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Experimental Comparison of the Bearing Capacity of GFRP Beams and 50% Recycled GFRP Beams

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Abstract

This manuscript investigates the possibility of using recycled glass fiber-reinforced polymer for the production of load-bearing elements in construction. Due to the increasing use of GFRP in the world, an increasing amount of waste is generated. The main objective of this research is to expand the use of composite materials in construction and, in particular, to examine the possibilities of original and recycled GFRP. Firstly, the basic characteristics of two different but very similar materials were determined using standard testing samples. Subsequently, experimental beam models were tested as a four-point bending beam model. The beam models used in this experiment were made of two types of materials, glass fiber reinforced polymer (GFRP) and recycled glass fiber-reinforced polymer (RGFRP). The experiments were conducted until the failure of the beam models. The test results are presented in the form of a force/displacement diagram, and the confirmation of the experimental results is shown by means of a numerical model of the beam. Both materials exhibited a very good strength-to-weight ratio, rendering them a suitable choice of material for load-bearing beam elements. Finally, the justification for recycling and the comparison of original and recycled material are presented in a dimensionless diagram. The comparison of these two materials provides some good insights for future research into GFRP beams.

Keywords: Load-bearing Elements; Glass Fiber Reinforced Polymer; Recycling; Dimensionless Diagrams.

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1. Introduction

Composites are materials reinforced with certain other materials to improve their mechanical properties, the most common being polymers reinforced with glass fiber, GFRP, shaped in the form of thin plates. Fibers are most commonly arranged in layers and lamellas, the orientation and arrangement of which can be different [1], as shown in Figure 1. The advantage of using polymers reinforced with glass fibers is primarily related to the reduced weight of the structure and a higher resistance to moisture, aggressive liquids, corrosion, and freezing. One very important characteristic is the ability to create a good connection (good adhesion ability) with materials such as steel, aluminum, or concrete. Due to these advantages, GFRP is most commonly used in civil engineering as a replacement for steel reinforcement in reinforced concrete structures, for structural rehabilitations, and for the post-strengthening of elements [2, 3]. Its most common use is in retrofitting reinforced concrete columns by wrapping the columns or as primary and/or secondary reinforcement [4, 5]. Due to its resistance to external influences and the greater need for fluid transportation, it is also often used in hydraulic engineering, e.g., in inspection shafts, pipelines, etc. [6, 7].

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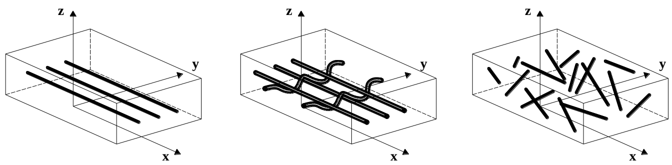


Figure 1. Different fiber layouts

The life cycle of any material, which also applies to GFRP, is important for its application, including in construction. The life cycle is extended, and through the use of recycled materials, building costs can be reduced by 30–35%. Following certain recycling processes, the recycled material has better mechanical characteristics than the original material [8]. Due to the influence of static and dynamic loads, water, climatic influences, and an aggressive environment, the lifetime of products made from GFRP is around 15–20 years. This results in a large amount of GFRP waste. Estimates indicate that there will be almost 700 thousand tons of waste in 2025. Most of this waste will come from building and construction, electrical parts and electronics, transportation, marine projects, wind turbines, aeronautics, and production [9, 10]. If we observe the ways of recycling GFRP material by considering the aspects of energy consumption and process cost, the most favorable technology is mechanical grinding [11]. Many researchers are proposing the use of mechanically produced recycled material as a substitute for aggregate in concrete [12–14]. Other researchers have examined the compressive strength of concrete by comparison with the percentage of recycled GFRP material used as aggregate. In relation to a percentage of 30 to 100%, the compressive strength declines from 56 to 85% [14]. Some researchers have compared the bearing capacity of thin-plated GFRP samples with different percentages of glass fibers ranging from 20%, 35%, and 50% of the volume [15]. Some researchers compared the load capacity of polyester samples with the addition of 10, 15, and 20% recycled GFRP [16]. It can be concluded that there is a considerable drawback regarding the use of recycled GFRP material in the production of multilayered thin plate elements, which was the primary motive for this research.

As most products made from GFRP are produced as multilayer thin plates, this is a valuable source of material for recycling. For the same reasons, in this manuscript, we compared beams produced from 50% of recycled GFRP material in the form of thin, multilayered plates (RGFRP). During the recycling process, the multi-layer plate polymer, reinforced with glass fibers are ground with 4 mm diameter blades, which produces particles with a small diameter of up to 2 mm. This process yields up to 50% of the raw material for the new recycled material, while for the remaining 50%, the original polyester resin and glass fibers are used. The original material (GFRP), from which the recycled material (RGFRP) was produced, was made from 2/3 of the mass of polyester resin and from 1/3 of the mass of glass fibers. As the recycled material (ground from GFRP) is re-mixed with the resin, the final characteristics of the recycled composite can be influenced in the same way as the original material. The smaller the size of the particles, the more similar the recycled material is to the original, that is, the larger they are, the more limitations in the use of new glass fibers. Recycled material, mixed with new resin, can behave as an additional micro reinforcement. It also has a more compact structure, behaves almost completely elastically and is more resistant to external influences. Its flaws are that it has around a 15% higher mass than the original material and a smaller load-bearing capacity.

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

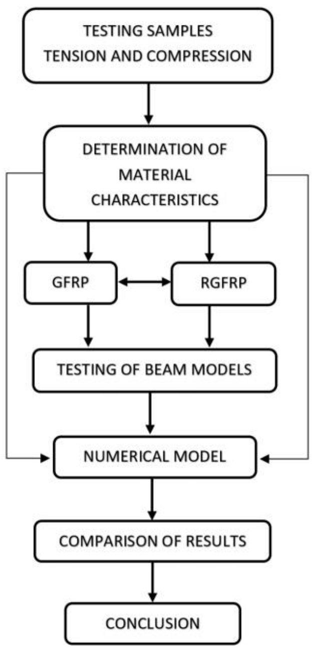


Figure 2. The flowchart of the research methodology

2. Material Characteristics: Determination and Dimensions of the Tested Samples

Samples for determining the material characteristics of the original GFRP and RGFRP were tested at tension and compression with a Shimadzu device, as shown in Figure 3, and the dimensions of the samples [17, 18] can be seen in Figure 4. These tests were carried out by the authors during previous research [19]. The test results can be seen in Figure 5. The testing of certain material characteristics of GFRP and RGFRP were carried out in a previous study [20].

Figure 3. Testing of the samples

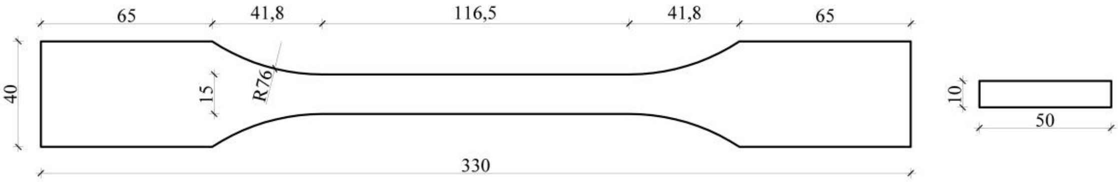
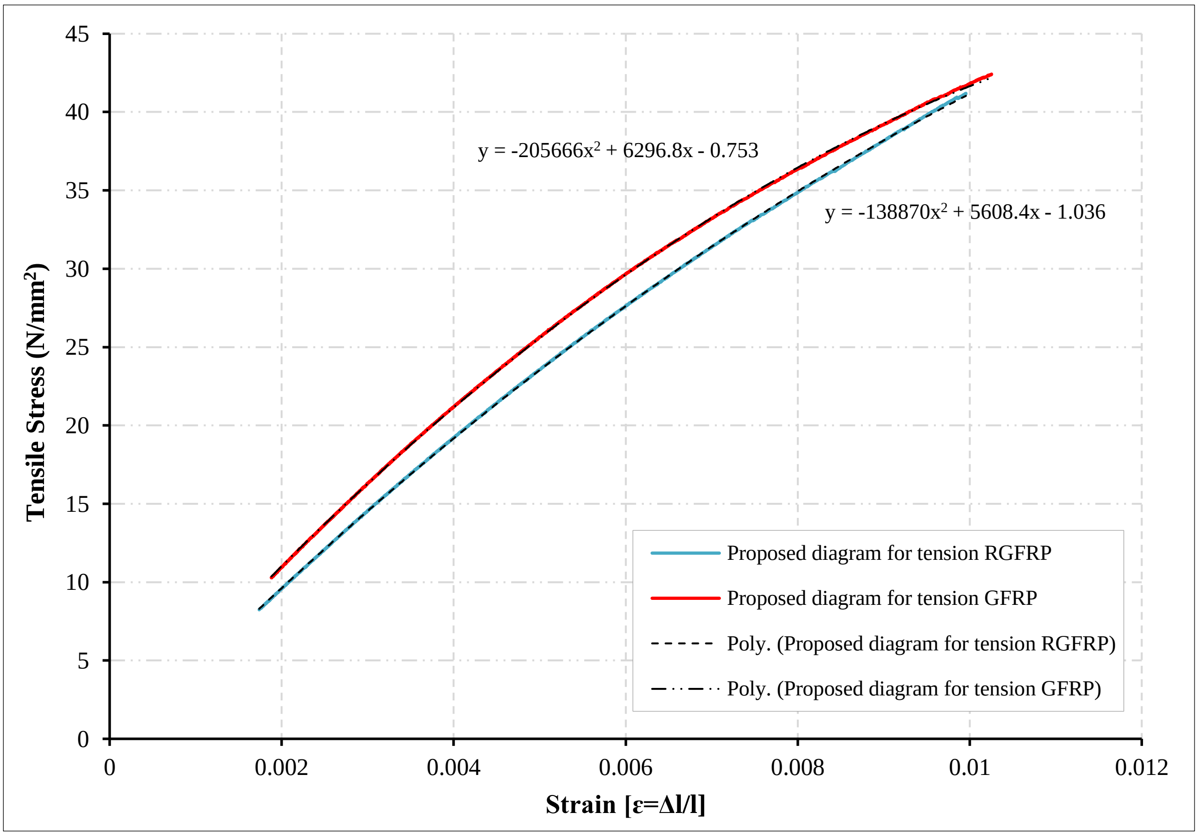


Figure 4. Dimensions of the testing samples



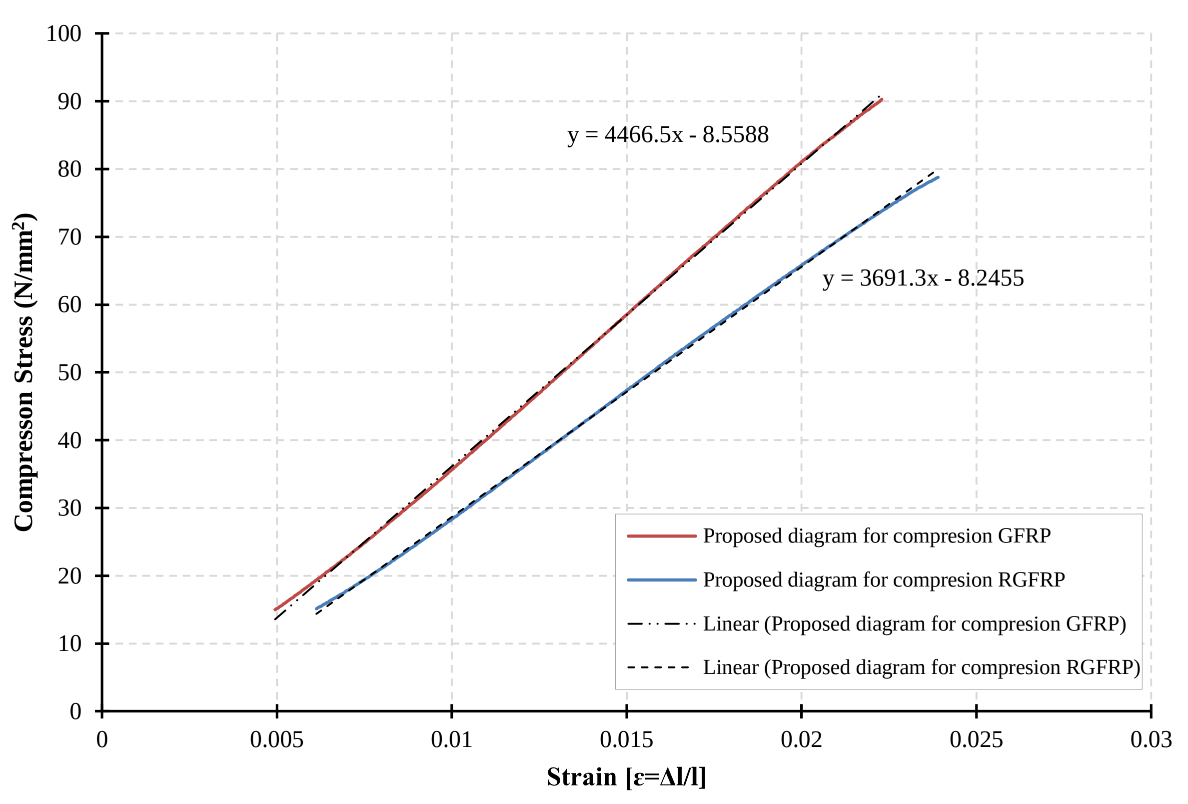


Figure 5. Average stress/strain diagrams for tension and compression

The obtained characteristics of the materials are presented through the modulus of elasticity, E and strength in tension and compression, f_t and f_c, and can be used in additional numerical research. For the tensile and compressive strength of the original polymer, reinforced with glass fibers, the approximate values of GFRP were: f_t=40 N/mm^2, f_c=100 N/mm^2 and the value of the modulus of elasticity was E=4000-4500 N/mm^2 [19]. For the tensile and compressive strength of recycled polymer reinforced with glass fibers, the approximate values of RGFRP were: f_t=32 N/mm^2, f_c=80 N/mm^2 and the value of the modulus of elasticity was E=3700-3900 N/mm^2 [19].

3. Testing of the Beams

The beams were produced by gluing two U-shaped profiles, which were chosen so that they could easily fit into the most common bearing elements, such as beams, prefabricated elements, ceiling or floor beams, or similar, as shown in Figure 6. The most important reason for choosing this cross-sectional shape relates to production limitations. The test is based on a beam model that represents an approximate ratio of 1:5 in relation to the most common span of L=5 m and cross-sectional dimensions of b/h=14/20. This means that the experimental models have an approximate span of 1 m and a cross-section of around w/h=3.5–4/6.5-8 cm. The thickness of the wall is in the range of t=4-7 mm, and the connection of the two parts of the cross section is made along the span of the beam with a width of around x=2-2.5 cm. In this way, it is possible to place any kind of filling or certain secondary beams on the main beam to make the floor or ceiling structure complete. All the geometric characteristics of the cross sections were measured and calculated for each sample.

Figure 6. Testing beam samples from GFRP and RGFRP

In order to acquire more reliable results, three almost identical beams were tested. They were tested using the 4BPT method with a clear span of 90 cm. The distance from the support to the first force was 30 cm and the distance between the forces was 30 cm. This achieved force input across 1/3 of the range, which places a sufficient part of the beam under the influence of pure bending moment, as shown in Figures 7 and 8. All hollow beams made of GFRP and RGFRP were loaded with a force increase of 100 N/s during loading and a force decrease of 250 N/s during unloading, which represents the intensity of deformation change from around 11-13 mm/min; therefore, the testing lasted for around 10 minutes. The GFRP beams were named OS1, OS2 and OS3, and the recycled beams (RGFRP) RS1, RS2 and RS3.

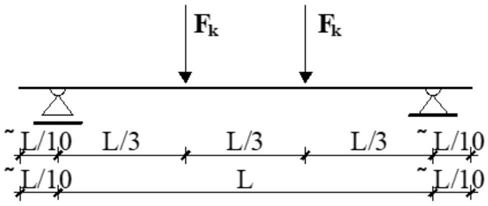


Figure 7. Testing beam model

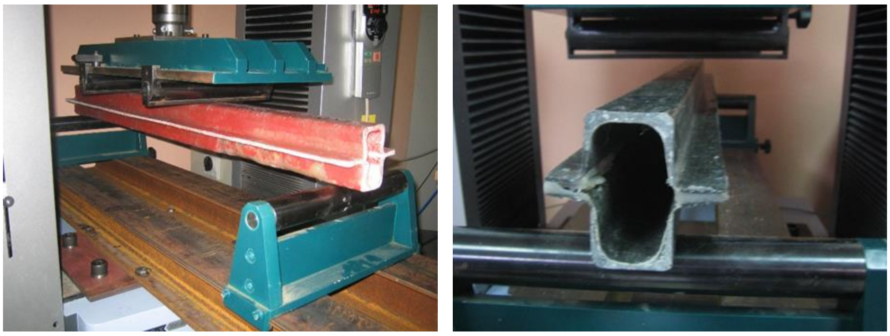


Figure 8. The testing of GFRP and RGFRP beams

4. Results

4.1. Test Results of the Original GFRP Beams

In Figure 9, the force-displacement diagram shows the manner of yielding and failure of the three tested beams made from the original material, GFRP. The OS1 beam exhibits an almost completely elastic behavior during testing (an almost linear increase in the force/displacement curve). The OS2 beam also shows a dominantly linear behavior, however, a significant difference in behavior from the previous beam is visible in the two different slopes of the curve. The OS2 beam failed through the separation of the two halves of the cross section on only one side of the beam. This continued increase of load caused a local failure. Beam OS3 behaved linearly with very few plastic deformations at around 2 mm, which occurred just prior to failure. The failure occurred as a result of bending moment stress. On all models, deformation was confirmed at the sites of concentrated loads, which indicates the need to increase the areas at the sites of supports and loads.

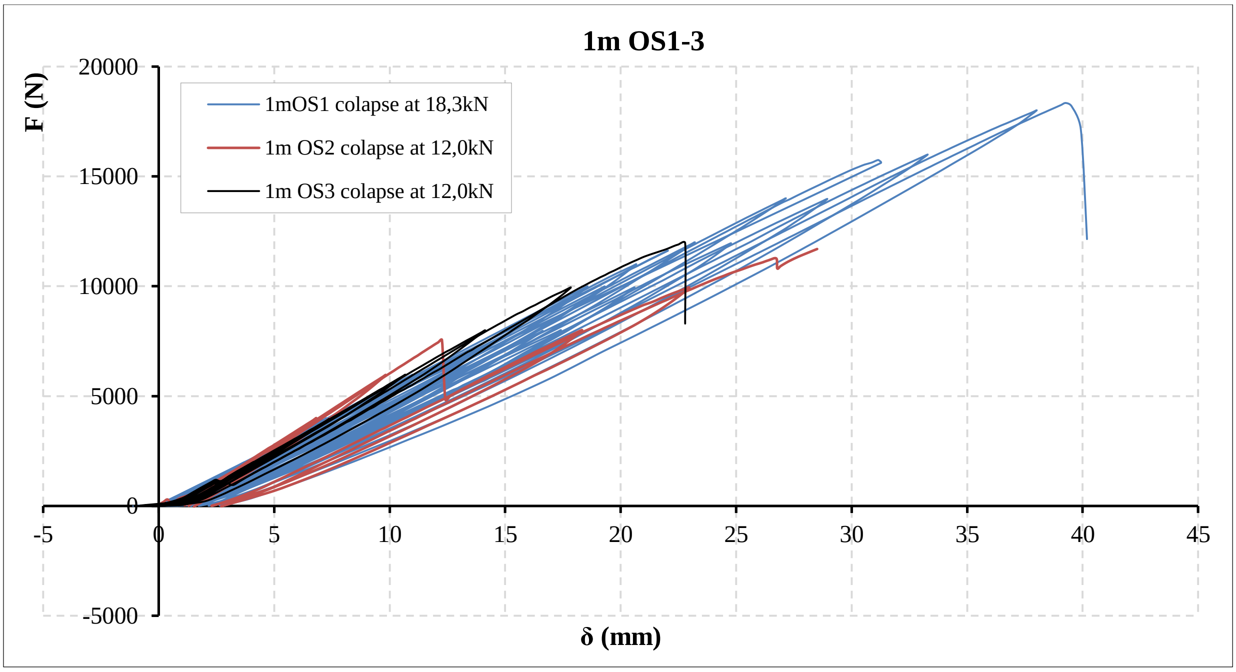


Figure 9. Diagrams of the testing of GFRP beams

4.2. Test Results of the RGFRP Beams

Figure 10, a force-displacement diagram, shows the manner of yielding and failure of the three tested beams, produced from the material which was made from the original, recycled material, RGFRP. The RS1 beam yielded following relatively short elastic behavior, with a brittle fracture in the tensile zone of the lower flange; the fracture or crack widened at the connection of the two halves of the section. At a force of around 75% of the breaking force, the RS2 beam exhibited the site where the failure begins to occur, with a different slope of the curve. Similar to beam RS1, a brittle fracture occurred after a short elastic region. The RS3 beam revealed similar characteristics to the previous two beams of the same type. On all three beams, the proportion of plastic deformation was almost negligible. After an almost brittle failure of the lower flange, loading continued. Although the applied forces were roughly half the value, the loading continued, which caused a separation of the cross-section halves and the failure of the beam.

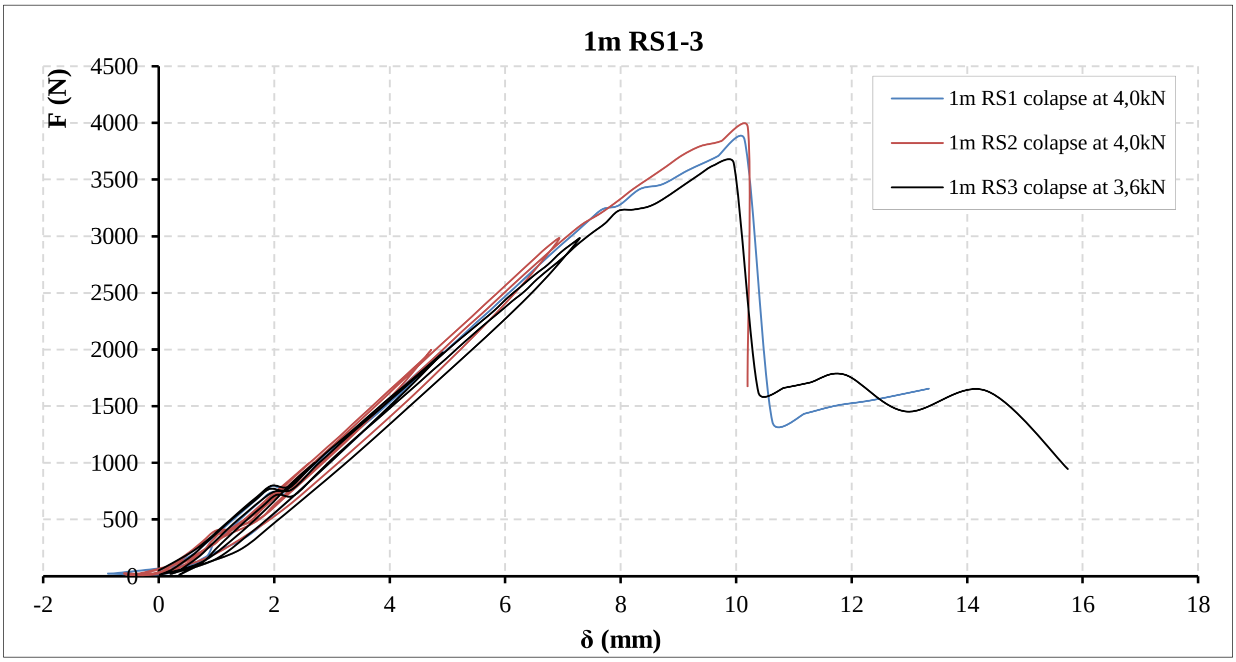


Figure 10. Diagrams from the testing of RGFRP beams

5. Numerical Model of the Beam

In order to compare and confirm the obtained experimental results, a beam was modeled using the same scale as in the experiment. As the behavior of the beam is mostly linear, the linear model in the software package [20] was chosen. Figure 11 shows the diagram of loads and inner forces.

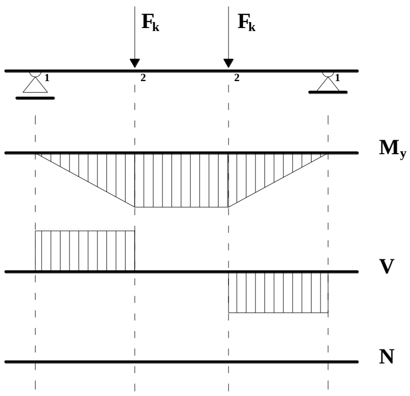


Figure 11. Scheme of loads and inner forces

When defining the density of the mesh of finite elements, the desired size of 1 cm for one element was chosen, which achieved sufficient density and a relatively simple model that provided satisfactory results. Since in nature these beams are composed of GFRP plates, shell elements were chosen for the beam model. In order to avoid undesirable phenomena, due to load concentration and to more accurately simulate the beam, the load was applied to an area 1 x 4 cm, which is also the width of the upper flange. As the load is applied to the two surfaces, this makes a total surface area of 8 cm^2. For easier comparison with the experimental models, the total applied load for the models of both materials was 1 kN; the mesh of finite elements and loads can be seen in Figure 12.

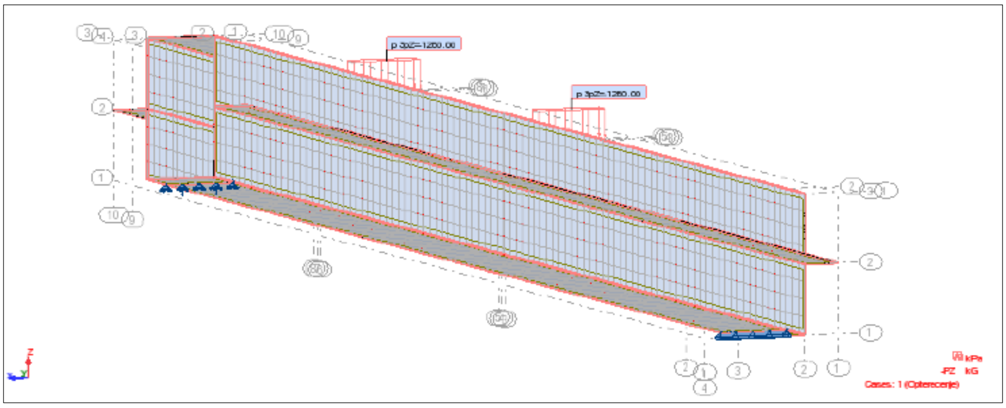


Figure 12. Mesh of finite elements and loads

5.1. Results of the Analysis of the Original GFRP Beams

The beam displacements are as expected, with the highest values in the middle of the span, as seen in Figure 13. Regarding the aforementioned load, the displacement in the middle of the span is 2.322 mm. For the same total load of 1 kN, the measured displacement of the experimental beam model, made from the original GFRP, has an average value of around 2.105 mm. The values of deformation from the numerical model coincide to a high percentage with the values from the experiment.

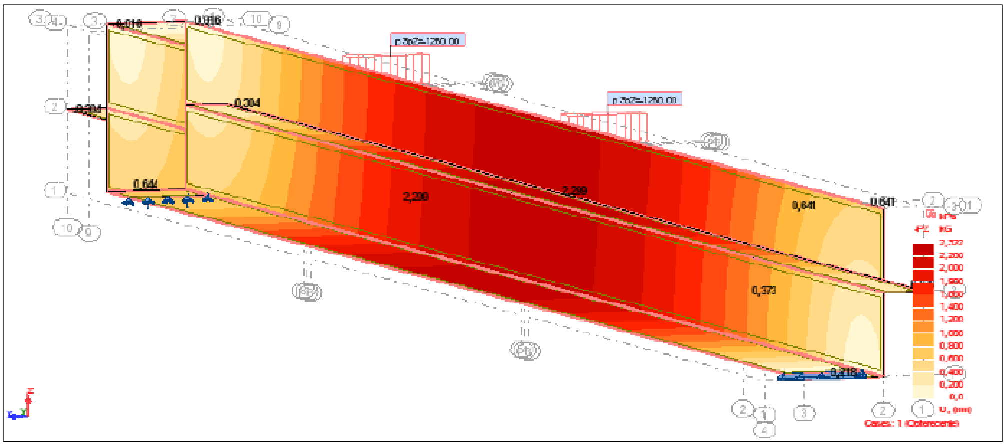


Figure 13. Displacements on the GFRP beam

5.2. Test Results of the RGFRP Beams

As with the original GFRP, beam displacements are as expected and exhibit the greatest values at the mid-span point, as seen in Figure 14. At the aforementioned load of 1 kN, the measured displacement at the mid-span point is 2.633 mm. For the same total load of 1 kN, the measured displacement of the experimental beam model made from recycled polymer reinforced with glass fibers, RGFRP, has an average value of around 2.230 mm. As with the original material, the values of deformation from the numerical model coincide to a high percentage with the values from the experiment.

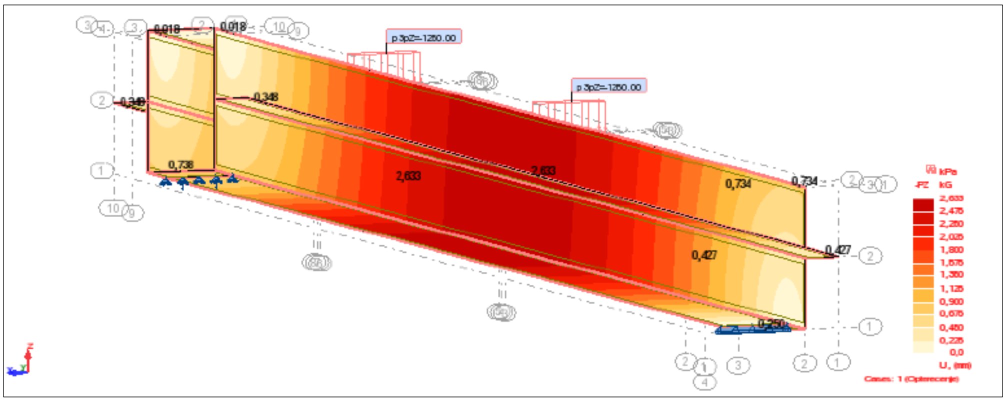


Figure 14. Displacements on the RGFRP beam

6. Comparison of Results

The relationship between the bearing capacities of the GFRP and RGFRP beams is shown in the form of a dimensionless diagram, as demonstrated in Figure 15. 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 the breaking force of the original GFRP. The RGFRP beam models show good material characteristics and a favorable load-bearing curve but have a lower total load capacity compared to the original GFRP beams of around 33%.

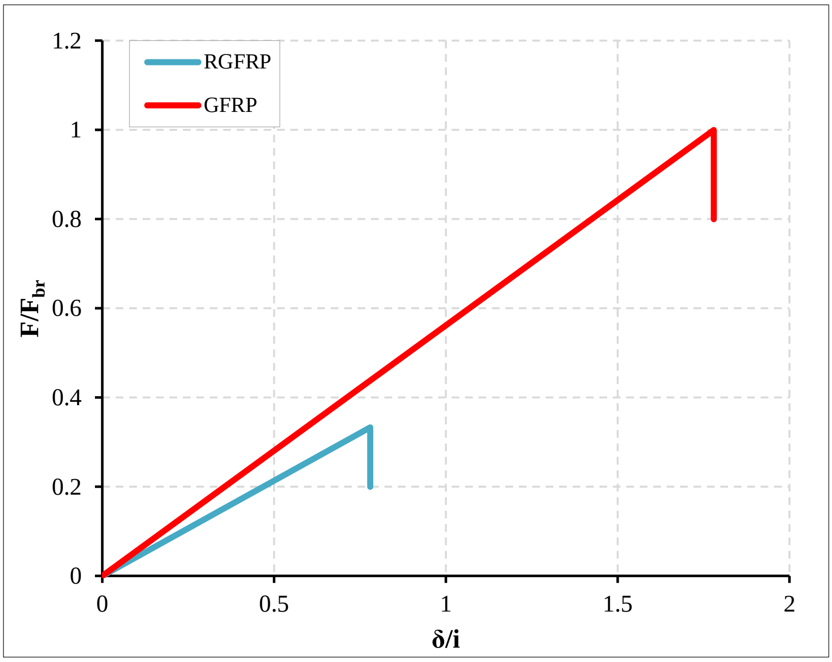


Figure 15. Comparison of dimensionless diagrams of GFRP and RGFRP

7. Conclusions

- This manuscript highlights the possibility of the use of recycled material obtained from the original thin plated GFRP material in load-bearing elements. The new thin plated material, RGFRP, was made from 50% of the original recycled GFRP, which was added to the resin.
- Despite the minimal imperfection of the recycled material and the production of the beam samples, the results of the experiments give a clear picture of the behavior beam models.
- The behavior of both materials is primarily elastic.
- The beam models made from both materials collapsed mainly because they exceeded the bending capacity.
- Both materials exhibited local deformations in the vicinity of the load application and supports. This effect is related to the position of concentrated loads in comparison with the supports and to the small area of the load application and the support area. This problem was researched by the authors in previous manuscripts [21-24].
- Beam models made from the recycled material, RGFRP, exhibited more elastic behavior compared to the original material, GFRP.
- The beam models from RGFRP exhibited fewer local deformations compared to GFRP.
- Due to its more compact structure, RGFRP can behave as a micro reinforcement and is more resilient to outer influences.
- With the use of different sizes of particles from the grinding procedure of the original GFRP, we can influence the amount of glass fiber used in a new material, RGFRP.
- The bearing capacity of the beam model made from RGFRP, with 50% recycled material, amounts to slightly more than 30% of the bearing capacity of the original material beam models. For this reason, it is recommended to broaden future research with new models made from different quantities of recycled material. The results of similar research show that the material sample with the addition of 20% recycled GFRP reduces the load capacity of the sample to 75% of the original material, [16].
- As there is a lack of research into the use of recycled GFRP material in the production of thin plated elements or RGFRP plates, the contribution of this manuscript is particularly important.

8. Declarations

8.1. Author Contributions

Conceptualization, A.J.; methodology, A.J.; validation, A.J. and T.Š.; formal analysis, A.J. and T.Š.; investigation, A.J. and T.Š.; resources, A.J.; data curation, A.J.; writing—original draft preparation, A.J. and T.Š.; writing—review and editing, A.J.; visualization, T.Š.; supervision, A.J.; funding acquisition, A.J. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

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8.4. Acknowledgements

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

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