Failure particularities of adhesively bonded joints between pultruded GFRP composite profiles

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Abstract. The failure particularities of the adhesively bonded joints between fibre reinforced polymer (FRP) composite elements represent a set of critical parameters in assessing the performance of these systems. If the failure process is not properly evaluated and controlled, it can lead to significant decrease of the overall efficiency of the joint. Usually, if the bond length is greater than the effective one, the failure process for these types of joints can be either progressive, if the initial failure is initiated in the adhesive layer, or brittle, if the failure occurs in the FRP elements. The ultimate failure occurs if any stress or strain component reaches a limit state, referring to the components (adherents and adhesive) or to the interfaces between them.

This paper presents some particularities related to the failure process of the adhesively bonded joints between pultruded glass fibre reinforced polymer (GFRP) composite members. The results were obtained through a complex experimental program conducted at the Faculty of Civil Engineering and Building Services from Iasi, where the structural behaviour of adhesively bonded single lap joins (SLJ) and thick adherents’ joints (TAJ) between pultruded GFRP composite flat profiles was studied. For the experimental program, 30 specimens were prepared by varying the connection type (SLJ, TAJ), the bond length (70, 100, 150 mm), the adhesive type and its thickness (1, 2, 3 mm). All specimens were loaded in axial tension, up to failure and the characteristic failure modes were investigated by in-depth microscopic analysis of the failure surfaces.

1. Introduction

Over the last three decades, fibre reinforced polymer (FRP) composite products have developed into sustainable and structurally viable construction materials, enabling their use as stand-alone load bearing members or as components of strengthening systems for the existing construction elements made of traditional materials (i.e. concrete, steel, wood, masonry) [1]. Regardless of the type of application, one of the most important requirements in using FRP composite materials consists in providing an appropriate type of connection between the components of the system that corresponds to its structural and functional demands. The two main connection types currently used in FRP structural assemblies are mechanical fastening and adhesive bonding [2].

Adhesive bonding has become the prominent joining method of FRP composite members since it provides significant advantages compared to the mechanical fastening technique. These advantages are the uniform distribution of the stresses between the adherents, lower connection weight and superior corrosion resistance [3-5].
Based on the function of the adhesive layer, the adhesively bonded joints can be divided into two main categories. The first category consists in the applications where the adhesive layer is responsible for the stresses (mainly shear) transfer between the FRP elements, being generally referred to as bond-critical connection. The second category includes the application where the main function of the adhesive layer is to ensure the contact between the FRP members for an effective transfer of axial stresses, being referred to as contact-critical connection [6, 7]. However, for load bearing elements connections only the contact-critical bonds can be applied since the bond-critical ones are generally subjected to complex stress states, including both shear and bending components [2]. These restrictions come from several difficulties and uncertainties which are directly related to the failure mechanism of the FRP adhesively bonded joints and to their long-term performance. For example, the latter can be negatively influenced by the curing conditions, the loading pattern, the bond geometry and the technology of assembling the joint.

This paper presents certain particularities related to the failure process of adhesively bonded joints between pultruded glass fibre reinforced polymer (GFRP) composite elements based on the results of a complex experimental program and by performing a set of microscopic investigations of the failure surfaces. The experimental program consisted in 30 specimens that were prepared by varying the type of connection (single lap joint - SLJ, thick adherent joint - TAJ), the bond length (70, 100, 150 mm), the type of adhesives and their thicknesses (1, 2, 3 mm). All specimens were loaded in axial tension, up to failure. Before bonding, the GFRP elements were surface treated, in order to improve their adhesion properties and the contact surfaces were microscopically studied. Based on the results provided by the experimental program, it was observed that the dominant failure mechanism for both connection types consisted in fibre tearing. However, some of the specimens exhibited different failure mechanisms, consisting of combinations between fibre-tear, de-bonding at the interface level and cohesive failures in the adhesive layer. The failure mechanisms were described and characterised through the microscopic study of the failure surfaces.

2. Experimental setup
The experimental program consists of a series of shear pull-off tests aiming to investigate the failure mechanisms of bonded SLJs and TAJs between FRP composite elements. For this purpose, pultruded GFRP composite profiles were cut to nominal shapes, canted, surface treated and bonded using two distinct types of epoxy adhesives to match the designed geometric configurations. Figures 1 and 2 illustrate the general configurations of the SLJs and TAJs specimens, while table 1 presents the geometry of the specimens and their failure modes.

| Code       | Joint type | Adhesive | Adhesive thickness, $t_a$ [mm] | Bond line length, $L_c$ [mm] | Failure mode |
|------------|------------|----------|---------------------------------|-------------------------------|--------------|
| S-70-1-30 (i) | SLJ        | Sika 30  | 1                               | 70                            | F-T-C        |
| S-70-1-30 (ii)| SLJ        | Sika 30  | 1                               | 70                            | F-T          |
| S-70-1-330 (i) | SLJ        | Sika 330 | 1                               | 70                            | F-T-C        |
| S-70-1-330 (ii)| SLJ        | Sika 330 | 1                               | 70                            | F-T-C        |
| S-70-2-30 (i) | SLJ        | Sika 30  | 2                               | 70                            | F-T-D        |
| S-70-2-30 (ii)| SLJ        | Sika 30  | 2                               | 70                            | F-T          |
| S-70-2-330 (i) | SLJ        | Sika 330 | 2                               | 70                            | F-T          |
| S-70-2-330 (ii)| SLJ        | Sika 330 | 2                               | 70                            | F-T          |
| S-70-3-30 (i) | SLJ        | Sika 30  | 3                               | 70                            | F-T          |
| S-70-3-30 (ii)| SLJ        | Sika 30  | 3                               | 70                            | F-T          |
| S-70-3-330 (i) | SLJ        | Sika 330 | 3                               | 70                            | F-T          |
| S-70-3-330 (ii)| SLJ        | Sika 330 | 3                               | 70                            | F-T          |
Failure modes: Fibre-tear (FT); Combined Fibre-tear and de-bonding (F-T-D); Combined Fibre-tear and cohesive (F-T-C)

- i - Number of identical specimens

**Figure 1.** General configurations of SLJs specimens

Not at scale.
2.1. Materials properties

For the experimental work described in this paper, Fiberline GFRP composite pultruded profiles with rectangular cross section were used. The internal structure of the GFRP composite elements consists of a central layer of unidirectional roving, in the mid-plane of the cross-section, and several additional exterior layers, both chopped strand mats and bi-directional woven mats (0°-90° alignment), embedded in isophthalic resin, symmetrically distributed with respect to the mid-plane [8-10]. Also, the exterior layers of the elements are protected by an overlay veil. The most relevant properties of the GFRP composite pultruded plate profiles, as given in their technical sheets, are presented in table 2.

Table 2. Properties of the GFRP composite elements [8].

| Density [kg/m³] | Fibre volume fraction [%] | Longitudinal modulus of elasticity [GPa] | Transverse modulus of elasticity [GPa] | Shear modulus [GPa] | Poisson’s ratio, \(v_{0,90}/v_{90,0}\) | Tensile strength, \(0°/90°\) [MPa] | Compressive strength, \(0°/90°\) [MPa] |
|-----------------|---------------------------|------------------------------------------|----------------------------------------|-------------------|---------------------------------|-----------------------------|-----------------------------|
| 1500            | ~65                       | 23                                       | 8.5                                    | 3                 | 0.23 / 0.09                     | 240 / 50                    | 240 / 70                    |

The GFRP elements were bonded using two distinct, bi-component epoxy adhesives with linear behaviour, Sikadur 30 and Sikadur 330. Table 3 presents the physical and the mechanical properties of the adhesives as declared by the producer. These values are valid for specific conditions of preparation and curing. As it can be observed, the ultimate strains and the tensile strength of the adhesives have similar values, while the modulus of elasticity of Sikadur 30 is almost three times higher than that of Sikadur 330 [11].
Table 3. Properties of the adhesives [11, 12].

| Type     | Density [kg/dm³] (mixed) | Compressive strength, fc [MPa] | Tensile strength, ft [MPa] | Modulus of elasticity, E [GPa] | Elongation at break, εₜₜₐₜₜ [%] |
|----------|--------------------------|--------------------------------|-----------------------------|---------------------------------|---------------------------------|
| Sika 30  | 1.65                     | 70-80 (7 days, +10°C)         | 25-28 9 (7 days, +15°C)    | 12.8 (7 days, +15°C)            | 1.0%                            |
| Sika 330 | 1.30                     | 30 (7 days, +23°C)           | 33.8 (7 days, +23°C)       | 4.5 (7 days, +23°C)             | 0.9%                            |

2.2. Preparation of the specimens

The GFRP composite elements were cut to their nominal dimensions (see Figures 1 and 2) to match the geometric specifications of the specimens. Prior to the joining stage, the overlap surfaces were treated to increase the adhesion properties. It has been observed that in case of FRP adhesively bonded joints, one of the most common mechanisms of adhesion is mechanical interlocking. Thus, if the roughness and the porosity degrees of the surface are increased, the intensity and the density of the interlocking adhesion forces are significantly improved [12-14].

The GFRP surface treatment was performed according to the specifications of the profiles manufacturer and it consisted in multiple stages of cleaning and grinding [8]. In the first stage, the bond surfaces were solvent-cleaned with acetone to remove the contaminants resulted from the cutting process. Secondly, the surfaces were ground by mechanical and manual techniques in order to increase their roughness and their porosity degrees. The mechanical grinding was performed using rotating wire brushes at a constant circular speed of 600 RPM, while the manual grinding was carried out by applying 30 passes with abrasive paper (200 grit) on each longitudinal direction. Finally, the bonding surfaces were air blasted and once again cleaned with solvents to eliminate any remaining residues and pollutants.

The changes in the surface topology of the GFRP composite elements prior and after treatment were analysed using a XJP-6A inverted microscope (figure 3). The images captured by the microscope camera were examined using the Material Plus Image Software.

![Figure 3. XJP-6A inverted microscope.](image)

First, the microscope lens was focalised on a specific region of 1.6 x 2.1 mm to capture any physical defects such as cavities or micro-cracks. As it can be observed in figure 4, small cavities were identified on the surface of the untreated specimen, which had probably occurred during the handling and storing stages. On the other hand, the surface of the treated specimens (figure 5) looked more homogenous, since no significant damages were recorded. Furthermore, the images were examined using a light filter, aiming to identify and measure the in-depth differences from the upper plane of the specimens to the bottom plane of the cavities. As presented in figure 6 and figure 7, several specific
regions consisting of either concentration of dark spots or light spots density areas (on grey scale intensity) were observed for both the untreated specimen and the surface-treated one.

Figure 4. Untreated surface, 25X. Detail A: Surface cavity, 250X; $L_1 = 1578.95 \mu m; L_2 = 2105.27 \mu m; L_3 = 163.16 \mu m; L_4 = 157.90 \mu m$.

Figure 5. Treated surface, 25X; $L_1 = 1578.95 \mu m; L_2 = 2102.64 \mu m$.

An approximately metric scale, based on the grey scale intensity, was used for the evaluation of the depth of the specific regions that were identified on the surface of the specimen. It has been observed that the maximum depth of the specific regions located on the surface of the untreated specimen is around 1.4 mm, while in case of the surface treated specimen, due to grinding procedures, the total depth was much higher, being close to 2.1 mm.

Figure 6. Specific regions located on the surface of the untreated specimen, 25X.

| Region | Max.    | Min.    | Avrg.    |
|--------|---------|---------|----------|
| SR1    | 403.65  | 102.19  | 226.34   |
| SR2    | 1178.49 | 612.79  | 958.90   |
| SR1    | 305.54  | 199.81  | 254.77   |

Total deepness = 1440.01 $\mu m$
Figure 7. Specific regions located on the surface of the treated specimen, 25X.

| Region | Max.     | Min.     | Avrg.     |
|--------|----------|----------|-----------|
| SR1    | 831.80 μm| 903.17 μm| 867.49 μm |
| SR2    | 551.50 μm| 531.58 μm| 541.54 μm |
| SR3    | 751.49 μm| 53.29 μm | 449.16 μm |
| SR4    | 657.44 μm| 2.63 μm | 289.16 μm |

Total deepness = 2147.35 μm

For a better understanding, the images were processed, and distinct colours were applied to each characteristic area, corresponding to their roughness degree. As it is depicted in figure 8 and figure 9, only two areas were determined for the untreated specimen, while for the surface treated specimen, six distinct areas were distinguished. Also, it can be observed that the surface treatment allows for a smooth transition from one area to another.

Figure 8. Untreated specimen. Processed image according to the roughness degree, 25X;
Red coloured area 43.21 %; Green coloured area 56.79%.

Figure 9. Surface treated specimen. Processed image according to the roughness degree, 25X;
Red coloured area 3.35 %; Green coloured area 7.36%; Blue coloured area 37.89 %; Yellow coloured area 30.05 %; Cyclam coloured area 16.23 %.
Furthermore, the pores located on the surface of the specimens were identified and measured according to ASTM B276 [16]. Figure 10 presents the density of pores (red coloured regions) for both the untreated and surface treated specimens.

![Figure 10. Porosity. Untreated and surface treated specimens, 25X.](image)

As the porosity of the surface-treated specimen is 63 %, ten times higher than the porosity of the untreated specimen (6 %), it can be concluded that the mechanical and manual grinding procedures, previously described, provided significant change in porosity and roughness to enhance the interlocking effect. Also, based on the fact that the transition between distinct areas with respect to the roughness/porosity degree is smooth, it can be deduced that the presented surface treatment method provides specimens with regular topographic profiles.

After the GFRP profiles were surface-treated, the specimens were bonded and fixed with clamps and stored in constant temperature and humidity conditions for 14 days, until the curing process was completed.

2.3. Loading procedures
The specimens were subjected to direct tension by loading in a Zwick/Roell 1000 kN hydraulic test machine (figure 11), located in The Composite Material Laboratory of Faculty of Civil Engineering and Building Services in Iasi. The tests were performed in force-control mode by setting a loading rate of 5 kN/min.

![Figure 11. Specimen fixed in the testing machine.](image)

3. Failure modes
By investigating the specimens after the pull-off tests, it has been concluded that in most of the cases, the ultimate failure developed in the outer mat layer at approximately 0.5-1.5 mm from the top surface. Based on the provision of ASTM 5573 [16], this type of failure falls into the ‘fibre-tear’ category.
However, some of the specimens exhibited different failure modes consisting of combinations between fibre-tear, de-bonding at the interface level \( i.e. \) S-70-2-30 (i), T-100-1-330 (i)) and local cohesive failures in the adhesive layer \( i.e. \) S-70-1-330 (ii), S-100-1-30 (i), S-100-1-30 (ii), S-100-1-330 (ii), S-100-2-30 (ii), S-100-3-330 (ii), S-150-2-330 (ii), T-100-1-30 (i), T-100-1-30 (ii). Figure 12 presents the characteristic failure modes of the specimens. Nevertheless, these failure modes are not common for similar bonded systems but with different substrates. For example, in case of FRP elements bonded to concrete substrates, the most common failure mode consists in FRP de-bonding, due to the low tensile strength and to the brittle behaviour of concrete, while in case of FRP elements bonded to steel substrates, the dominant failure mode consists in a combination between cohesive failure (adhesive level) and interface de-bonding, due to the high tensile and shear strength of the steel [12].

![Figure 12](image_url)

**Figure 12.** a, b - Dominant failure mode – S-70-3-30 (i); S-70-2-30 (ii); c – combination between the dominant failure mode and local failure by interface de-bonding – T-70-2-30 (i); d, e, f – combination between the dominant failure mode and cohesive failure – S-70-1-330 (i); T-100-1-30 (ii); S-100-3-330 (i).

### 3.1. Fibre tear mode

The dominant failure mode for both SLJ and TAJ connection types consisted in premature fibre-tearing, being recorded as singular failure mode for 17 specimens, and in combination with distinct failure modes (interface de-bonding and cohesive) for 13 specimens. Thus, it can be concluded that the failure of the specimens was not controlled, as expected, by the shear strength of the adhesive, but by the inferior tensile strength of the mat layers of the GFRP composite element. Also, as it can be observed in figure 13, the fibres were extruded from their matrix cover.
Figure 13. Dominant failure mode: Fibre tear a) 25X; b)250X; c)250X.

The majority of the micro-cracks were located inside the GFRP elements, with significant concentration in the vicinity of the fibre-matrix separation regions. The dimensions of the micro-cracks and the perimeters of the regions where the fibres were separated from the matrix are presented in table 4.

Table 4. Micro-cracks locating inside the GFRP composite element.

| Notation | Description | Results (μm) |
|----------|-------------|--------------|
| A1       | Region      | 96516.62     |
| A2       | Region      | 24667.59     |
| A3       | Region      | 18434.903    |
| L1       | Micro - crack | 547.425   |
| L2       | Micro - crack | 269.175    |
| L3       | Micro - crack | 417.475    |
| L4       | Micro - crack | 303.757    |
| L5       | Micro - crack | 285.1      |
| L6       | Micro - crack | 284.514    |
| L7       | Micro - crack | 419.626    |
| L8       | Micro - crack | 352.415    |
| L9       | Micro - crack | 205.892    |
| L10      | Micro - crack | 479.972    |
| L11      | Micro - crack | 1192.109   |
| L12      | Micro - crack | 732.808    |
| L13      | Micro - crack | 614.033    |

By applying different colours to the fibres (green) and the matrix (red) (figure 14), and by measuring the obtained coloured regions, it can be observed that the fibres represent almost 65 %, while the matrix covers 35 % from the total area. These results are in good agreement with the provisions related to the fibre and to the matrix volume fraction, declared by the GFRP composite elements manufacturer [8].
3.2. Combined Fibre-tear and de-Bonding failure mode

Two of the specimens (S-70-2-30 (i), T-100-1-330 (i)) failed in a combined mode that consists in both fibre-tear and de-bonding at the interface level. By investigating the failure surfaces, it can be observed that the bond areas were characterized by insufficient preparation and by a high irregular topographic profile (figures 15). Several cracks and isolated cavities were found on the GFRP surface, which most likely occurred during the mechanical grinding stage. The dimensions of these irregularities are presented in table 5.

![Figure 14](image1.png)  
**Figure 14.** Fibre-tear failure, 25X. Fibre – green coloured areas; Matrix – red coloured areas.

![Figure 15](image2.png)  
**Figure 15.** Combined Fibre-tear and de-Bonding failure mode, 25x; Detail A, 250X.

| Notation | Description | Results (μm) |
|----------|-------------|--------------|
| A1       | Micro-crack | 867.424      |
| A2       | Micro-crack | 549.301      |
| A3       | Micro-crack | 403.799      |
| L1       | Micro-crack | 538.163      |
| L2       | Micro-crack | 343.54       |
| L3       | Micro-crack | 440.418      |
| L4       | Micro-crack | 356.275      |
| L5       | Micro-crack | 792.105      |
| L6       | Micro-crack | 1013.404     |
| L7       | Micro-crack | 1565.046     |
| L8       | Micro-crack | 1349.415     |

| Notation | Description | Results (μm) |
|----------|-------------|--------------|
| A4       | Micro-crack | 867.424      |
| A5       | Micro-crack | 549.301      |
| A6       | Micro-crack | 403.799      |
| L7       | Micro-crack | 538.163      |
| L8       | Micro-crack | 343.54       |
| L9       | Micro-crack | 440.418      |
| L10      | Micro-crack | 356.275      |
| L11      | Micro-crack | 792.105      |
| L12      | Micro-crack | 1013.404     |
| L13      | Micro-crack | 1565.046     |
| L14      | Micro-crack | 1349.415     |
For better understanding, the regions where the failure occurred by adhesive debonding from the GFRP substrate were coloured in red (figure 16). Thus, the difference between a proper surface treated region and an insufficient or over grinded one can be easily observed.

![Figure 16. Insufficient surface treated areas, 25X.](image)

### 3.3. Combined Fibre-tear and Cohesive failure mode

Some of the specimens (i.e. S-70-1-330 (i), S-70-1-330 (ii), S-100-1-30 (i), S-100-1-30 (ii), S-100-1-330 (i), S-100-1-330 (ii), S-100-2-30 (ii), S-100-3-330 (i), S-150-2-330 (ii), T-100-1-30 (i), T-100-1-30 (ii)) exhibited a complex failure mode that consists of a combination between fiber-tear and cohesive failure. The cohesive failure represents the optimum failure mode of the FRP adhesively bonded joints, as it has been proved that it enables the most efficient use of the mechanical properties of the adhesive [2, 17]. However, for the specimens described in this experimental work, the cohesive failure was recorded only as a secondary failure mode which generally occurred on rather small and isolated regions of the bond surface. As it can be observed in figure 17, the cohesive failure regions are characterised by several failure planes, each of them developing micro-cracks (table 6) and cavities in the adhesive layer.

![Figure 17. Combined Fibre-tear and Cohesive failure mode, 25X; Detail A, 250X, Detail B, 500X.](image)

|   | Cavity perimeter |   |
|---|-----------------|---|
| A1 | 6475.069        |   |
| A2 | 5969.529        |   |
| A3 | 4078.947        |   |
| A4 | 2139.889        |   |
| A5 | 13421.053       |   |
| A6 | 19882.271       |   |
| A7 | 6.925           |   |
| A8 | 4099.723        |   |
| A9 | 4771.468        |   |

|   | Cavity perimeter |   |
|---|-----------------|---|
| A1 | 6475.069        |   |
| A2 | 5969.529        |   |
| A3 | 4078.947        |   |
| A4 | 2139.889        |   |
| A5 | 13421.053       |   |
| A6 | 19882.271       |   |
| A7 | 6.925           |   |
| A8 | 4099.723        |   |
| A9 | 4771.468        |   |
Table 6. Micro-cracks locating inside the adhesive layer.

| Notation | Description | Results (μm) |
|----------|-------------|--------------|
| A1       | Micro-crack | 803.589      |
| A2       | Micro-crack | 1175.196     |
| A3       | Micro-crack | 1404.791     |
| L1       | Micro-crack | 1803.004     |
| L2       | Micro-crack | 2252.046     |
| L3       | Micro-crack | 2318.382     |
| L4       | Micro-crack | 2376.999     |
| L5       | Micro-crack | 2261.137     |
| L6       | Micro-crack | 1801.797     |
| L7       | Micro-crack | 1090.63      |
| L8       | Micro-crack | 721.478      |

4. Conclusions

This paper presents some of the essential features related to the failure modes of the adhesively bonded joints between GFRP composite pultruded elements. Based on the microscopic study of the failure surfaces and image processing approach, the following conclusion can be drawn:

The GFRP adhesively bonded joints failed, in most of the cases, by fibre-tearing in the outer region of the exterior mat layers at approximately 0.5 - 1.5 mm from the profile surface. This failure mechanism was exhibited for both types of bond configuration (SLJ and TAJ), regardless of the values of the geometry variable parameters (adhesive layer length and thickness). Furthermore, no significant changes of the failure modes were recorded with respect to the elastic properties of the adhesive. The failure surfaces were characterised by multiple regions where the reinforcing fibres were extruded from their matrix cover. Also, a significant concentration of micro-cracks, ranging from 0.2 mm to 1.2 mm, was observed near the fibre-matrix separation areas.

Failure by de-bonding was observed only on relatively small areas for 2 of the 30 specimens. Therefore, it can be concluded that the surface treatment method that was applied to the GFRP composite pultruded elements is efficient and provides considerable bond at the interface level. However, the small surface areas where de-bonding failure occurred were characterized by a highly irregular topographic profile. The later consist in both micro-cracks concentrations ranging from 0.4 mm to 1.6 mm and isolated cavities with average perimeters ranging from 2 mm to 6 mm.

The cohesive failures were developed as a subsidiary mechanism to the dominant failure mode (fibre-tear failure) in case of 11 specimens. The cohesive failure regions are characterised by several failure planes, each of them developing micro-cracks of 0.7 to 2 mm in length and small cavities in the adhesive layer. Also, no fibres were observed on the cohesive failure areas. Since the cohesive failure mechanism is considered to be the optimum failure mode of adhesively bonded joints, the main concern related to FRP adhesively bonded connections should consist in avoiding the premature de-bonding so that the failure be controlled by the shear strength of the adhesive and not by the inferior tensile strength of the exterior mat layers of the composite elements. Several improvements can be made to GFRP adhesively bonded joints, such as securing the bonds with mechanical fasteners or using multiple types of adhesives, with different elastic properties.

5. References

[1] Țăranu N, Oprișan G, Isopescu D-N, Ențuc I, Munteanu V and Banu C 2008 Bulletin of Polytechnic Institute of Jassy 54 7-20
[2] Ascione L, Caron J-F, Godonou P, van Ijselmujiden K, Knippers J, Mottram T, Oppe M, Gantriis Sorensen M, Taby J and Tromp L *Prospect for new guidance in the design of FRP: EUR 27666 EN* doi 10.2788/22306

[3] Heshmati M, Haghani R and Al-Emrani M 2015 *Composites Part B* 81 259-75

[4] Ascione F 2009 *Composites Part B: Engineering* 40 116-24

[5] Ascione F, Feo L, Lamberti M and Penna R 2017 *Composites Structures* 176 702-14

[6] Ungureanu D, Ţăranu N, Lupășteanu V, Mihai P and Hudișteanu I 2016 *Bulletin of the Polytechnic Institute of Jassy* 62 29-41

[7] Ascione F, Lamberti M, Razaqpur AG and Spadea S 2017 *Composite Structures* 160 1248-57

[8] Fiberline design manual, Flat profiles, plates and sheets 2012

[9] Valle T and Keller 2006 *Composites Part B: Engineering* 37 328-36

[10] Valle T, Keller T, Foureste G, Fournier B and Correia J R 2009 *Probabilistic Engineering Mechanics* 24 358-66

[11] Sikadur 30, Product data sheet, Identification no: 02040104001000001, 2014, UK

[12] Ungureanu D, Ţăranu N, Lupășteanu V, Roșu AR and Mihai P 2016 *Bulletin of the Polytechnic Institute of Jassy* 62 37-45

[13] Lupășteanu V, Ţăranu N, Mihai P, Oprișan G, Lupășteanu R and Ungureanu D 2016 *Rev Rom Mat* 46 515-522

[14] Ungureanu D, Ţăranu N, Isopescu DN, Lupășteanu V, Mihai P and Hudișteanu I 2017 *Rev Rom Mat* 47 252-266

[15] ASTM B276 – 05 2015 Standard test method for apparent porosity in cemented carbides.

[16] ASTM D5573 – 99 2012 Standard practice for classifying failure modes in fiber reinforced plastic (FRP) joints

[17] Budhe S, Banea MD, de Barros S, da Silva LFM 2017 *International journal of adhesion and adhesives* 72 30-42