International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 03 Mar. 2025, pp: 300-310 www.ijaem.net ISSN: 2395-5252

Experimental and Numerical Model of Load-Bearing Capacity of GFRP Beams with Polyurethane Foam Filling

Aleksandar Jurić[1], Tihomir Štefić[2]
[1]Associate Professor, Kakatiya University of J.J.Strossmayer in Osijek, Faculty of Civil Engineering and Architecture Osijek, Osijek, Croatia
[2]Tihomir Štefić,NOVOprojekt Ltd., Osijek, Croatia.
Corresponding Author: Tihomir Štefić

Date of Submission: 10-03-2025 Date of Acceptance: 20-03-2025

ABSTRACT: Recently in the world the use of fibre-reinforced composites, FRP, has been steadily increasing. Glass fibres are most often used as polymer reinforcement, which is GFRP. Most common ap-plication of GFRP in constructions is as an addition or replacement of steel reinforcement in reinforced concrete. In this manuscript, the bearing capacity analysis was conducted through an experimental and a numerical calculation of a GFRP beam model filled with polyurethane foam, PUF. Application of polyurethane foam is very common in construction, most often as a material for sealing, filling various cavities and insulation. The results of the experimental load-bearing test of the beam model with PUF filling, showed in the force/displacement diagram and were com-pared with the results of the load-bearing test of the beam model without filling. The comparison results are shown in the dimensionless diagram. The nonlinear numerical model confirmed the experimental results. Material properties used in the nonlinear numerical model were obtained by experimental testing of samples. The results of numerical testing are presented through deformations and tensile stresses in the middle of the span.

KEYWORDS: Composites; GFRP; Experiment; polyurethane foam; PUF; Dimensionless Diagrams; Deformations; Tensile Stress.

I. INTRODUCTION

Although they can be a combination of any number of different materials, most often composites consist of fibres that are stronger and transfer loads and a mouldable matrix. The matrix at the same time protects and joins the fibres or load-bearing elements. Since the material for making fibres is significantly better quality and more expensive, it is usually used in a much smaller proportion in the composite.

[1].Fibres in the composite can be placed in different directions, randomly and as a mesh, Figure 1, and differently placed fibres greatly affect the characteristics of the material such as the modulus of elasticity, shear modulus, strength in different directions and yield strength.

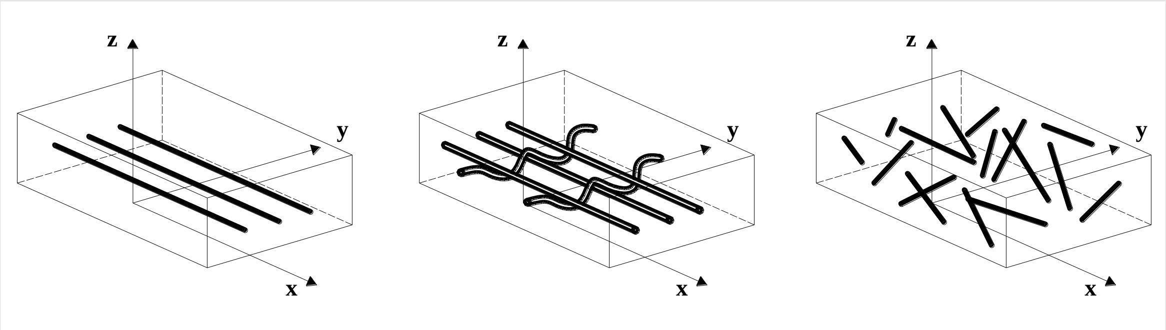

Figure 1. Different fibre layouts

The most commonly used matrices are polymer resins or unsaturated polyesters. A wide range of resin properties enables a wide selection of composite properties, depending on the selected matrix. Resins have a relatively favourable resistance to chemicals, low residual stresses and good ductility and strength. In fibre-reinforced polymer composites, the most common are glass-fibre reinforced polymers (GFRP).

[2,3,4].In addition to the fact that it is most often used as a supplement or replacement for steel in reinforced concrete beams, it is also often used as formwork for concrete columns and beams. It is often used in the rehabilitation of "classic" reinforced concrete structures. It completely replaces steel or reinforced concrete in different plateaus because of the reduced weight of the construction. It is characterized by greater resistance to corrosion, moisture, freezing and other aggressive environments, high tensile load capacity and low self-weight.

[5].It is also very often used in hydraulic engineering, such as inspection shafts, etc. Therefore, GFRP is generally characterized by high durability, which usually ranges between 15 and 20 years. In recent times, due to the increasingly massive application of GFRP in various areas such as auto industry, aviation industry, electric and electronic industry, as well as in the construction of wind power plants, a large amount of waste is generated after their life cycle. Because of this there are numerous studies on the utilization of waste GFRP materials. A very important characteristic is the ability to join (adhere) to materials such as steel, aluminium or concrete. Some of the disadvantages are sensitivity to delamination (mainly due to poor interaction between the fibres and the matrix), local load-bearing capacity, i.e., crumbling and crushing at places of concentrated loads and support, crack propagation along the fibres, as well as the possibility of residual stresses appearance during and after production.

[6,7,8].Local load-baring capacity is a very common problem, and the authors re-searched it in former studies.

In addition to being used in reinforced concrete structures, GFRP has recently been used as reinforcement and for the rehabilitation of structures made of other materials.

[9,10].Some authors dealt with the connection of GFRP and wood, and examined the connection with soft and hard wood, using steel connectors, as well as the modelling of knots and strengthening of defective parts of wood.

[11,12].Other authors investigated wooden beams reinforced with GFRP rods with bending load until failure, experimentally and numerically.

Some authors dealt with the strengthening of laminated glass using GFRP strips.

[13,14].They worked on a numerical model of the static load capacity of structural glass, i.e. glass beams glued with polyurethane and epoxy glue, as well as prestressed laminated plates reinforced with GFRP strips.

If we look at the use of polyurethane foam as a filling, the most common example of use is in sandwich panels, which are combined with GFRP, but also with other materials.

[15,16].Shear and other characteristics are investigated, when drilling or at four-point bending tests.

[17,18].The load-bearing capacity of sandwich panels in load-bearing elements of bridges is investigated depending on external influences or dynamic impacts.

[19].This research can be correlated with some previous research, related to the ex-amination of beam supports made of GFRP thin-walled multi-layer plates. This research is based on the examination of beam models reduced in size, with appropriate length and cross-section. The length of the beam model and the cross-section were chosen so that they represent the most common types of beams, prefabricated elements, ceiling/floor supports and similar. Since the application of polyurethane foams, PUF, is very common in construction, in this paper, through a experimental and a numerical model, the bearing capacity of beams made of multi-layered GFRP plates, filled with polyurethane foam, was analysed.

In order to present the workflow of this manuscript, a flowchart is shown in Figure 2.

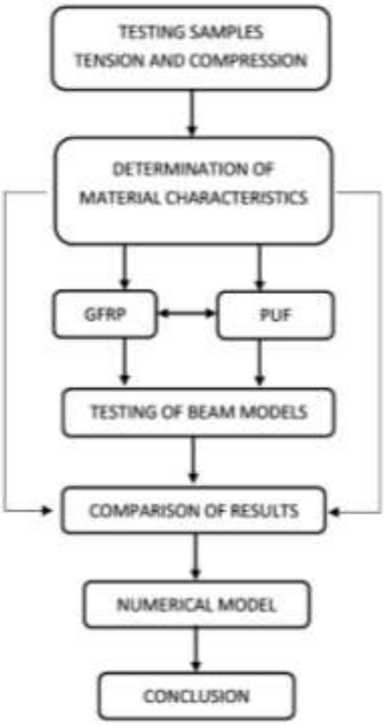

Figure 2. The flowchart of the research methodology

II. DETERMINATION OF MATERIAL CHARACTERISTICS

GFRP

For the purposes of the numerical model, it is necessary to define the characteristics of the material.

[20,21].The dimensions of the samples for determining the characteristics of the polymer material reinforced with glass fibres, GFRPcan be seen in Figure 3.

[22].The samples were tested for tension and compression on a Shimadzu testing device, and tests with the results were taken from literature.

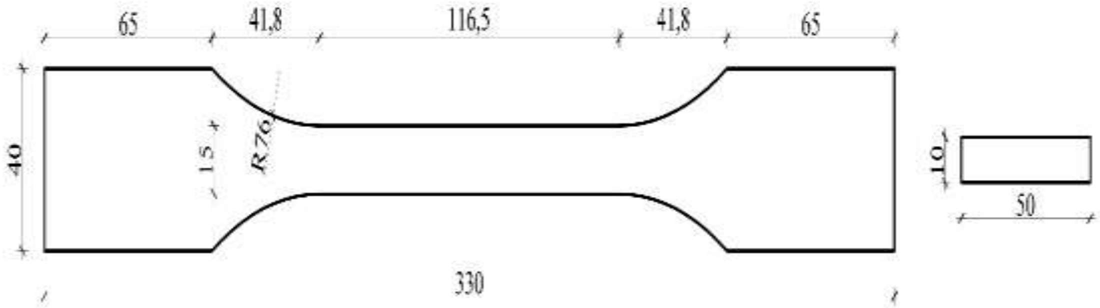

Figure 3. Testing samples dimensions

The obtained results, in the form of stress-strain diagrams, can be seen in Figures 4 and 5.

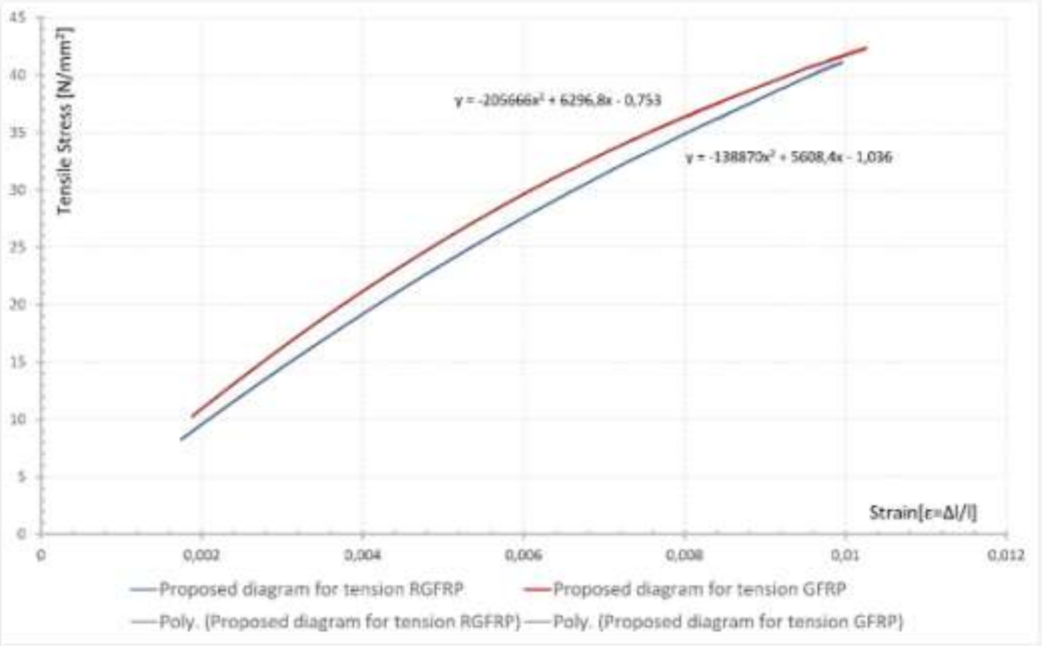

Figure 4. Stress-strain diagram for tension

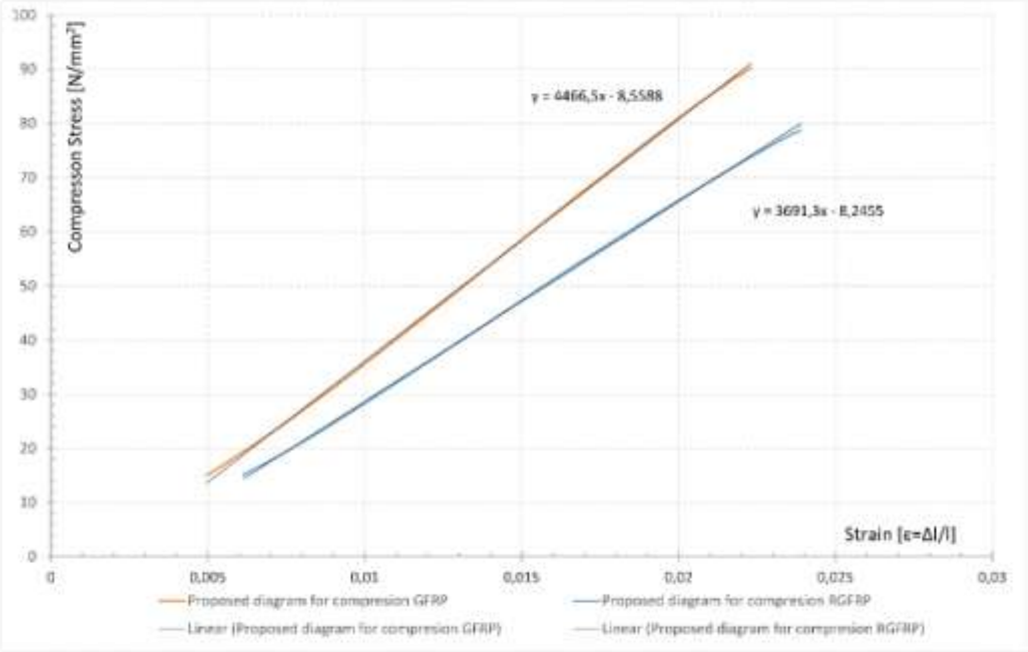

Figure 5. Stress-strain diagram for compression

The obtained characteristics of the material are expressed through the modulus of elasticity E and tensile and compressive strength, ft i fc.

[22].The following values were obtained for the tensile and compressive strength of GFRP: ft=40 N/mm^2, fc=100 N/mm^2, and the value of the modulus of elasticity is within the values of E=4000-4500 N/mm^2.

PUF

Polyurethane foam, PUF, is commonly used in construction as a sealant or connector used to join and seal various materials and elements made of wood, different types of masonry, reinforced concrete, plastic, etc. It is installed in a foamy liquid state, and in the air, it turns into a foamy solid state.

[23,24,25].Polyurethans are polymers that are formed by the re-action between the OH (hydroxyl) groups of a polyol with the NCO (isocyanate functional group) groups of an isocyanate, and the name is associated with the resulting urethane linkage. As it is also a polymer at its core, it supports bonding with GFRP. In this work, a simple, affordable and the least load-bearing polyurethane foam, usually used as a sealant, was used. Polyurethane foam has a density of approximately 25 kg/m3, and compressive and tensile strength of approximately 0,2 kPa.

III. THE SELECTED BEAM AND LOAD MODEL

[7].The beam model was chosen from previous researches, that in addition to numerical analysis also included experimental analysis, Figure 6.The actual force required in the application is need to move the engine valve along with spring that must be considered.

Figure 6. Testing beam model

Therefore, the dimensions and shapes of the cross-section resulted from methods and possibilities of manufacturing load-bearing beams from thin-walled GFRP plates, and were chosen according to the most common forms of load-bearing beams. A beam with a rectangular cross-section was chosen, produced from two U shaped parts, two identical halves that are joined during production. In this way, a joint most similar to the original material is achieved. The rectangular cross-section was chosen because these types of beams are dominantly loaded in direction of one axis while the other axis is under much smaller load. Ultimately, the goal of this manuscript is to examine the possibility of bind-ing GFRP with some other materials, in order to expand the application of GFRP materials and composite constructions made from GFRP and other materials. The beams were made as models of the most common beams with span of 5m and cross-sections of ap-proximately w/h=14/20cm in a scale of 1:5. This means that the models have a span of 1m and a cross-section of approximately w/h=3/4cm. The plate thickness is about 6 mm, which represents a plate thickness of approximately 3 cm. The connection of the two parts is made at a length of approximately 2 cm, which in nature represents approximately 10 cm. This is a sufficient length for achieving a proper connection and it makes it possible to insert any type of filling or a secondary load-bearing beam, as a complete load-bearing structure. The beams were tested by the 4BPT (four-point bending) method with a span of 90 cm. The distance of the support and the first force is 30 cm, and the distance between the two forces is 30 cm. For each sample, all the geometric characteristics of the cross-sections were measured and calculated. Forces are applied in the thirds of the span, in the order to achieve a condition on the girder where the middle third of the girder is loaded under pure bending. Figure 7 shows the load and boundary conditions scheme of the beam model.

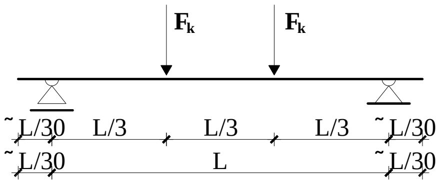

Figure 7. Load and boundary conditions scheme

In the beam model, hinged supports have been selected that enable rotation. The other support enables rotation and horizontal displacement. Figure 8 shows the inner forces on the beam model, which are symmetrically distributed considering the half of the span.

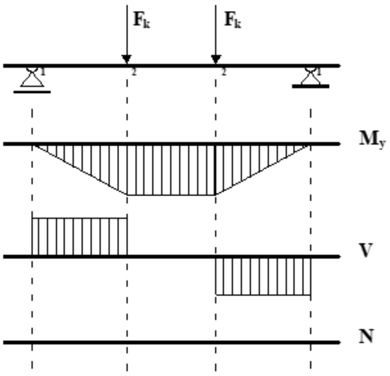

Figure 8. Inner forces on the beam model

IV. THE SELECTED BEAM AND LOAD MODEL

Figure 9 shows the testing of the beam model with and without PUF filling.

Figure 9. Testing of GFRP with and without PUF

Test results of the filled GFRP beam

In Figure 10, the force-displacement diagram shows the mode of yielding and failure of the three tested beams made of GFRP filled with PUF. Beam OPP1 shows almost completely elastic behaviour during the test (almost linear increase in the force/displacement curve). Beam OPP2 also shows a dominant linear behaviour, however, a significant difference in behaviour compared to the previous beam is visible in an earlier plastic collapse. This pronounced and long plastic behaviour can be attributed to the influence of the PUF filler in combination with the base material, immediately after failure. Beam OPP3 behaved mostly linearly with a very large plastic deformation after failure of the base material. It can be concluded that beam OPP3 behaved almost the same as beam OPP2, with a slightly earlier failure. On all models, deformation was observed at the places of concentrated loads, which indicates the need to increase the areas at the places of supports and loads.

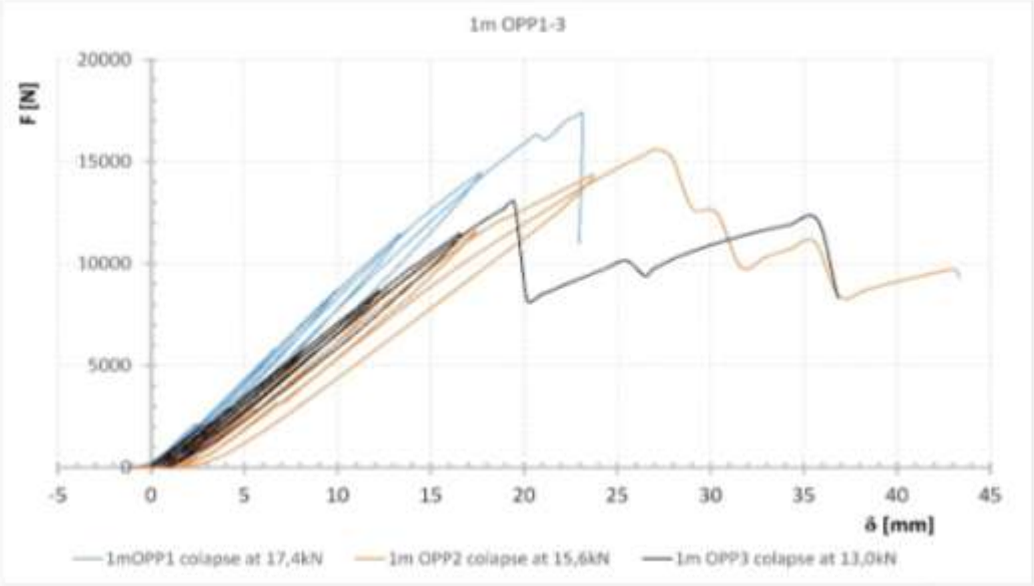

Figure 10. Diagrams of the testing of GFRP with PUF

Test results of the GFRP beam without PUF

In Figure 11, the force-displacement diagram shows the mode of yielding and failure of the three tested beams made of the original GFRP material without filling. Beam OS1 shows almost completely elastic behavior during the test (almost linear increase in the force/displacement curve). Beam OS2 also shows a dominant linear behavior, however, a significant difference in behavior compared to the previous beam is visible in two different slopes of the curve. Beam OS2 failed due to separation of the two halves of the cross-section on one side of the beam only. This continuous increase in load caused local failure. Beam OS3 behaved linearly with very little plastic deformation of about 2 mm, which occurred just before failure. The failure occurred as a result of bending moment stress.

[19].As with the filled models, the deformation at the places of concentrated loads was confirmed on all models.

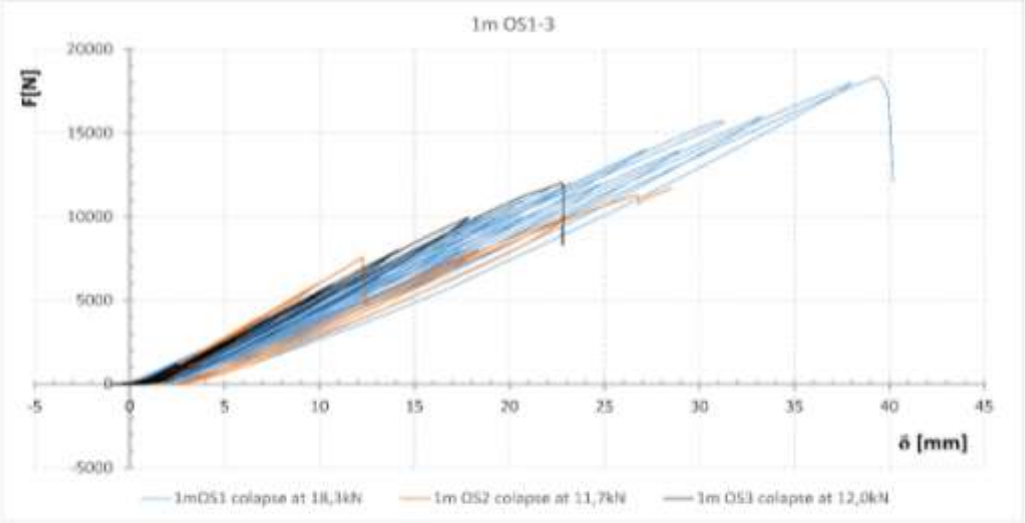

Figure 11. Diagrams of the testing of GFRP without PUF

V. COMPARISON OF RESULTS

The relationship between the bearing capacity of GFRP beams with and without filling is shown in the form of a dimensionless diagram, as shown in Figure 12. On the abscissa is the relationship between the deflection in the middle of the beam and the radius of inertia, and on the ordinate is the relationship between the force and breaking force of the GFRP beam without fillings. If the average failure values of three models are adopted, the load capacity of the GFRP beam model with PUF infill is about 8% higher than the load capacity of the GFRP beam without infill.

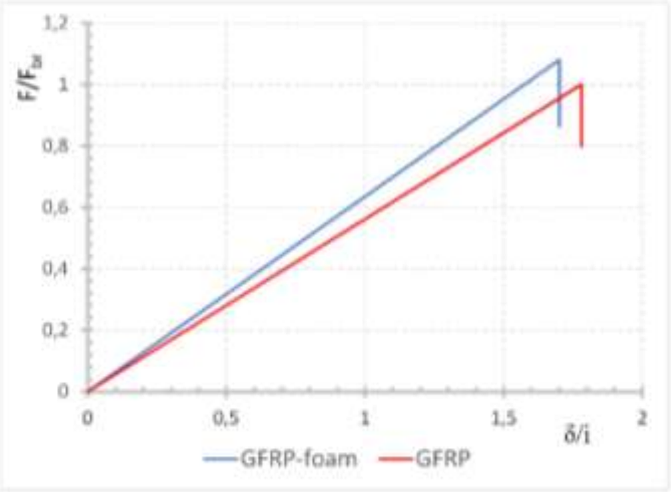

Figure 12. Comparison of dimensionless diagrams of GFRP with and without PUF

VI. NUMERICAL MODEL OF THE BEAM

Since these beams are composed of thin GFRP plates, shell elements were chosen for the beam model, and three-dimensional, "solid" elements were chosen for the polyurethane foam infill model. When defining the mesh density of the GFRP finite elements, the desired size of 1 cm was chosen for one element, rendering sufficient density and a relatively simple model, which gave satisfactory results.

In order to avoid unwanted kneading and grinding, due to load concentration and for more accurate simulation of the beam, the load was placed on an area of 1 x 4 cm, which is also the width of the upper flange. As the load is applied to two surfaces, this makes a total surface area of 8 cm^2. [26].Although the behaviour of this material is approximately linear, due to the aforementioned negative phenomena, a nonlinear model was selected in the software package. Figure 13 shows the FE mesh, as well as the load and support model for the filled and hollow model of the GFRP beam.

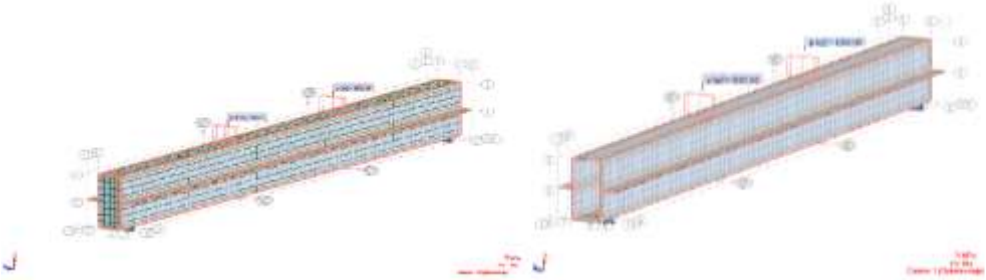

Figure 13. FE mesh and loads on the GFRP beam filled with PUR and without filling

In order to avoid unwanted local deformations, a total force of 1 kN distributed in two places of 4 cm2 was chosen for the static load, that is, each place was loaded with 1.25 kPa. The displacements of the beam are as expected, with the highest values in the mid-span, which can be seen in

Figure 14. The displacement in the mid-span is 2,150 mm.

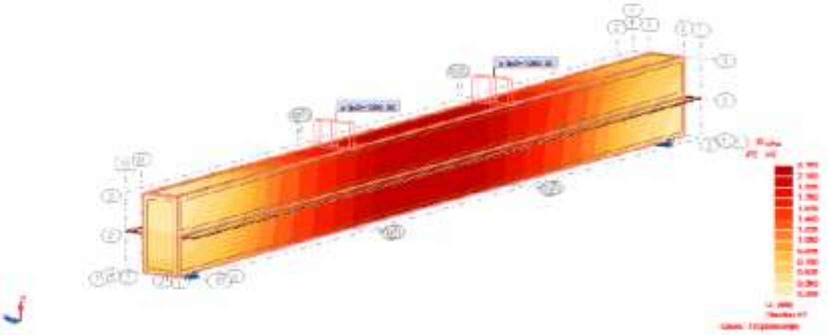

Figure 14. Displacements on the GFRP beam filled with PUR

For comparison, a GFRP beam model without filling was taken and loaded with the same load. The largest displacements were, as expected, in the middle of the beam, with the largest displacement measured at a value 2,290 mm. The displacements of the beam model without filling can be seen in Figure 15.

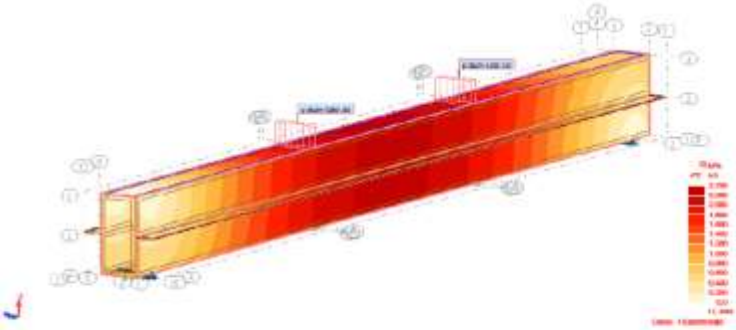

Figure 15. Displacements on the hollow GFRP beam

If the normal stresses in the tensile area within the GFRP material are observed, it can be seen that the measured stresses are ft=5.8837 kPa, as shown in Figure 16.

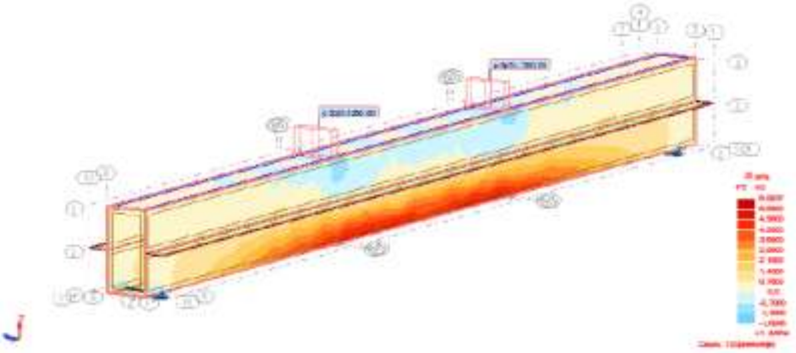

Figure 16. Tensile stresses on the GFRP beam filled with PUR

In comparison, if the normal stresses in the tensile area within the GFRP material of the unfilled beam model are observed, the measured stresses are found to be ft=5.9000 kPa, as shown in Figure 17.

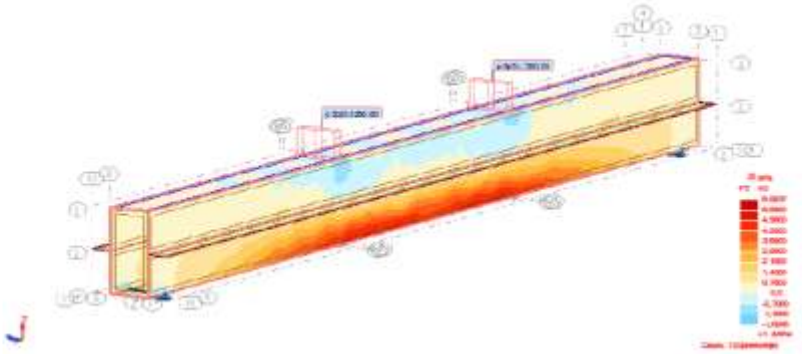

Figure 17. Tensile stresses on the hollow GFRP beam

VII. CONCLUSIONS

This test indicates one of the possibilities of applying thin-walled plate GFRP material in load-bearing structure elements.

The most common model of a beam with a rectangular section filled with infill was used.

Polyurethane foam, PUF, is used to fill GFRP beams, which is widely used in construction as a sealant, infill or insulation.

PUR is a type of polymer and has good bonding properties for all materials, and mostly for similar materials, such as GFRP.

Although this material has a very low load-bearing capacity, as a filling it contributes to a smaller part in the load-bearing capacity of the bent beams.

The results of the experimental test show that the total load capacity of the GFRP beam model with infill is greater by about 8% compared to the GFRP beam model without infill.

The results of the numerical model show that the vertical displacements of the GFRP beam model with infill are lower by about 6% compared to the GFRP beam model without infill.

Simultaneously, the tensile stresses in the base material, in the GFRP model with filling, are lower by about 0,3% compared to the GFRP model without filling.

Some authors, [17], have shown that when using approximately twice as dense filling, the load capacity increases approximately three times.

The influence of PUF filling on the load-bearing capacity of load-bearing GFRP elements with rectangular cross section is not great, but as it is a simple, acceptable and least load-bearing PUF, its choice for this purpose is justified.

REFERENCES

[1]. James C., Gerdeen; Harold W., Lord; Ronald A.L. Rorrer. Engineering Design with Polymers and Composites. (November 1, 2015). DOI: 10.1201/9781420056372.

[2]. Naser, Kabashi; Besart, Avdyli; Enes, Krasniqi; Arbër Këpuska. Comparative Approach to Flexural Behavior of Reinforced Beams with GFRP, CFRP, and Steel Bars. Civil Engineering Journal Vol. 6, No. 1 (January 2020): 50–59. DOI: 10.28991/cej-2020-03091452.

[3]. Amir, Reza; Tabkhi, Wayghan; Massood, Mofid; Behnam, Babaei, Ravandi; Seyed Morteza Zinati Yazdi. Increasing the Contribution of GFRP Bars on the Compressive Strength of Concrete Columns with Circular Cross Section. Civil Engineering Journal Vol. 5, No. 8 (August 2019): 1850–1862. DOI: 10.28991/cej-2019-03091377.

[4]. Tuna, Ülger; Ahmad Shayan Sharifi. Numerical Performance Analysis of Concrete-Filled Hollow GFRP Beams including Inner Surface Bearing Stresses at the Interface. Buildings 2022, 12, 1340. DOI: 10.3390/buildings12091340

[5]. [4] Aleksandar, Jurić; Tatjana, Svetinović; Držislav Vidaković. Use of fiberglass in sanitary hydrotechnics. Proceedings 17 of the PLIN 2019/10th International Natural Gas, Heat and Water Conference, ISSN 1849-0638. Crosbi ID: 1026035.

[6]. Junušić, S.; Štefić, T.; Jurić, A. (2014). Deformation in multilayer fiberglass beams at different positions of concentrated load. ElektroničkiČasopisGrađevinskogFakulteta Osijek, 27–36. doi:10.13167/2014.8.4.

[7]. Sanja, Junušić; Tihomir, Štefić; Aleksandar Jurić. Numerical model of local kneading of a glass fibre reinforced beam. e-GFOS (July 2016): 39–45. DOI: 10.13167/2016.12.5.

[8]. Tihomir, Štefić; Aleksandar, Jurić; Pavao Marović. Problem of stress concentration and deformation in the use of multilayer GFRP (Glass Fibre Reinforced Polymer) in bearing structures. 16th European

Conference on Composite Materials - ECCM16, Composite Materials: The Future/Paris, Federico (ur.). Seville: University of Seville, ESM Group, 2014. str. 1235/1-1235/7 (ISBN 978-84-616-9798-4), Crosbi ID: 704516.

[9]. Marco, Corradi, Thuc P. Vo, Keerthan, Poologanathan; Adelaja, Israel, Osofero. Flexural behaviour of hardwood and softwood beams with mechanically connected GFRP plates, Composite Structures, Volume 206, 15 December 2018, Pages 610-620, DOI: 10.1016/j.compstruct.2018.08.056.

[10]. Khaled, Saad; András, Lengyel. Strengthening Timber Structural Members with CFRP and GFRP: A State-of-the-Art Review. Polymers 2022, 14(12), 2381, DOI:/10.3390/polym14122381.

[11]. Chris, Gentile; Dagmar, Svecova; Sami, H. Rizkalla. Timber Beams Strengthened with GFRP Bars: Development and Applications. Journal of Composites for Construction, DOI: 10.1061/(ASCE)1090-0268(2002)6:1(11)

[12]. Satheeskumar, Navaratnam, Deighton, Widdowfield, Small, Marco, Corradi, Perampalam, Gatheeshgar, Keerthan, Poologanathan; Craig, Higgins. Numerical Modelling of Timber Beams with GFRP Pultruded Reinforcement. Buildings 2022, 12, 1992. DOI: 10.3390/buildings12111992.

[13]. Jorge, Rocha, Eduardo, Pereira, José, Sena-Cruz, Luís, Valarinho; João, Ramôa, Correia. Numerical simulation of GFRP-reinforced glass structural elements under monotonic loading. Engineering Structures, Volume 234, 1 May 2021, 111968, DOI: 10.1016/j.engstruct.2021.111968.

[14]. Chiara, Bedon; Christian, Louter. Numerical analysis of glass-FRP post-tensioned beams – Review and assessment. Composite Structures, Volume 177, 1 October 2017, Pages 129-140, doi: 10.1016/j.compstruct.2017.06.060.

[15]. K.N. Kaushal, L. Sunith, Babu; Rajesh, Mathivanan. Study on drilling parameters of GFRP-PUF sandwich composites. Materials Today: Proceedings, Volume 5, Issue 11, Part 3, 2018, Pages 24439-24447, DOI: 10.1016/j.matpr.2018.10.240.

[16]. M.A. Mohamed, Aqhil, Ahmed; M. Safiulla. Evaluation of apparent shear modulus of multilayer PUF cored sandwich beams using novel experimental technique, Materials Today: Proceedings, Volume 5, Issue 1, 2018, DOI: 10.1016/j.matpr.2017.11.102.

[17]. Tayyab, Khan, Volkan, Acar, M. Raci, Aydin, Burak, Hülagü, Hamit, Akbulut; M. Özgür, Seydibeyoğlu. A review on recent advances in sandwich structures based on polyurethane foam cores. Polimercomposytes, Volume41, Issue6, June 2020, Pages 2355-2400, DOI: org/10.1002/pc.25543.

[18]. Hesham, Tuwair, Jeffery, Volz, Mohamed, ElGawady, Mohaned, Mohamed, K. Chandrashekhara; Victor Birman. Behavior of GFRP bridge deck panels infilled with polyurethane foam under various environmental exposure. Structures, Volume 5, February 2016, Pages 141-151, DOI: 10.1016/j.istruc.2015.10.008.

[19]. Aleksandar, Jurić; Tihomir, Štefić. Experimental Comparison of the Bearing Capacity of GFRP Beams and 50% Recycled GFRP Beams, Civil Engineering Journal, (E-ISSN: 2476-3055; ISSN: 2676-6957), Vol. 8, No. 12, December, 2022, DOI: 10.28991/CEJ-2022-08-12-017.

[20]. ASTM D3039/D3039-08. (2014). Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. ASTM International, Pennsylvania, United States. doi:10.1520/D3039_D3039M-08.

[21]. ASTM D3410/D3410M-16e1. (2021). Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading. ASTM International, Pennsylvania, United States. doi:10.1520/D3410_D3410-16E01.

[22]. Tihomir, Štefić; Aleksandar, Jurić; Pavao Marović. Determination of modulus of elasticity for glass fibre reinforced polymers. Technical Gazette (January-March 2011): Vol. 18, No. 1 (2011): 69-72. Crosbi ID:

[23]. Ashida, K. Polyurethane. Related Foams Chemistry and Technology; Taylor & Francis Group: Boca Raton, FL, USA, 2007. [Google Scholar]

[24]. Szycher, M. Szycher’s Handbook of Polyurethanes, 2nd ed.; CRC Press: New York, NY, USA, 2006. [Google Scholar]

[25]. Król, P. Linear Polyurethanes: Synthesis Methods, Chemical Structures, Properties and Applications; VSP: Leiden, The Netherlands, 2008. [Google Scholar]

[26]. Autodesk® RobotTM Structural Analysis Professional (RSAPRO) 2016, Version 29.0.0.5650 (x64), Autodesk, Inc., 2015.