytical estimation of the total strain energy, the S-N curves of each specimen at different orientations were well predicted. It was shown that total work and fatigue life is strongly correlated for unidirectional laminates. Since similar total cyclic hysteresis energies of the full and milled specimens tested within this work were found at similar number of cycles to failure, it is suggested that considerations made on unidirectional laminate could hold true for SFRP. However, more investigation should be performed to assess this hypothesis. If an analytical estimation of the total cyclic hysteresis energy can be found, it could be used to predict the fatigue life as done in [46]. In this work, the lack of sufficient number of experiments prevented proceeding in this sense. Since all tests were carried out at the same frequency, the same load rate and the same moisture content, it is not known whether these this parameter and also cyclic mean strain parameter are still unifying parameters in tests performed under different conditions. This may need further study and depending

on the results obtained it may also be useful to combine hysteresis energy parameter with cyclic mean strain rate parameter, which is also a unifying parameter.

As discussed in Chapter 1, stiffness degradation of the specimens can be used as a measure of damage of the material. Stiffness degradation of the specimens should be observed as change of the hysteresis areas throughout the tests. Decrease of modulus should cause an increase of the hysteresis area because the slope of the hysteresis loops decreases, while maximum and minimum stresses remain constant. Stiffness degradation should also cause shifting of the hysteresis loops rightwards together with cyclic creep effect. Figure 4-4 and Figure 4-5 shows the evolution of the hysteresis areas at some percentage of fatigue life for all specimen types.

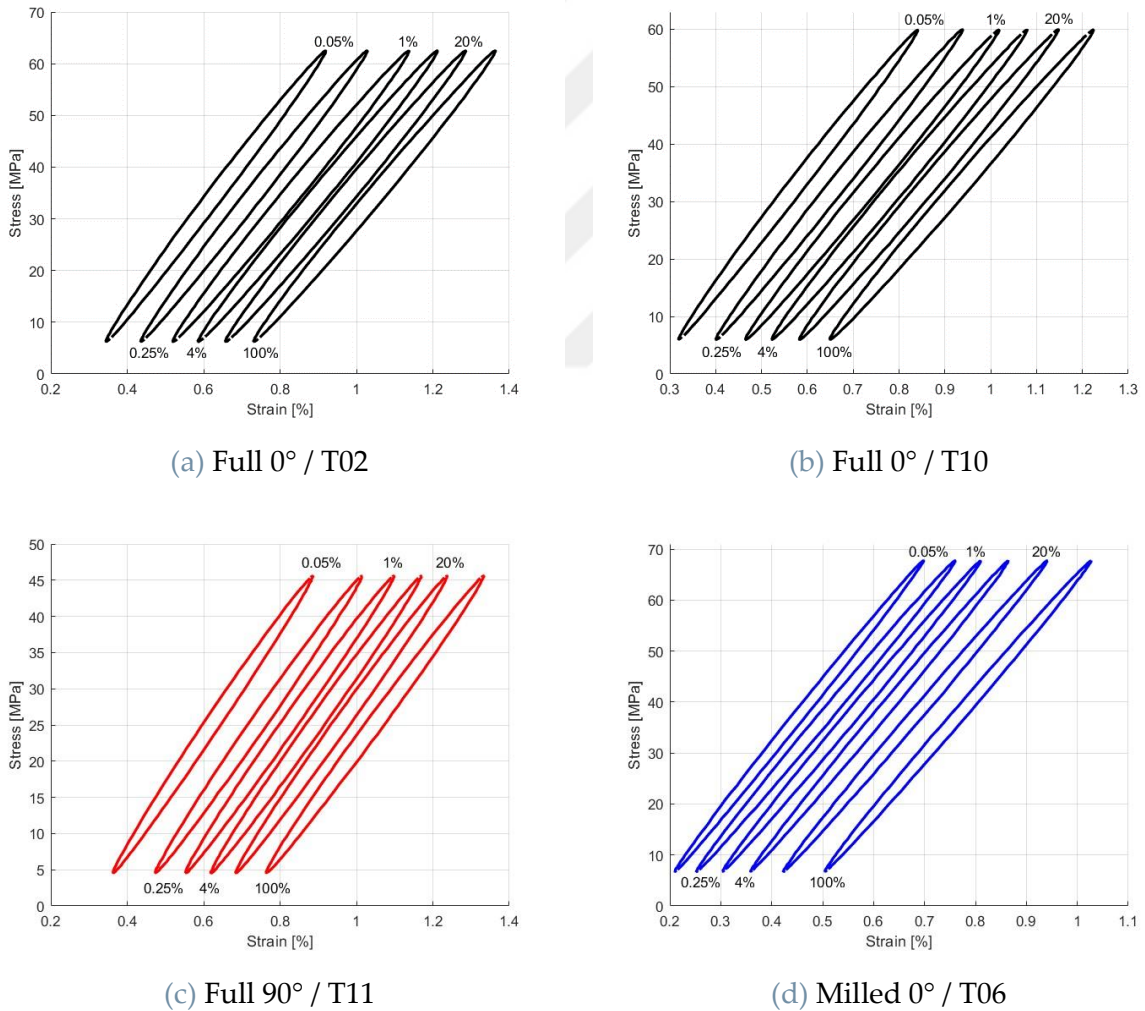


Figure 4-4: Evolution of hysteresis loops at selected percentage of fatigue life

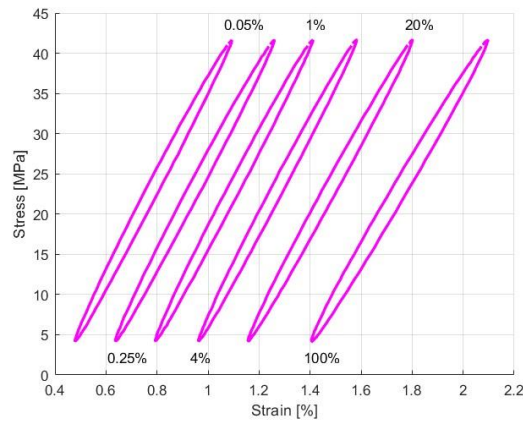


Figure 4-5: Evolution of hysteresis loops of Milled 90° / T14 at selected percentage of fatigue life

Stiffness degradation of all specimens was monitored by calculating modulus of the specimens using hysteresis loops obtained from the full cycle acquisitions in Figure 4-4 and Figure 4-5. In Figure 4-6, stiffness degradation of full specimens was shown as normalized elastic modulus with respect to the modulus computed from analysis of the first loading cycle and was plotted against the number of cycles. Degradation trend can be divided into three regions. The first region was where a rapid drop of modulus occurred within the first 1000-2000 cycles. Then, the second region was apparent where a quite gradual decrease up to the cycles just before the failure. Finally, the third region was observed where a rapid drop of modulus occurred. This region was associated with failure.

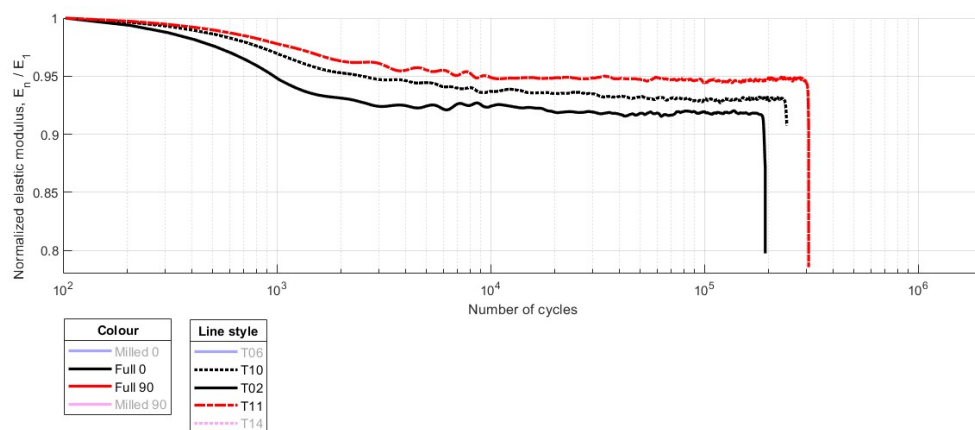


Figure 4-6: Stiffness degradation of full specimens

The observed behavior was coherent with damage accumulation of composite materials proposed in the literature as in Figure 4-7. Damage index in Figure 4-7 is

formulated as $D = 1 - E/E_1$. Damage in composite materials is assumed to initiate at various locations at different orientations. Accumulation of damage within the first cycles occurs very quickly, which explains the rapid decay of the modulus in the first region. Then, microcracks grow slower in the second region once most of the cracks reach the fiber-matrix interface. Thus, a gradual decay of modulus was observed in the second region. In the third and final region, damage accumulation accelerates again just before the final catastrophic failure [47]–[49].

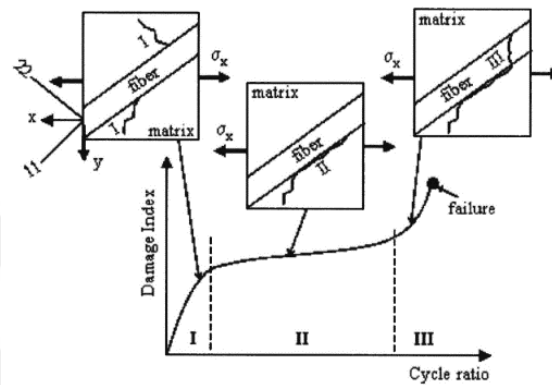


Figure 4-7: Proposed fatigue damage development [48]

Stiffness degradation of the milled specimens was plotted in Figure 4-8. Milled 90° specimen, which was indicated with pink line, went to run-out. Therefore, the third region is not visible for this test. However, when the slope of the second region for both milled specimens was investigated, a different behavior than full specimens is observed. The slope of the second region for milled specimens seemed to be higher than full specimens. This behavior was much clearer for the milled 90° specimen. The trend of stiffness degradation of the milled 0° and 90° specimens started to differ after approximately 10000 cycles as was shown in Figure 4-8.

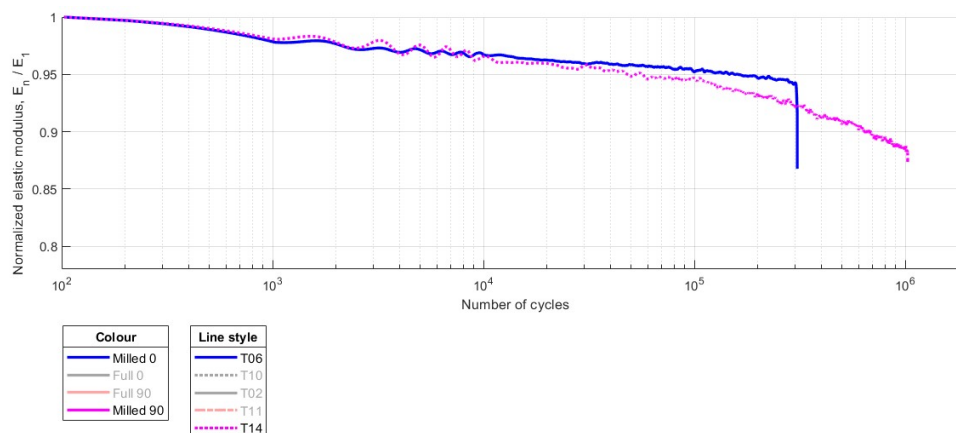


Figure 4-8: Stiffness degradation of milled specimens

Several damage mechanisms play a role in stiffness degradation of composite materials depending on loading type and properties of fiber, matrix, and interface [9], [50]–[52]. Fiber-matrix debonding, one of the damage mechanisms in fatigue loading, was reported to be observed around fibers perpendicular to the loading direction in some studies [20], [53], [54]. In [51], it was reported that debonding was not observed in the early stages of fatigue lifetime. This could be the reason why milled 90° specimens showed a faster stiffness degradation rate after a certain cycle. Since stiffness degradation is an indication of damage development, it can be said that milled and full specimens have different damage development or damage development has a different effect on the overall behavior.

A rough estimation of the stresses acting in each layer of fatigue tested full specimens was supported by the tensile stress-strain curves of each specimen type. It could be assumed that the very first loading of a fatigue test is similar to a tensile test as shown in Figure 4-9. This reasonable assumption, however, does not account for the dependency of the tensile modulus on the test displacement rate and on the loading function. Under this assumption, the estimation of the stresses in each layer (shells and core) of the full specimens at the very first fatigue cycle was performed as follows:

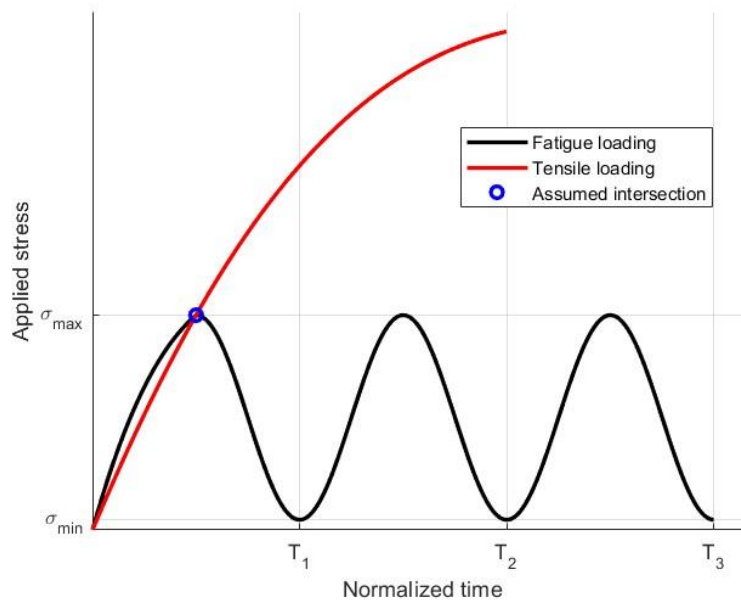


Figure 4-9: An arbitrary representation of a fatigue loading and a tensile loading

- Step 1: Maximum applied stress for the full specimens were obtained from S-N chart of the fatigue tests (e.g. $\sigma_{\max, 2E6} = 62.5$ MPa for T02)

- Step 2: Strain corresponding to the maximum applied fatigue stress was found in the tensile stress-strain curve of that specimen under analysis (e.g. $\epsilon_{\text{tensile}} = 0.7\%$ at 62.5 MPa for T02)
- Step 3: Stresses corresponding to that specific strain level were found in the tensile stress-strain curve of the milled specimens (e.g. $\sigma_{0^\circ} = 95.7 \text{ MPa}$, $\sigma_{90^\circ} = 35.5 \text{ MPa}$ at 0.7% of strain)

The steps were schematized in Figure 4-10.

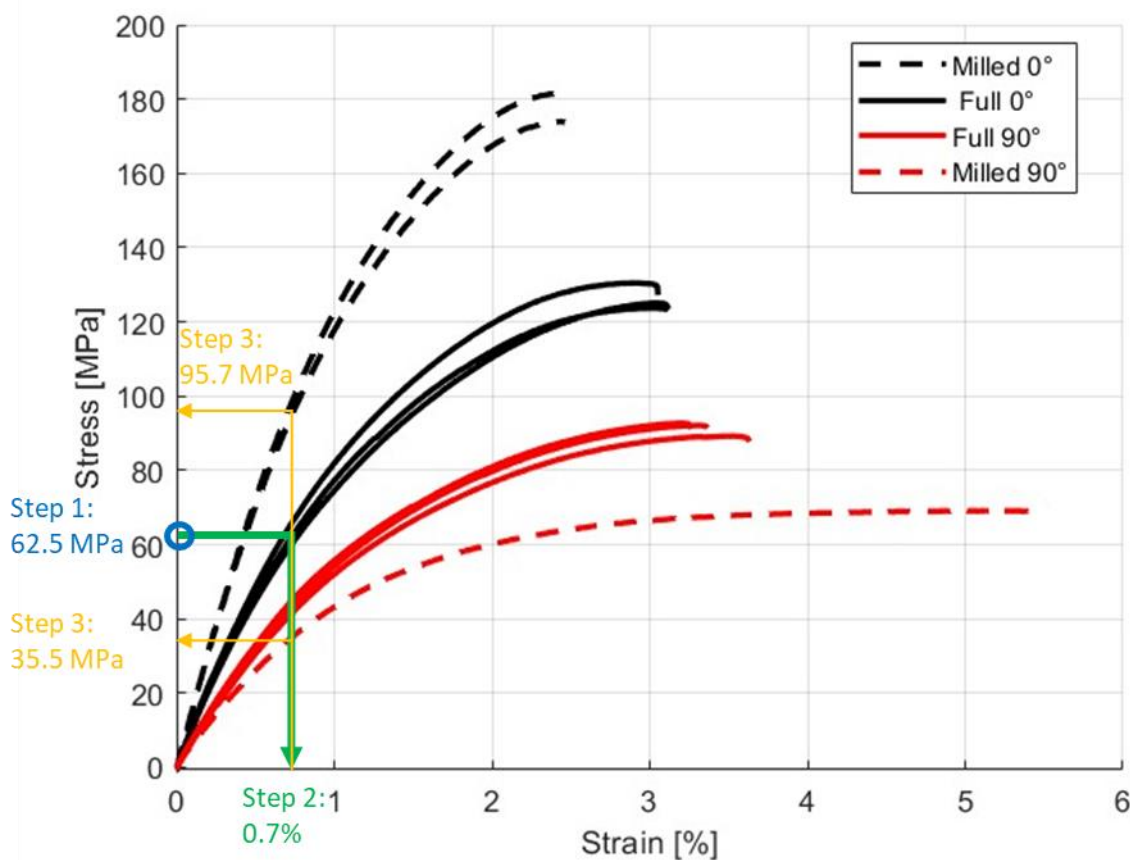


Figure 4-10: Schematization of steps for estimating stresses for each layer

This evaluation step relies on the assumption that any layer within the specimen's cross section undergoes the same strain level under displacement controlled uniaxial tensile test. The calculated strains for full specimens were reported in Table 8. The fatigue strength of the milled 0° specimen between 200000-300000 cycles was 67.8 MPa. Stresses within the 0° layers of the full specimens appeared to be much higher than its fatigue strength at the very first fatigue cycle. The fatigue strength of the milled 90° specimen between 200000-300000 cycles was unknown. However, it was known that it should be higher than 41.8 MPa. Thus, stresses within the 90° layers of

the full specimens appeared to be lower than its fatigue strength. This may mean that the 0° layers of the full specimens initially suffered early damage, while the 90° layer were more stress relieved as loaded by far a lower than its fatigue strength. Therefore, based on the estimation of stress distribution within each layer in the first cycle of fatigue loading, the 0° layers may be the critical layer for both full specimen types. This was expected for full 0° specimens but not for full 90° specimens. Therefore, it is not possible to evaluate the fatigue strength of SFRPs, where fibers aligned transversally with respect to loading direction, by testing full 90° specimens with a non-negligible core layer. Moreover, how stresses were distributed within each layer throughout the fatigue test is still unknown. A future development of the work, aimed at refinement in prediction of the stresses, may concern the implementation of a TPM approach. This would give a more accurate numerical estimation of the stress distribution across the specimen thickness, depending on the local fiber orientation. Moreover, by implementing a sophisticated material model, as an elasto-plastic model accounting for progressive damage (for stiffness degradation), within a finite element fatigue simulation could be possible to evaluate stress evolution and eventually redistribution across the specimen's thickness accordingly to the local fiber orientation. In this way more insight into the local fiber orientation dependent fatigue strength could be possible.

Specimen ID	Specimen Type	$\sigma_{\max}$ [MPa]	$\varepsilon_{\text{tensile}}$ [%]	σ_{0° [MPa]	σ_{90° [MPa]
T02	Full 0°	62.5	0.7	95.7	35.5
T11	Full 90°	45.6	0.8	104.8	38

Table 8: Rough estimation of stresses in each layer of the full specimens by using tensile test data

In Chapters 3.1.6 and 3.3.7, a correlation between the highly and localized strained regions of specimen surfaces and failure surfaces was found. Therefore, this could be an indication that strength was underestimated. Therefore, stress distribution on the specimen surfaces together with stiffness distribution can be found for a more accurate evaluation of the strength of the layers as a future development of the work. There exist several methods to calculate the stress and stiffness distribution on specimen surfaces starting from the strain distribution obtained by DIC analysis [55]–[61]. The methods generally depend on finding an admissible stress field and stiffness distribution by iteratively altering stress and stiffness tensors.

5. Conclusions

Mechanical behavior of the specimens made of 50% in weight Short Glass Fiber Reinforced Polyamide 66 were investigated in this study. Dog-bone shaped specimens were extracted from injected molded rectangular plates at 0° and 90° with respect to the mold flow direction. Some of the specimens were tested as they were molded (full specimens) while some of them were machined to obtain specimens of highly coherent fiber orientation (milled specimens). Specimens were conditioned and tested under fatigue and tensile loadings. For both load-controlled fatigue and displacement-controlled tensile tests, DIC analysis was performed.

Tensile tests showed that the tensile strength and tensile modulus increased in the order of milled 90° , full 90° , full 0° and milled 0° specimens, respectively. The quite opposite behavior was observed for tensile strain-at-break. This was imputed to the highest degree of alignment of fibers along the loading direction for milled 0° specimens and the least degree of alignment of fibers along the loading direction for milled 90° specimens. The same behavior was also observed in fatigue strength for the same reasons.

Maximum applied stress for the fatigue tests were normalized with respect to the tensile strength of each specimen type. Normalized fatigue strength was found to be the highest for milled 90° specimen and the lowest for the milled 0° specimen. This behavior has not been reported in the literature on SFRPs. Full specimens resulted in the same normalized strength independent from the fiber orientation and an intermediate normalized strength between the milled ones.

The comparison of displacements and strains obtained by DIC analysis and direct measurement tools resulted in a certain degree of deviation. However, the deviation was more pronounced in the fatigue tests. Less accurate evaluation of displacements and strains may be related to the lesser ability of a single camera to project the specimen surface into a 2D image.

While investigating a possible stress concentration around fillet radii for milled specimens, strain concentration was observed for a few cases. It was concluded that a probability distribution for milled specimens exists whether strain concentration occurs or not.

A correlation was found between the fracture surfaces and maximum strained regions. Stress distribution on the specimen surfaces together with stiffness distribution can be found by using strain field obtained by DIC analysis for a more accurate evaluation of the strength of each specimen as a future development of the work.

The evolution of strains throughout the testing duration was observed by using DIC analysis for both fatigue and tensile tests. For all the tests, strains were observed to be more localized within the gauge length.

The evolution of strains was also investigated for fatigue tests by using testing machine data. An increasing strain trend throughout the fatigue tests was evident due to the damage development and cyclic creep effects. Cyclic mean strain rate was reported as an indicator of fatigue life in literature, thus it was calculated at specimen's midlife. Both full and milled specimens collapsed at a similar mean strain rate for the specimens with similar fatigue life. Thus, cyclic mean strain rate parameter may be a unifying fatigue parameter for milled and full specimens. It may be used to assess fatigue life of SFRPs without fully modeling the layered structure.

The area of the hysteresis loops was calculated for fatigue tests in order to obtain hysteresis area per cycle. Then, it was integrated to calculate total hysteresis energy to find out energy dependency of failure for full specimens and each individual layer. All the specimens failed between 200000 and 300000 cycles appeared to have the same total hysteresis energy at the failure. Thus, it may be used solely or together with cyclic mean strain rate to assess fatigue life of SFRPs after obtaining data concerning the failure of milled 90° specimens and performing a statistical analysis.

Stiffness degradation of fatigue tests was monitored by using force and displacement data of the testing machine. First, a rapid decrease of stiffness was observed due to the early damage development. Then, a second region where stiffness decreased linearly and gradually was observed. Finally, a rapid decrease was observed prior to the final catastrophic failure. The slope of the second region of stiffness degradation curves, where degradation trend is quite linear, appeared to be similar for full specimens. Milled specimens showed a higher degradation rate in the second region. Especially, milled 90° specimens showed a much lower degradation rate than full and milled 0° specimens. This showed that damage development mechanisms or the

effect of the damage development on the overall behavior were different for full and milled specimens.

By combining the fatigue and tensile test data, a rough estimation of the stresses in each layer of the full specimens in the first cycle of the fatigue tests was performed. It was found that stresses in 0° layers were much more than the fatigue strength of that layer. Stresses in 90° layers were found to be lower than the fatigue strength of that layer. Based on the rough estimation of stress distribution in the first cycle, the 0° layers may be the critical layer for full specimens. However, in order to further assess the role of each layer on fatigue behavior of SFRPs, a numerical simulation accounting for local material properties as well as a damage model over fatigue could provide more insight on stress redistribution in each layer of the full specimens throughout the fatigue tests.

Bibliography

- [1] M. Akay and D. Barkley, 'Fibre orientation and mechanical behaviour in reinforced thermoplastic injection mouldings', *J Mater Sci*, vol. 26, no. 10, pp. 2731–2742, 1991, doi: 10.1007/BF02387744.
- [2] A. Bernasconi, P. Davoli, A. Basile, and A. Filippi, 'Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6', *Int J Fatigue*, vol. 29, no. 2, pp. 199–208, 2007, doi: <https://doi.org/10.1016/j.ijfatigue.2006.04.001>.
- [3] S. Mortazavian and A. Fatemi, 'Effects of fiber orientation and anisotropy on tensile strength and elastic modulus of short fiber reinforced polymer composites', *Compos B Eng*, vol. 72, pp. 116–129, 2015, doi: <https://doi.org/10.1016/j.compositesb.2014.11.041>.
- [4] Y. Zhou and P. K. Mallick, 'Fatigue performance of an injection-molded short E-glass fiber-reinforced polyamide 6,6. I. Effects of orientation, holes, and weld line', *Polym Compos*, vol. 27, no. 2, pp. 230–237, Apr. 2006, doi: <https://doi.org/10.1002/pc.20182>.
- [5] Z. Wang, Y. Zhou, and P. K. Mallick, 'Effects of temperature and strain rate on the tensile behavior of short fiber reinforced polyamide-6', *Polym Compos*, vol. 23, no. 5, pp. 858–871, Oct. 2002, doi: <https://doi.org/10.1002/pc.10484>.
- [6] M. De Monte, E. Moosbrugger, and M. Quaresimin, 'Influence of temperature and thickness on the off-axis behaviour of short glass fibre reinforced polyamide 6.6 – Quasi-static loading', *Compos Part A Appl Sci Manuf*, vol. 41, no. 7, pp. 859–871, 2010, doi: <https://doi.org/10.1016/j.compositesa.2010.02.018>.
- [7] M. De Monte, E. Moosbrugger, and M. Quaresimin, 'Influence of temperature and thickness on the off-axis behaviour of short glass fibre reinforced polyamide 6.6 – cyclic loading', *Compos Part A Appl Sci Manuf*, vol. 41, no. 10, pp. 1368–1379, 2010, doi: <https://doi.org/10.1016/j.compositesa.2010.02.004>.
- [8] P.-Y. Le Gac, M. Arhant, M. Le Gall, and P. Davies, 'Yield stress changes induced by water in polyamide 6: Characterization and modeling', *Polym*

- Degrad Stab*, vol. 137, pp. 272–280, 2017, doi: <https://doi.org/10.1016/j.polymdegradstab.2017.02.003>.
- [9] M. F. Arif, F. Meraghni, Y. Chemisky, N. Despringre, and G. Robert, 'In situ damage mechanisms investigation of PA66/GF30 composite: Effect of relative humidity', *Compos B Eng*, vol. 58, pp. 487–495, 2014, doi: <https://doi.org/10.1016/j.compositesb.2013.11.001>.
- [10] N. Jia, H. A. Fraenkel, and V. A. Kagan, 'Effects of Moisture Conditioning Methods on Mechanical Properties of Injection Molded Nylon 6', *Journal of Reinforced Plastics and Composites*, vol. 23, no. 7, pp. 729–737, May 2004, doi: 10.1177/0731684404030730.
- [11] A. Ishisaka and M. Kawagoe, 'Examination of the time–water content superposition on the dynamic viscoelasticity of moistened polyamide 6 and epoxy', *J Appl Polym Sci*, vol. 93, no. 2, pp. 560–567, Jul. 2004, doi: <https://doi.org/10.1002/app.20465>.
- [12] S. Barbouchi, V. Bellenger, A. Tcharkhtchi, Ph. Castaing, and T. Jollivet, 'Effect of water on the fatigue behaviour of a pa66/glass fibers composite material', *J Mater Sci*, vol. 42, no. 6, pp. 2181–2188, 2007, doi: 10.1007/s10853-006-1011-x.
- [13] N. Jia and V. A. Kagan, 'Mechanical Performance of Polyamides with Influence of Moisture and Temperature – Accurate Evaluation and Better Understanding', in *Plastics Failure Analysis and Prevention*, J. Moalli, Ed., Norwich, NY: William Andrew Publishing, 2001, pp. 95–104. doi: <https://doi.org/10.1016/B978-188420792-1.50014-7>.
- [14] P. E. Bretz, R. W. Hertzberg, and J. A. Manson, 'Influence of absorbed moisture on fatigue crack propagation behaviour in polyamides', *J Mater Sci*, vol. 16, no. 8, pp. 2061–2069, 1981, doi: 10.1007/BF00542365.
- [15] P. K. Mallick and Y. Zhou, 'Effect of mean stress on the stress-controlled fatigue of a short E-glass fiber reinforced polyamide-6,6', *Int J Fatigue*, vol. 26, no. 9, pp. 941–946, 2004, doi: <https://doi.org/10.1016/j.ijfatigue.2004.02.003>.
- [16] A. Bernasconi and R. M. Kulin, 'Effect of frequency upon fatigue strength of a short glass fiber reinforced polyamide 6: A superposition method based on cyclic creep parameters', *Polym Compos*, vol. 30, no. 2, pp. 154–161, Feb. 2009, doi: <https://doi.org/10.1002/pc.20543>.
- [17] J. J. Horst and J. L. Spoormaker, 'Mechanisms of fatigue in short glass fiber reinforced polyamide 6', *Polym Eng Sci*, vol. 36, no. 22, pp. 2718–2726, Nov. 1996, doi: <https://doi.org/10.1002/pen.10671>.

- [18] J. L. Thomason, 'Micromechanical parameters from macromechanical measurements on glass reinforced polyamide 6,6', *Compos Sci Technol*, vol. 61, no. 14, pp. 2007–2016, 2001, doi: [https://doi.org/10.1016/S0266-3538\(01\)00062-8](https://doi.org/10.1016/S0266-3538(01)00062-8).
- [19] A. Canegrati, L. M. Martulli, P. J. Hine, C. Grassini, and A. Bernasconi, 'On the use of milled shell-only specimens to study the effect of fiber orientation on the fatigue behavior of a short fiber-reinforced polyamide', *Fatigue Fract Eng Mater Struct*, vol. 46, no. 2, pp. 616–630, Feb. 2023, doi: <https://doi.org/10.1111/ffe.13890>.
- [20] J. J. Horst, 'Influence of fibre orientation on fatigue of short glassfibre reinforced Polyamide', Doctoral thesis, TU Delft, 1997.
- [21] P. J. Hine, N. Davidson, R. A. Duckett, and I. M. Ward, 'Measuring the fibre orientation and modelling the elastic properties of injection-moulded long-glass-fibre-reinforced nylon', *Compos Sci Technol*, vol. 53, no. 2, pp. 125–131, 1995, doi: [https://doi.org/10.1016/0266-3538\(95\)00011-9](https://doi.org/10.1016/0266-3538(95)00011-9).
- [22] A. Bernasconi, E. Conrado, A. Cavallaro, and P. J. Hine, 'A local stress analysis of the effect of fibre orientation on the fatigue behaviour of a short fibre reinforced polyamide', in *20th International Conference on Composite Materials*, Copenhagen, 2015.
- [23] Y. Zhou and P. K. Mallick, 'Fatigue performance of injection-molded short e-glass fiber reinforced polyamide-6,6. II. Effects of melt temperature and hold pressure', *Polym Compos*, vol. 32, no. 2, pp. 268–276, Feb. 2011, doi: <https://doi.org/10.1002/pc.21045>.
- [24] S. G. Advani and C. L. Tucker III, 'The Use of Tensors to Describe and Predict Fiber Orientation in Short Fiber Composites', *J Rheol (N Y N Y)*, vol. 31, no. 8, pp. 751–784, Nov. 1987, doi: [10.1122/1.549945](https://doi.org/10.1122/1.549945).
- [25] T. C. Chu, W. F. Ranson, and M. A. Sutton, 'Applications of digital-image-correlation techniques to experimental mechanics', *Exp Mech*, vol. 25, no. 3, pp. 232–244, 1985, doi: [10.1007/BF02325092](https://doi.org/10.1007/BF02325092).
- [26] H. A. Bruck, S. R. McNeill, M. A. Sutton, and W. H. Peters, 'Digital image correlation using Newton-Raphson method of partial differential correction', *Exp Mech*, vol. 29, no. 3, pp. 261–267, 1989, doi: [10.1007/BF02321405](https://doi.org/10.1007/BF02321405).
- [27] J. Blaber, B. Adair, and A. Antoniou, 'Ncorr: Open-Source 2D Digital Image Correlation Matlab Software', *Exp Mech*, vol. 55, no. 6, pp. 1105–1122, 2015, doi: [10.1007/s11340-015-0009-1](https://doi.org/10.1007/s11340-015-0009-1).

- [28] J. Abanto-Bueno and J. Lambros, 'Investigation of crack growth in functionally graded materials using digital image correlation', *Eng Fract Mech*, vol. 69, no. 14, pp. 1695–1711, 2002, doi: [https://doi.org/10.1016/S0013-7944\(02\)00058-9](https://doi.org/10.1016/S0013-7944(02)00058-9).
- [29] G. Vendroux and W. G. Knauss, 'Submicron deformation field measurements: Part 2. Improved digital image correlation', *Exp Mech*, vol. 38, no. 2, pp. 86–92, 1998, doi: [10.1007/BF02321649](https://doi.org/10.1007/BF02321649).
- [30] B. Mouhmid, A. Imad, N. Benseddiq, and D. Lecompte, 'An experimental analysis of fracture mechanisms of short glass fibre reinforced polyamide 6,6 (SGFR-PA66)', *Compos Sci Technol*, vol. 69, no. 15, pp. 2521–2526, 2009, doi: <https://doi.org/10.1016/j.compscitech.2009.07.003>.
- [31] A. Godara and D. Raabe, 'Influence of fiber orientation on global mechanical behavior and mesoscale strain localization in a short glass-fiber-reinforced epoxy polymer composite during tensile deformation investigated using digital image correlation', *Compos Sci Technol*, vol. 67, no. 11, pp. 2417–2427, 2007, doi: <https://doi.org/10.1016/j.compscitech.2007.01.005>.
- [32] A. L. Highsmith and K. L. Reifsnider, 'Stiffness-Reduction Mechanisms in Composite Laminates', in *Damage in Composite Materials: Basic Mechanisms, Accumulation, Tolerance, and Characterization*, K. L. Reifsnider, Ed., West Conshohocken, PA: ASTM International, 1982, pp. 103–117. doi: [10.1520/STP34323S](https://doi.org/10.1520/STP34323S).
- [33] A. Bernasconi, E. Conrado, and P. J. Hine, 'Experimental investigation on the true local fatigue strength of shell-core shell layered, injection moulded specimens of short fibre reinforced polyamide', in *ECCM 18*, Athens, 2018.
- [34] ISO 527-2, 'Plastics — Determination of tensile properties — Part 2: Test conditions for moulding and extrusion plastics', 2012.
- [35] GOM mbH, 'ARAMIS: User Manual - Software'. 2013.
- [36] J. Blaber and A. Antoniou, 'Ncorr: Instruction Manual'. 2017.
- [37] J. C. H. Afdl and J. L. Kardos, 'The Halpin-Tsai equations: A review', *Polym Eng Sci*, vol. 16, no. 5, pp. 344–352, May 1976, doi: <https://doi.org/10.1002/pen.760160512>.
- [38] H. B. Motra, J. Hildebrand, and A. Dimmig-Osburg, 'Assessment of strain measurement techniques to characterise mechanical properties of structural steel', *Engineering Science and Technology, an International Journal*, vol. 17, no. 4, pp. 260–269, 2014, doi: <https://doi.org/10.1016/j.jestch.2014.07.006>.

- [39] P. Santharam *et al.*, 'Fatigue criteria for short fiber-reinforced thermoplastic validated over various fiber orientations, load ratios and environmental conditions', *Int J Fatigue*, vol. 135, p. 105574, 2020, doi: <https://doi.org/10.1016/j.ijfatigue.2020.105574>.
- [40] S. Mortazavian and A. Fatemi, 'Fatigue behavior and modeling of short fiber reinforced polymer composites including anisotropy and temperature effects', *Int J Fatigue*, vol. 77, pp. 12–27, 2015, doi: <https://doi.org/10.1016/j.ijfatigue.2015.02.020>.
- [41] A. Zago and G. S. Springer, 'Constant Amplitude Fatigue of Short Glass and Carbon Fiber Reinforced Thermoplastics', *Journal of Reinforced Plastics and Composites*, vol. 20, no. 7, pp. 564–595, May 2001, doi: [10.1177/073168401772678607](https://doi.org/10.1177/073168401772678607).
- [42] M. Kawai, S. Yajima, A. Hachinohe, and Y. Kawase, 'High-temperature off-axis fatigue behaviour of unidirectional carbon-fibre-reinforced composites with different resin matrices', *Compos Sci Technol*, vol. 61, no. 9, pp. 1285–1302, 2001, doi: [https://doi.org/10.1016/S0266-3538\(01\)00027-6](https://doi.org/10.1016/S0266-3538(01)00027-6).
- [43] F. E. Fiorini, L. M. Martulli, P. Steck, and A. Bernasconi, 'A modified energy-based fatigue parameter for short fiber reinforced polymers: Performance analysis with varying thicknesses, load ratios, and fiber orientations', *Fatigue Fract Eng Mater Struct*, vol. 46, no. 9, pp. 3372–3386, Sep. 2023, doi: <https://doi.org/10.1111/ffe.14072>.
- [44] S. Gillet, T. Jacopin, S. Joannès, N. Bedrici, and L. Laiarinandrasana, 'Short-term creep and low cycle fatigue unified criterion for a hybridised composite material', *Int J Fatigue*, vol. 155, p. 106571, 2022, doi: <https://doi.org/10.1016/j.ijfatigue.2021.106571>.
- [45] I. Raphael, N. Saintier, H. Rolland, G. Robert, and L. Laiarinandrasana, 'A mixed strain rate and energy based fatigue criterion for short fiber reinforced thermoplastics', *Int J Fatigue*, vol. 127, pp. 131–143, 2019, doi: <https://doi.org/10.1016/j.ijfatigue.2019.06.003>.
- [46] M. M. Shokrieh and F. Taheri-Behrooz, 'A unified fatigue life model based on energy method', *Compos Struct*, vol. 75, no. 1, pp. 444–450, 2006, doi: <https://doi.org/10.1016/j.compstruct.2006.04.041>.
- [47] H. Mao and S. Mahadevan, 'Fatigue damage modelling of composite materials', *Compos Struct*, vol. 58, no. 4, pp. 405–410, 2002, doi: [https://doi.org/10.1016/S0263-8223\(02\)00126-5](https://doi.org/10.1016/S0263-8223(02)00126-5).

- [48] Varvani-Farahani A. and Shirazi A., 'Prediction of Stiffness Degradation and Damage of Unidirectional GRP Composites Under Fatigue Cycles', vol. 14, no. 3, pp. 197–204, 2007, doi: doi:10.1515/SECM.2007.14.3.197.
- [49] B. Klimkeit *et al.*, 'Fatigue damage mechanisms in short fiber reinforced PBT+PET GF30', *Materials Science and Engineering: A*, vol. 528, no. 3, pp. 1577–1588, 2011, doi: <https://doi.org/10.1016/j.msea.2010.10.081>.
- [50] M. F. Arif, N. Saintier, F. Meraghni, J. Fitoussi, Y. Chemisky, and G. Robert, 'Multiscale fatigue damage characterization in short glass fiber reinforced polyamide-66', *Compos B Eng*, vol. 61, pp. 55–65, 2014, doi: <https://doi.org/10.1016/j.compositesb.2014.01.019>.
- [51] H. Rolland, N. Saintier, I. Raphael, N. Lenoir, A. King, and G. Robert, 'Fatigue damage mechanisms of short fiber reinforced PA66 as observed by in-situ synchrotron X-ray microtomography', *Compos B Eng*, vol. 143, pp. 217–229, 2018, doi: <https://doi.org/10.1016/j.compositesb.2017.12.051>.
- [52] E. Belmonte, M. De Monte, C.-J. Hoffmann, and M. Quaresimin, 'Damage mechanisms in a short glass fiber reinforced polyamide under fatigue loading', *Int J Fatigue*, vol. 94, pp. 145–157, 2017, doi: <https://doi.org/10.1016/j.ijfatigue.2016.09.008>.
- [53] R. W. Hertzberg and J. A. Manson, *Fatigue of Engineering Plastics*. Academic Press, 1980. [Online]. Available: <https://books.google.it/books?id=C7tRAAAAMAAJ>
- [54] H. Nouri, S. Guessasma, F. Roger, A. Ayadi, and H. Maitournam, 'Exploring damage kinetics in short glass fibre reinforced thermoplastics', *Compos Struct*, vol. 180, pp. 63–74, 2017, doi: <https://doi.org/10.1016/j.compstruct.2017.07.096>.
- [55] G. Geymonat and S. Pagano, 'Identification of Mechanical Properties by Displacement Field Measurement: A Variational Approach', *Meccanica*, vol. 38, no. 5, pp. 535–545, 2003, doi: 10.1023/A:1024766911435.
- [56] F. Latourte, A. Chrysochoos, S. Pagano, and B. Wattrisse, 'Elastoplastic Behavior Identification for Heterogeneous Loadings and Materials', *Exp Mech*, vol. 48, no. 4, pp. 435–449, 2008, doi: 10.1007/s11340-007-9088-y.
- [57] S. Avril *et al.*, 'Overview of Identification Methods of Mechanical Parameters Based on Full-field Measurements', *Exp Mech*, vol. 48, no. 4, pp. 381–402, 2008, doi: 10.1007/s11340-008-9148-y.
- [58] E. Florentin and G. Lubineau, 'Identification of the parameters of an elastic material model using the constitutive equation gap method', *Comput Mech*, vol. 46, no. 4, pp. 521–531, 2010, doi: 10.1007/s00466-010-0496-y.

- [59] J. M. P. Martins, A. Andrade-Campos, and S. Thuillier, 'Comparison of inverse identification strategies for constitutive mechanical models using full-field measurements', *Int J Mech Sci*, vol. 145, pp. 330–345, 2018, doi: <https://doi.org/10.1016/j.ijmecsci.2018.07.013>.
- [60] E. Florentin and G. Lubineau, 'Using constitutive equation gap method for identification of elastic material parameters: technical insights and illustrations', *International Journal on Interactive Design and Manufacturing (IIJDeM)*, vol. 5, no. 4, pp. 227–234, 2011, doi: [10.1007/s12008-011-0129-5](https://doi.org/10.1007/s12008-011-0129-5).
- [61] F. Hild and S. Roux, 'Digital Image Correlation: from Displacement Measurement to Identification of Elastic Properties – a Review', *Strain*, vol. 42, no. 2, pp. 69–80, May 2006, doi: <https://doi.org/10.1111/j.1475-1305.2006.00258.x>.

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2. List of Symbols

Variable	Description	SI unit
σ	stress	Pa
ε	strain	[-]
$\dot{\varepsilon}$	strain rate	1/s
N_f	number of cycles to failure	[-]
a_{ij}	component of orientation tensor	[-]
x, y	positions in in-plane directions	m
u, v	components of in-plane displacements	m
E	elastic modulus	Pa
L_f	fiber length	m
d_f	fiber diameter	m
ξ	reinforcement parameter	[-]
v_f	fiber volume fraction	[-]

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