NEU PRESS

FEN ve MÜHENDİSLİK BİLİMLERİ DERGİSİ

Cilt/Vol: 6 Sayı/No: 1 Yıl/Year: 2024 Araştırma Makalesi/Research Article e-ISSN: 2667-7989

https://doi.org/10.47112/neufmbd.2024.34

Filaman Sarım CETP Kompozit Boruların Mekanik Özelliklerinin ve Hasar Gelişiminin Halka Çekme Testi ile İncelenmesi

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Makale Bilgisi

Makale Geçmişi

Geliş Tarihi: 13.12.2023

Kabul Tarihi: 23.01.2024

Yayın Tarihi: 30.04.2024

Keywords:
Delaminasyon,
Filaman sarım,
Halka çekme testi,
Kompozit boru.

ÖZET

Filaman sarım yöntemi ile üretilen kompozit borular; hafiflikleri, korozyon dirençleri ve yüksek mukavemetlerinden dolayı birçok mühendislik alanlarında kullanılmaktadır. Özellikle doğalgaz ve petrol boru hatlarında basınç altında çalışan kompozit borular kullanılacağı alanda taşıyabileceği yükleri karşılayabilmesi için özel tasarımlar yapılmaktadır. Filaman sarım üretim yöntemi ile elyaf türü, elyaf sarım açısı ve tabaka sayısı değiştirilerek ihtiyaca göre farklı özelliklerde ve mukavemetlerde kompozit borular üretilebilmektedir. Değişken parametreler ışığında üretilen her borunun mekanik özelliklerinin belirlenmesi gerekmektedir. İç basınç altında çalışan kompozit boruların mekanik özelliklerinin belirlenmesinde kullanılan yöntemlerden bir tanesi de halka çekme testidir. Bu çalışmada Filaman sarım yöntemi ile ±55° elyaf konfigürasyonu ile 72 mm iç çapında ve 1 m boyunda cam elyaf takviyeli plastik (CETP) borular üretilmiştir. Üretilen borulardan ASTM D2290 standardına göre 30 mm genişliğinde 20 mm daraltılmış bölgelere sahip halka çekme test numuneleri hazırlanmıştır. Deneyler Instron 8801 test cihazında yapılmış ve veriler kaydedilmiştir. Kompozit boruların halka çekme deneyleri sonrasında elde edilen veriler işlenmiş ve grafik haline dönüştürülerek yorumlanmıştır. Deney sonrası hasar bölgeleri yüksek çözünürlüklü olarak fotoğraflanarak ayrıntılı makro ve mikro (SEM) hasar analizi yapılarak oluşan hasar modları belirlenmiştir.

Investigation of Mechanical Properties and Damage Development of Filament Wound GFRP Composite Pipes by Ring Tensile Test

Article Info

Article History

Received: 13.12.2023

Accepted: 23.01.2024

Published: 30.04.2024

Keywords:
Composite pipe,
Delamination,
Filament winding (FW),
Ring test.

ABSTRACT

Composite pipes produced by the filament winding (FW) method are used in many engineering fields due to their lightness, corrosion resistance and high strength. Composite pipes working under pressure, particularly in natural gas and oil pipelines, are specially designed to withstand the loads they will be exposed to in the area where they are used. With the FW production method, composite pipes with different properties and strengths can be produced according to the needs by changing the fiber type, fiber winding angle and number of layers. In the light of varying parameters, it is necessary to determine the mechanical properties of each pipe produced. One of the methods of determining the mechanical properties of composite pipes operating under internal pressure is the ring tensile test. In this study, glass fiber reinforced plastic (GFRP) pipes with an inner diameter of 72 mm and a length of 1 m with ±55° fiber configuration were produced by the FW method. Ring tensile test specimens with 30 mm wide and 20 mm reduced sections were prepared from the produced pipes according to ASTM D2290 standard. Experiments were carried out on an Instron 8801 tester and data were recorded. The data obtained after the ring tensile tests of composite pipes were processed, converted into graphics and interpreted comparatively. After the experiment, the damage areas were photographed at high resolution. Detailed macro and micro (SEM) damage analysis was performed to determine the damage modes.

To cite this article:
Gemi, L., Azeem, M., Yazman, Ş., Kayrıcı, M. & Gök, O. (2024). Investigation of mechanical properties and damage development of filament wound GFRP composite pipes by ring tensile test, *Necmettin Erbakan University Journal of Science and Engineering*, *6*(1), 93-104. https://doi.org/10.47112/neufmbd.2024.34

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INTRODUCTION

Composite materials have begun to replace traditional materials in aerospace, aviation, and defense industries and other engineering applications where weight is important. Composites produced in different geometries and components are classified according to the types of reinforcement used [1-4]. Commonly used polymer matrix composites are classified as fiber-reinforced (FRP) [5-9], nanofiber-reinforced [10-13] and nanoparticle-reinforced [14-18]. In order to determine the mechanical properties of composites that can be produced by different methods, they are subjected to a series of tests such as tensile, compression [19-21], fatigue [22-26], burst [27-31], buckling, vibration and low-velocity impact [32-36]. Determination of the mechanical properties of composite pipes and high-pressure tubes exposed to internal pressure must be made according to certain standards that are valid worldwide [37]. The main ones are the American Petroleum Institute (API) and the American Society for Testing and Materials (ASTM). The strength tests of composite pipes used in natural gas and oil transmission are carried out by exposing them to load in the radial direction. The maximum strength values of the composite pipes, which are tested until they are damaged under these loading conditions, are determined in an open-ended manner. One of the main tests is internal pressure bursting tests as specified in the ASTM D1599 standard. This test is known as one of the most accurate tests in the literature. Many researchers have carried out studies to determine the strength values of composite pipes produced from different fiber types [38, 39]. When the studies in the literature were examined, it was seen that different special sealed apparatuses were designed to apply internal pressure to the pipes produced. These apparatuses, fitted with high-pressure seals, are placed inside the composite pipes and connected to a hydraulic pump. Before starting the experiments, the liquid was filled into the area limited by the apparatus. Stresses in the radial direction (Hoop) are created on the pipes pressurized by a hydraulic pump and the loading is continued until they are damaged [40, 41]. In many studies conducted in the literature, the strength values of composite pipes have been obtained and their damage developments have also been examined. The damage modes occurring in the burst tests of GFRP FW pipes with different winding angles were determined as; outer surface matrix cracking, whitening where the matrix structure started to deteriorate, debonding damages in the fiber direction, intense whitening with the increase of pipe diameter, delamination, droplet leakage, intense leakage in the form of water jet and explosion damages with fiber breaks [4, 41-43]. As can be seen from the literature, bursting tests are quite laborious as many equipment and hydraulic units are used. One of the alternative strength determination tests is the ring tensile test, known as the ASTM D2290 standard. When the standard is examined, it can be seen that this test is simpler than the burst test and can be applied on any tensile device. When the studies in the literature are examined, it is seen that apparatuses have been prepared for pipes of different diameters and can be adjusted according to existing tensile tester. When the studies in the literature are examined; It can be seen that apparatus has been prepared for pipes of different diameters produced and can be adjusted according to the existing tester [44-46]. Obtaining fast results with this test, small sample sizes used and easy applicability have become the reason for preference of researchers [47-51]. Kaynak et al. applied split-disc tests to composite pipes manufactured with two different resin systems, five different fibers and winding angles [52]. It was concluded that split-disc tests were effective in determining the performance of the pipes. Gemi et al. comparatively investigated the effect of stacking sequence on the strength of FW hybrid pipes manufactured in the $[\pm 55°]_3$ configuration by internal pressure and ring test [53, 54]. They found that the strength test results were 15-30% lower than the burst test results due to the disruption of fiber continuity and the reduction of sample sizes in the filament wound pipes prepared for the ring tensile test. In addition, although an apparatus is used to minimize the moment effect in the ring tensile test, this effect is not completely eliminated, so there is a difference in the behavior compared to the under internal pressure. Because there is no bending moment effect due to axial symmetry in pipes subjected to internal pressure. For this reason, while apparent hoop tensile strength is obtained from the ring tensile test, real hoop tensile strength is obtained from the burst test performed under internal pressure. In the literature, damage analyzes are also included in studies conducted with ring tensile tests and damage developments are mentioned. It is stated that the damages are concentrated in reduced sections and the fiber winding configurations affect the damage development.

MATERIALS AND METHODS

The GFRP pipes used for this experimental study were produced using the facilities of İzmir İzoreel composite company. In the production of pipes, the FW method was used, which meets all winding parameter needs. The data obtained as a result of the literature review was effective in determining the pipes used and their parameters. The ring tensile test method, which is one of the fastest tests used to determine the approximate mechanical properties of the composite pipe, was used. Tests were made on the Instron 8801 tensile tester. In order to perform the tests, a ring tensile test apparatus suitable for the tester was designed and used. The obtained data were recorded and stress-strain graphs were drawn. During and after the experiment, GFRP composite pipe samples were examined in detail and interpreted by damage analysis.

Manufacturing of the Composite Pipes

A steel mandrel with a diameter of 72 mm has been specially designed for the production of composite pipes. E glass (1200 tex - 17 µm diameter) was used as reinforcement material. Momentive (Bisphonel A-Epikote 828) resin was used as the matrix material. Epicure 875 was used as a hardener in the resin system to accelerate the polymerization process. In the resin/hardener system, an additive ratio of 100:80 by weight was used. Before starting production, mold release material was applied to the mandrel (QZ-13). For the pipe design, a program was written on the CNC filament winding machine and the number of bobbins required for the winding width was determined. Fiber winding angle configuration $[\pm 55°]_3$ has been determined. The pipes were produced with a total of 6 layers of wet winding, with an inner diameter of 72 mm and an outer diameter of 76.8 mm (Figure 1). After the winding process, the composite pipe-wrapped mandrel was removed from the FW machine and placed in the curing oven. The oven curing process was carried out at 135 ºC and 150 ºC for two hours each. The produced pipes were cut into 300 mm dimensions and prepared for use in experimental studies.

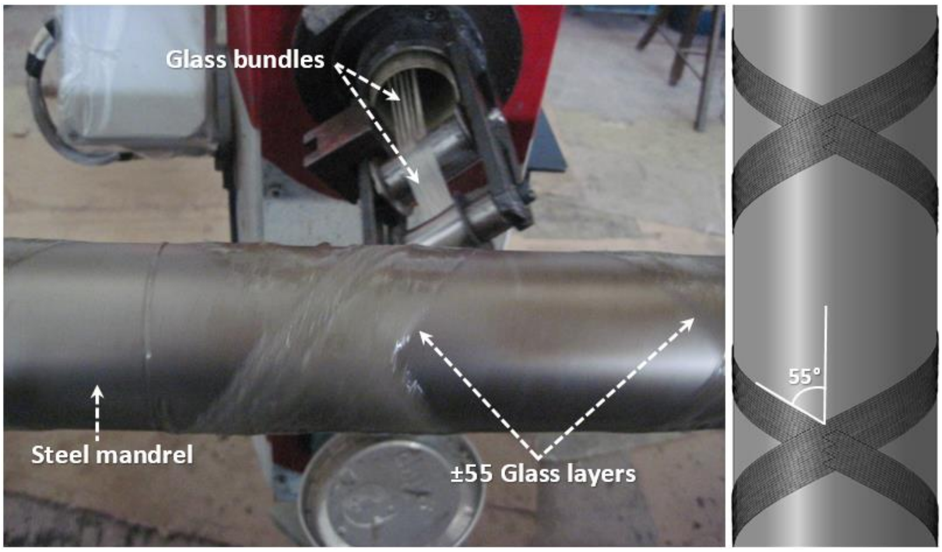

Figure 1. *Production of GFRP composite pipes with the FW method*

Ring tensile test

Ring tensile test samples were prepared according to ASTM D2290 standard [48, 55]. The stage of preparing samples from composite pipes in accordance with the standard is shown in Figure 2. Marking was carried out on the pipes for a sample width of 30 mm and a reduced sections of 20 mm. After marking, drilling was performed on a universal drill machine to prepare the reduced sections. In order to prevent hole exit damages such as push-out delamination during drilling, a 72 mm diameter wooden back-up was manufactured to be placed inside the composite pipes. In order to create reduced sections of the samples in standard sizes, drilling operations were carried out using the advancement mechanism with mm divisions on the bench. Radial cutting process was applied to the composite pipes with marking and reduced sections prepared and ring test samples were obtained. After the cutting process, the sample dimensions were checked and the cut surfaces were ground with wet sandpaper as needed. Tensile tests were carried out after the prepared samples were mounted on the apparatus. The machine speed was set as 2 mm/min during the tension process. After the gaps of the apparatus were eliminated, the loading process was started. Tensile data of three repeated tests were recorded.

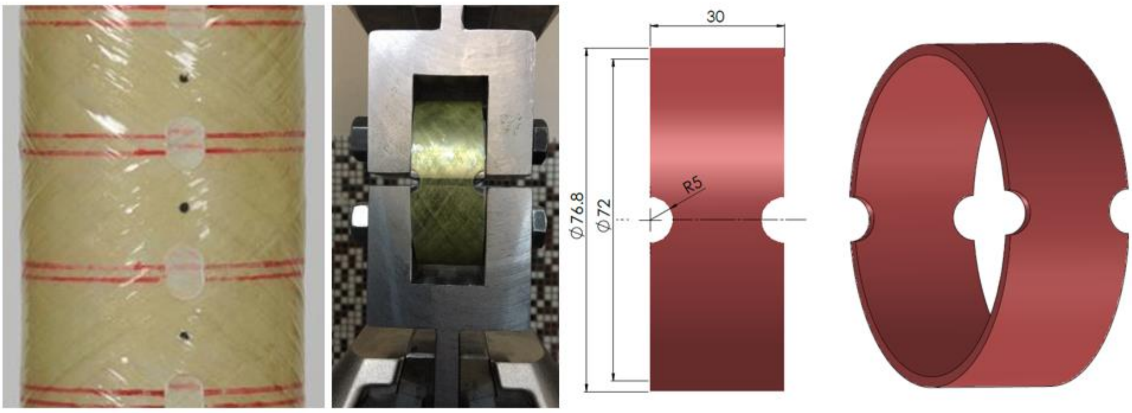

Figure 2. *Ring test sample preparation stage and sample geometry.*

Damage analysis

After the tensile test, macro and micro damage analysis was performed on the damaged samples. For macro damage analysis, images of the outer and inner parts of the specimens were taken with high resolution cameras in studio conditions (Figure 3). For micro damage analysis, images obtained from optical microscope and SEM device were used (Figure 4). Micro-scale damages in the damage areas were detected and interpreted by processing on the images.

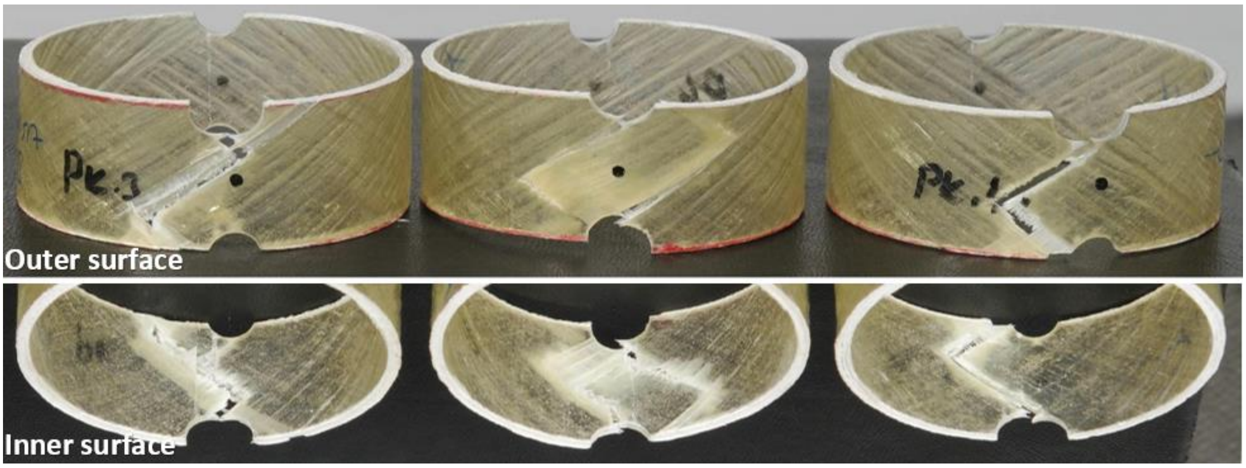

Figure 3. *Outer and inner surface images of damaged specimens after the test*

RESULTS

The load-elongation data recorded during tensile tests were analyzed and stress-strain graphs were drawn. During the processing of the data, the area calculation was made by taking into account the reduced section on both sides of the ring tensile specimen during calculating the stress. The stress-strain graphs obtained as a result of the processed data are given in Figure 5, and the maximum stress and strain values are given in Table 1. When Figure 5 and Table 1 were examined comparatively, it is seen that although the maximum stress values obtained in the three tests were close to each other, there are some differences in the strain values. It is thought that these differences are due to the fact that the excess resin accumulated on the sample after the winding of the last layer in the sample production cannot be removed homogeneously. It is understood that the mechanical properties of the samples taken from resin-rich areas differ (Test-3).

Figure 4. *Optical microscope and SEM device used for damage analysis*

As a result of the observations made during the experiment, significant damage development was observed in the specimens loaded at a speed of 2 mm/min [55]. The onset of damage was determined as an average stress value of 250 MPa in all three specimens. It was observed that the damage first occurred in the resin-rich zone in the reduced section, where matrix cracks and crazing-whitening occurred in the direction of the fiber winding angle. As the loading continued, debonding damage occurred in certain areas due to whitening in the fiber direction.

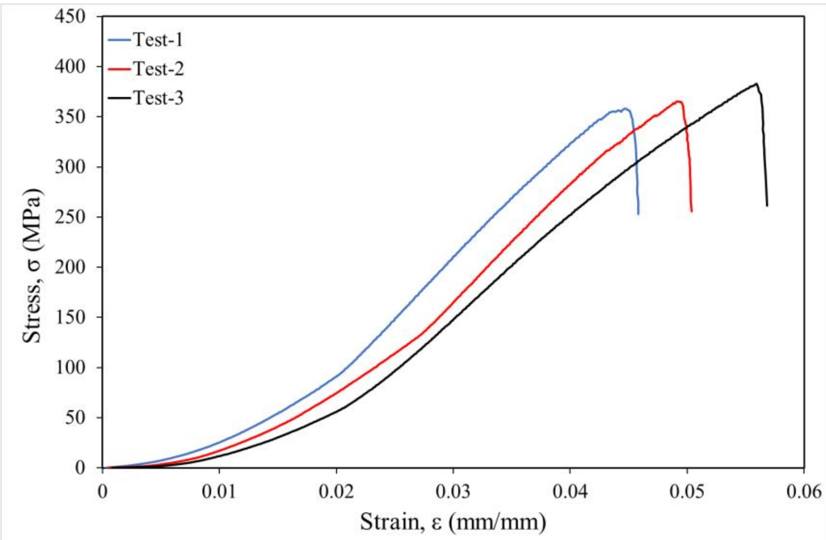

Figure 5. *Stress-strain graphs obtained after ring test*

It was observed that delamination damage started at the 337 MPa stress level in areas where whitening and debonding were intense. It was observed that with increasing load, some fibers began to break at the radius edges of the reduced section and fiber pull-outs occurred with the angular direction change. It was observed that with increasing load, some fibers started to break at the radial edges of the reduced section and fiber pull-outs/fracture layer occurred with angular direction change. At an average stress level of 368 MPa, catastrophic damage started in the direction of -55° winding angle. The final damage was caused by splitting and fracture layers and pull-out of the fiber bundles in the +55° layer.

Table 1. *Maximum Stress-Strain values after the test*

No	Max. Stress (σ) MPa	Max. Strain (ε) mm/mm
Test-1	358	0.0458
Test-2	365	0.0504
Test-3	382	0.0568
Average	*368.3*	*0.051*

Figure 6 shows comparative images of the outer and inner surface of the damaged specimens. When the macro damages were analyzed, it was observed that the damages started from the ends of the reduced section. Subsequently, it is seen that the damage progresses in the direction of -55° winding angle and occurs in the form of brittle fracture in the layers. It was observed that the damages progressing in the -55° fiber winding direction reached a certain size and changed direction towards the +55° winding direction (Test-1, Test-2). Especially when the Test-2 specimen is examined, it is understood that fracture occurs with the onset of double-sided damage in the layers and when it reaches a certain stage, the fracture changes direction. When the damages in all three specimens are examined, it is seen that severe delamination and matrix crack damages occurred in the fracture direction.

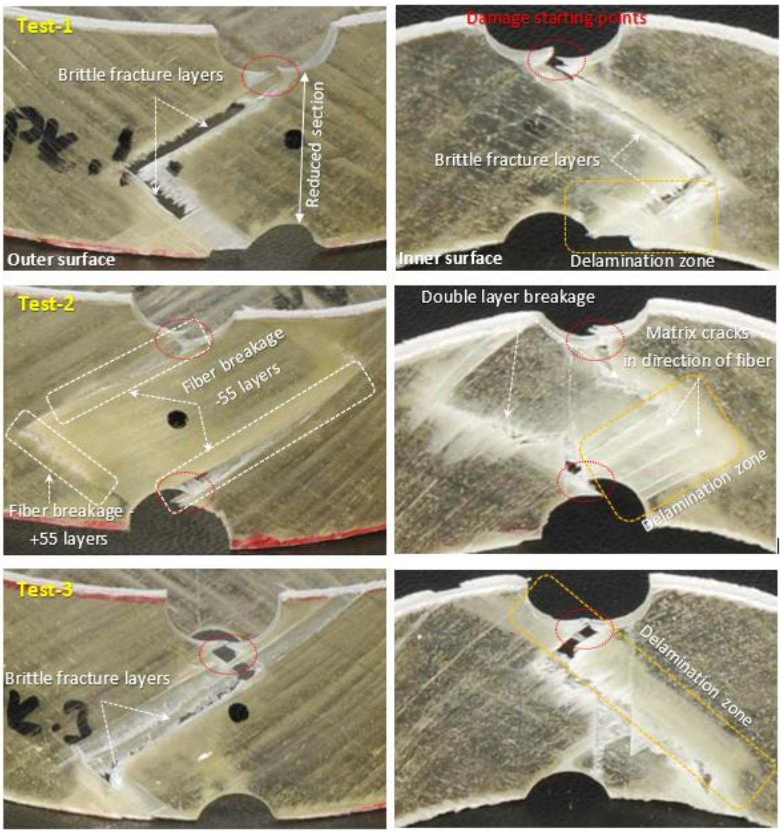

Figure 6. *Macro damage analysis of samples after ring test*

After the macro damage analysis, a general cross-sectional image was taken from the damaged area of the Test-3 specimen with an optical microscope. After the cross-sectional image examinations, the specimen was removed from the damage zone where brittle fracture occurred for SEM analysis. The damages occurring in the fracture zone and within the layer were examined in detail by SEM analysis (Figure 7). When the image given in Figure 7a is examined, it is seen that fracture, layer fractures and delamination damages occur in the direction of the winding angle. In Figure 7b, the general view of the damage zone is photographed by SEM and the layer stacking is analyzed. It was determined that the -55° layer suffered from multiple damage in addition to delamination. Figure 7d and 7e shows the micro analysis of debonding and fiber fracture damage on the fracture surface. Figure 7c shows the debonding damage caused by radial cracks near the fracture zone. In the reduced sections of the specimen, the damage modes detected before the final failure also occurred during fracture and spread throughout the damage zone.

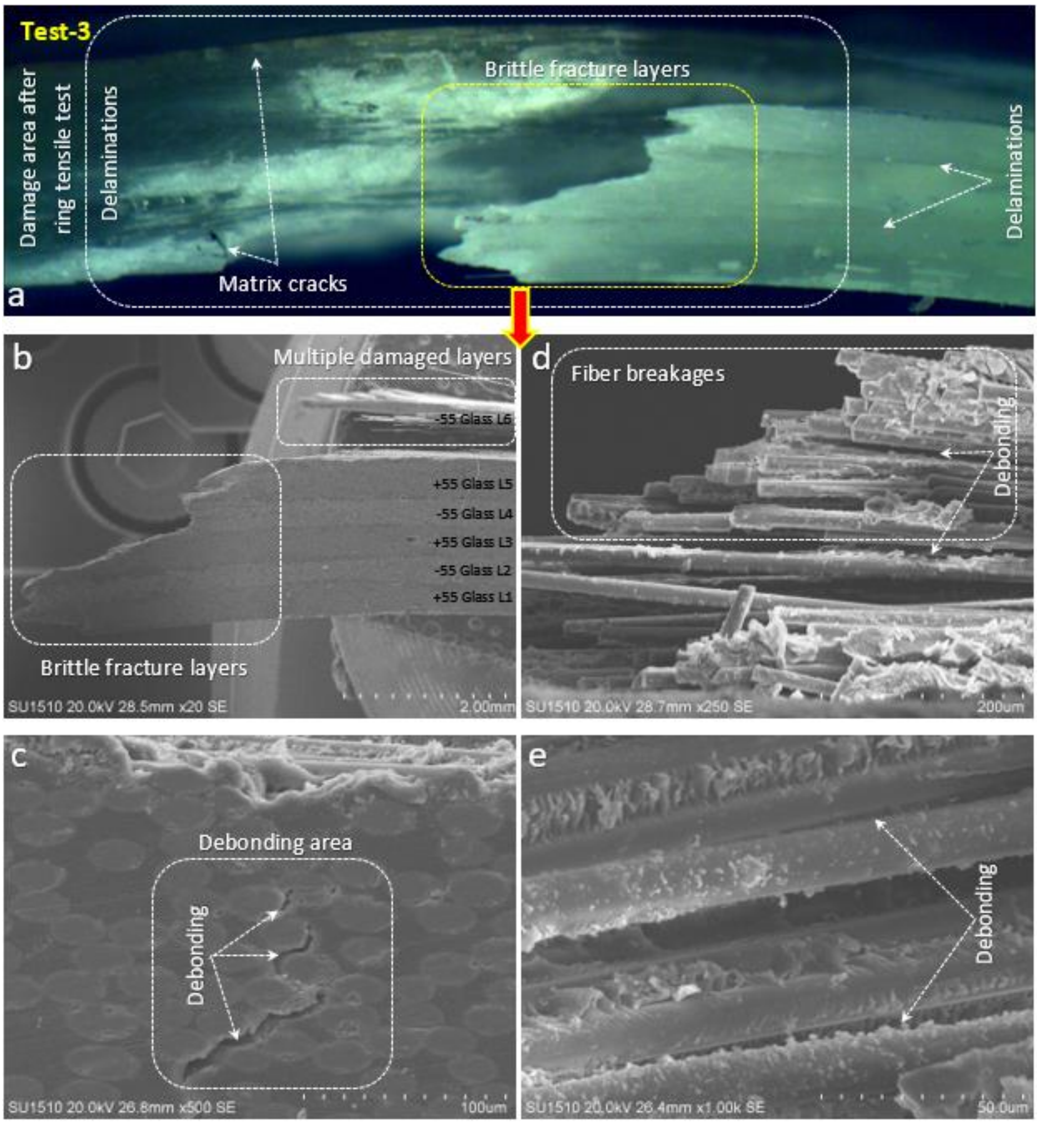

Figure 7. *Micro damage analysis of samples after ring test*

DISCUSSION AND CONCLUSIONS

In this study, the mechanical properties of GFRP composite pipes produced by filament winding method were determined by ring tensile test and the damage development of the material during the test was analysed. In the detailed damage analysis, damage modes were determined and the behaviour of layered composites produced by filament winding method under radial load was interpreted and following conclusions are drawn:

- Although the ring tensile test specimens were cut from the same pipes, it was observed that there were differences in their mechanical properties. The maximum strengths of the pipes were close to each other and reached up to an average value of 368 MPa (Max. Stress-σ). The maximum % strain results varied between 0.045-0.057 mm/mm (Max. Strain-ε). The reason for this is thought to be that there are local resin-rich regions on the composite pipe due to the production method and the reduced sections coincide with these regions.
- All of the damage to the specimen occurred in the reduced sections. Damage initiation occurred at the ends of the reduced sections. In all three specimens, the progression of damage occurred in the fiber direction in the -55° layer and the fractures were found to change direction in the +55° layer direction after a certain point.
- The damage modes were as follows: matrix cracking, crazing, debonding, delamination, fiber fractures, layer fractures in the fiber direction, and fiber bundle pull-out during fracture.
- From the literature reviews conducted for this study, it is understood that the hoop tensile strength obtained from ring tensile test are 15-30% lower than the strength values obtained from static burst under internal pressure of open-end pipes. The reason for this is thought to be the change in sample dimensions (shrinkage in the axial direction) and disruption of fiber continuity. Also, in the ring tensile test, the apparent hoop tensile strength is obtained due to the bending moment, while in the burst test, the real hoop tensile strength is obtained.

Conflict of Interest

The authors have no conflicts of interest to disclose for this study.

Authorship Contribution Statement

L.G.: Conceptualization, Resources, Formal Analysis, Writing - Original Draft, Resources, **M.A.:** Writing - Review & Editing, Supervision, **Ş.Y.:** Investigation, Data Curation, Formal Analysis, **M.K.:** Methodology, Writing - Review & Editing, **O.G.:** Data Curation, Writing - Review & Editing

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