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ANALYSIS OF COMPOSITE MATERIAL PROPERTIES AND THEIR POSSIBILITIES TO USE THEM IN BUS FRAME CONSTRUCTION

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Abstract. Energy consumption and the emission of harmful particles have increased significantly in recent decades. The constant development of transport poses an increasing threat to the environment. The search for alternative energy-saving solutions is closely linked to the development and improvement of new vehicles, reducing their negative impact on the environment. Fiberglass or carbon fiber are among the most promising materials that can reduce weight in all types of vehicles. They are also much easier to recycle than steel. Fiberglass or carbon fiber composite materials are widely used in a variety of applications: construction, ships, and trains. Vehicles and buses are no exception. These innovative materials are used not only for interior elements but also in constructional units for the production of light duty vehicles. Meanwhile in buses these material are not yet used in safety frame. Bus safety frames are made out of steel. Therefore, in this work the fiberglass composite material from which the tubes are made by pultrusion process would replace the steel tube in the safety frame construction of the bus. Such technology could reduce the weight of the bus safety frame by about 20%. Other parameters would also be affected by weight reduction: safety: bus would be less overloaded, the braking distance would be reduced, the center of gravity position would be closer to the ground; environmental: lower air pollution due to lower CO_2 emissions; economic: lower fuel consumption. However, before using such technology, it is necessary to determine the properties of the composite material. Properties were determined by tensile and shear tests (ISO 527-2:2012 and ASTM D5379/D5379M-19). Comparison tests of different materials (tensile and crushing tests) were also performed. According to the experimental results, conclusions were drawn regarding the possibility of using fiberglass for the bus frame.

Keywords: composite, glass fiber-reinforced polymer (GFRP), tensile test, crushing test, shear test, bus, construction, weight.

Introduction

At present, the general transport sector accounts for 19% of all harmful human activity, and the industry has to find eco-efficient and effective ways to reduce this interest (Ivković *et al.* 2019; Žurauskienė *et al.* 2012). Global climate change and the greenhouse effect are forcing the automotive industry to find ways to reduce energy consumption and emissions. The major countries in the world are setting emission limits for new vehicles, for example, the European Union has set a target of 95 g CO_2/km for passenger cars (Helms, Kräck 2016).

The data presented (Figure 1) show that the largest reduction in CO_2 emissions per 100 kg is for petrol and diesel for passenger cars. Commercial vehicles and city buses also significantly reduce CO_2 emissions by changing their weight. Vehicle weight is identified as one of the main factors influencing fuel consumption and emissions. However, according to the authors Fontaras *et al.* (2017), fuel consumption and CO_2 emissions are influenced by: driving behaviour, vehicle configuration, traffic conditions, cross wind, rain, road surface.

In order to make vehicles as environmentally friendly as possible, various solutions are used: using electric motors, using more efficient fuel and reducing the weight of the vehicle. Weight reduction is a very important aspect in the design and production of modern vehicles. Innovative materials or various optimization techniques can be used to reduce vehicle weight (Topaç *et al.* 2020). More and more car manufacturers are using carbon or fiberglass composite materials. The composite material is made up of two main components, the fiber and the matrix, also

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known as the filler. Fibers can be metallic, synthetic, natural, biomedical, hybrid and other. In the automotive industry, it uses composite materials that contain metallic, synthetic, natural fibers. Synthetic fibers can be such as glass, carbon, aramid, kevlar and others. Natural fibers can be such as flax, hemp, jute, sisal, kenaf, coir, kapok, banana, henequen, and many others (Mahir *et al.* 2019). Compared to synthetic fibers, they have the following advantages: relatively low weight, low cost, less damage to processing equipment, good relative mechanical properties such as tensile modulus and flexural modulus, processing flexibility, biodegradability and minimal health risk (Mohammed *et al.* 2015). Nowadays, the use of composites based on natural fiber-reinforced polymers is gradually increasing. Due to their advantages, they are widely used in civil engineering, automobiles, aerospace and many others (Keya *et al.* 2019). However, they also have disadvantages: their mechanical properties are affected by moisture, they have weak fire resistance properties, low tensile strength and Young's modulus (Mahir *et al.* 2019; Keya *et al.* 2019). Natural fiber composites are used only for the production of interior finishes (Mahir *et al.* 2019; Keya *et al.* 2019). They are not suitable for structural elements due to the low tensile strength and Young's modulus. Therefore, this work deals with a synthetic fiber composite, which is composed of glass fiber.

Fibers provide strength and stiffness to the composite material, and the matrix serves as a medium for transferring stresses to the fibers. Depending on the matrix type and fiber distribution, the fiber content in the composite is between 30 and 75% of the total volume of the element. In order for such composite material to be used in structural members and to maximize the properties of this material, the fiber surface must be completely coated with a matrix (Mukesh, Godara 2019). Composite materials are increasingly used in bridges, buildings, automotive structures as an alternative to traditional materials because of their many advantages including high strength, low dead weight, short installation time, low maintenance requirements and improved durability (Vanagas *et al.* 2017). It is also an advantage of composite materials that by changing the reinforcing material or matrix (filler) different composite properties of the material can be obtained. Various combinations of reinforcing materials are also available. Such composite materials are called hybrids. As the authors Atmakuri *et al.* (2019) state, hybrid composites show better results in bending, shear tests than pure composite materials. Carbon and fiberglass composite materials are used in passenger cars for both exterior and interior design (Liu *et al.* 2013). In the bus and coach industry, these lightweight materials are currently used exclusively in the production of interior elements and finishes (Liu *et al.* 2013). Vehicle manufacturers continue to increase the amount of fiber-reinforced plastic in their products to reduce weight, strengthen details and save money (Stewart 2011). However, these materials are not used in bus safety frame construction. All bus safety frames are manufactured in the traditional way, i.e. they are made of steel. In order to reduce the overall weight of the bus, steel tubes can be replaced by fiberglass tubes produced by pultrusion.

Of course, composite materials can be produced not only by pultrusion processes. It can be produced in the following way: resin casting and manual laying. Fiberglass composites tubes also can be made via vacuum forming of the product with a polyethylene (PET) filler core, polyvinyl chloride (PVC) filler core, with reinforced polyurethane core. However, in terms of cost, quality and speed of production, the pultrusion method was chosen. Among these technologies, pultrusion is distinguished by its abil-

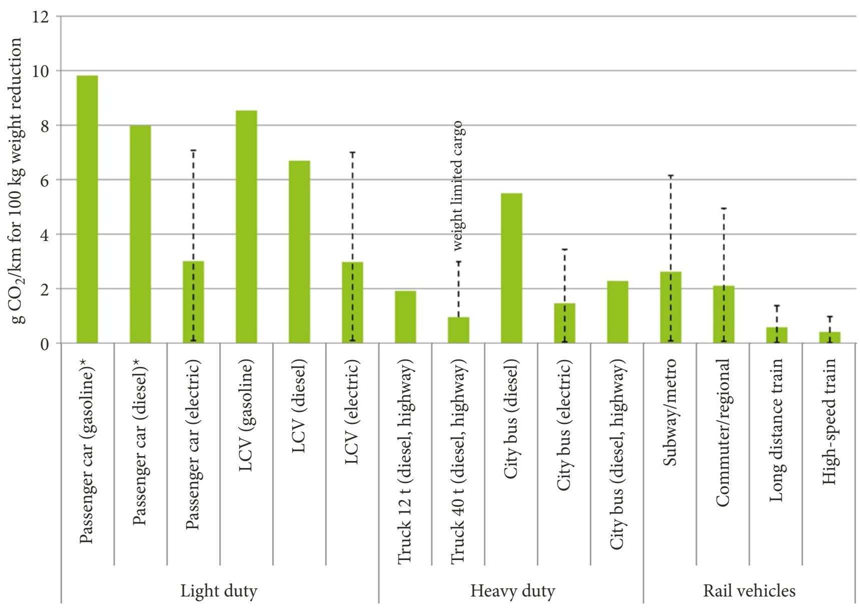

Figure 1. Reduction in CO_2 emissions through weight loss (Helms, Kräck 2016)

Notes: LCV – light commercial vehicle; * – for passenger cars secondary effects by maintaining the power-to-weight ratio of the vehicle are considered.

ity to combine high-speed production with high-quality parts produced. Moreover, in order to obtain a polymer composition with good properties (high and uniform degree of cure) and a process with minimal energy consumption, it is necessary to calculate the optimum temperature profile (Santos *et al.* 2015). So, this high-quality pultruded fiberglass tube can be used in bus safety construction. The weight of such a construction should, in theory, be reduced by about 20% compared to classical structural design solutions (Liu *et al.* 2013; Park *et al.* 2014; Jeon *et al.* 2013).

In addition, using fiberglass in the bus construction would significantly reduce its weight, which would have a direct impact on braking distance, fuel consumption and CO_2 emissions – all of which would be reduced (Luty 2018; Nasrollahi *et al.* 2018; Zefreh *et al.* 2017). Road safety and reducing CO_2 is a major challenge today. Researchers carry out various studies to assess existing pollution, its dependence on other parameters (development of countries, socio-economic situation, types of vehicles used) and what measures need to be taken to ensure sufficient safety and reduce air pollution (Török 2017; Lebedevas *et al.* 2017).

However, before using fiberglass tubes, it is necessary to determine the properties of the material and compare them with the properties of the steel. To determine these properties and to make comparisons, the following materials shall first be subjected to tensile tests according to the standard ISO 527-2:2012, crushing tests. Among other things, the glass fiber composite material is orthotropic and the orthotropic material is material, which: does not have the same mechanical properties in each direction, has three axes of symmetry, while an isotropic material has the same mechanical properties in each direction and has an infinite number of planes of symmetry (Bojtár *et al.* 2016; Ficzere *et al.* 2018). Because this material is orthotropic, it is also necessary to perform shear testing to determine its properties. There are several different methods of material shear testing. The methods are for different types of materials or specimens size (Grzesiak *et al.* 2018). In this work, the shear modulus test is performed according to the standard ASTM D5379/D5379M-19.

The goal of this research is to determine the mechanical properties of a specific pultruded fiber glass tube, to perform tensile and crushing tests on three different materials (steel, aluminium, Glass Fiber-Reinforced Polymer (GFRP)) and to compare obtained values. In the second step, according to the obtained values, to evaluate the possibilities of using composite tubes in the construction of the bus safety frame. All this is done to reduce the weight of the bus, which would reduce fuel consumption and CO_2 emissions.

1. Hybrid constructions

Hybrid constructions are structures that are composed of several different materials. For example, in the buildings construction sector, a hybrid construction is a structure consisting of wood and concrete or a construction made of composite material and concrete. In this case of a hybrid bus frame, hybrid frame is a frame consisting of steel and fiber glass composite material (Figure 2).

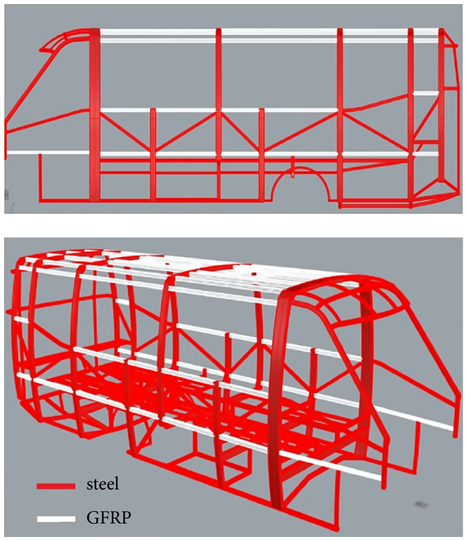

Figure 2. Bus frame of steel and composite material

A composite material is made by combining two or more materials – often those with very different properties. These two materials together give the composition unique properties. However, within the composite you can easily distinguish between different materials because they do not dissolve or mix with one another. Most composites are made of only two materials. One is a matrix or binder. It surrounds and binds fibers or fragments of another material called reinforcement. The individual components remain separate and differ in their final structure, distinguishing the compositions from mixtures and solid solutions. Composite materials have the following advantages over other materials: low weight, high stiffness, high corrosion resistance, high wear resistance, and so on (Li *et al.* 2017; Varvani-Farahani 2010). These materials are widely used in various manufacturing sectors: ships, aircraft, buildings, bridges, automobiles and other vehicles (Correia *et al.* 2010; Varvani-Farahani 2010). Composite materials are used in vehicles to reduce vehicle weight. For example, *Comobus* was developed using fiberglass composite and polypropylene components, which reduced their weight by 30% compared to bus safety frame made of steel. Fiberglass fabrics were used in roof, floor, frame and seat elements, reducing their weight in ranges from 40 to 60% (Liu *et al.* 2013). Using GFRP for vehicle bumper it is possible save 51…58 % weight, compared with bumper made of traditional materials (Duan *et al.* 2018). In order to use composite materials in the construction of a bus, it would be possible to use fiberglass tubes, which are produced by pultrusion process.

Pultrusion is the process where fibers are dipped in bath of polymer matrix and then they are pulled through a heated die, where the continuous composite profile is created. The term pultrusion connects the words "pull" and

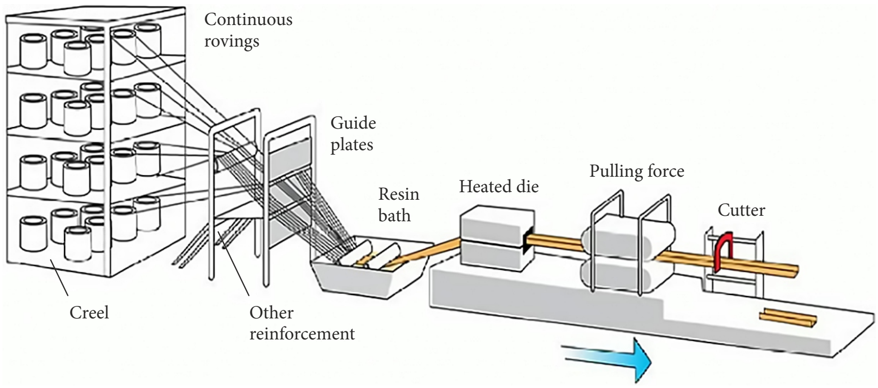

Figure 3. Pultrusion machine process and its main components

"extrusion". Pultrusion is the drawing of materials such as glass fiber and resin through a formed die. The usual process of pultrusion begins with shelves or gratings having roving rolls of continuous fiber. Most often the reinforcement is fiberglass, but also it can be carbon, aramid, or a mixture of this fibers (Varvani-Farahani 2010; Silva *et al.* 2017). Figure 3 shows the scheme of a pultrusion process (machine) and its main components.

2. Experimental research

2.1. Tensile test

Tensile tests were performed in order to determine the mechanical properties of the composite material. The principle of this test is as follows: the test specimen is extended along its major longitudinal axis at a constant test speed until the specimen fractures or until the load or elongation reaches some predetermined value. During this procedure, the load sustained by the specimen and the elongation are measured.

The tensile test must follow the following procedure:

- the specimen is placed into tensile grips;
- the extensometer is attached to the specimen (an extensometer or strain gauge is used to determine the elongation and tensile modulus of the test specimen);
- the test is started by separating the tensile grips at a constant rate of speed. The speed depends on the shape of the sample and can range from 0.125 to 500 mm/min. The time from the start of the test to the break should be between 30 s and 5 min;
- the test is stopped when the specimen break.

Fiberglass specimens for tensile testing were made of fiberglass tube.

The fiberglass tube was made from vinyl ester resin using the pultrusion process. Tubes from which specimens for tensile testing were cute out were made in the JSC "Ugira" (*http://www.ugira.lt*, Marijampole District, Lithuania). Composition of the composite material used in the tests: e-glass fiber and vinyl ester resin. The fiber to resin ratio is equal to 76 and 24% respectively. The density of the composite material is 2000 kg/m^3. All specimens for tensile testing were manufactured according to the standard ISO 527-2:2012 (Figure 4). All specimens' thickness is 3 mm.

Typically, the tensile test is carried out on flat or round specimens. The ends are adjusted in different directions. Ends larger than 150 mm long, 20 mm wide and 10 mm narrow are recommended for testing in accordance with the standard ISO 527-2:2012 (Figure 5). The tensile test determined the maximum force to break the material.

In the specimens, the fibers are oriented longitudinally. However, two types of test specimens were produced during the fabrication of the specimens: 1 – where the fibers are arranged crosswise the tensile direction; 2 – when the fibers are arranged longitudinal to the tensile direction.

Specimens were tested on a *Zwick Z250* material test machine with a central ball lead screw (Figure 6). All tests were performed at room temperature.

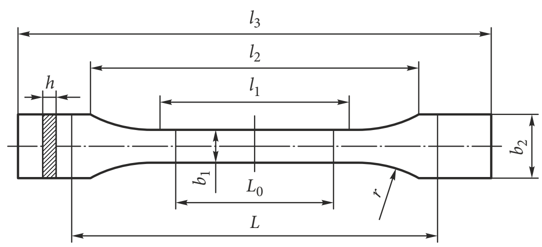

Figure 4. Tensile test specimen layout: l_3 – overall length ≥150 mm; l_1 – length of narrow parallel-sided portion 60.0 ± 0.5 mm; r – radius 60 ± 0.5 mm; l_2 – distance between broad parallel-sided portions 108 ± 1.6 mm; b_2 – width at ends 20.0 ± 0.2; b_1 – width at narrow portion 10.0 ± 0.2 mm; h – preferred thickness 4.0 ± 0.2 mm; L_0 – gauge length 50.0 ± 0.5 mm; L – initial distance between grips 115 ± 1 mm (ISO 527-2:2012)

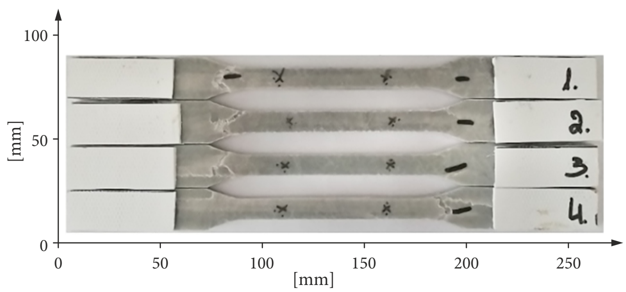

Figure 5. Prepared fiber glass material specimens

According to Suresh, M. G., Suresh, R. (2019) and Yang, Wu (2016) the typical test speed is 2 mm/min, but Soric *et al.* (2008) compared three different speeds (2, 5, 10 mm/min) and found that the deformation speed does not have a significant influence on the tensile strength values, thus could be neglected. Thus, a speed of 5 mm/min was assumed for this tensile test. The test time for breaking the specimens ranged from 70 to 80 s.

The modulus of elasticity and Poisson's ratio of the material (when the fiber is arranged longitudinally and the specimens are stretched longitudinally and when the fiber is arranged crosswise and the specimens are stretched longitudinally) were determined by tensile tests. The results are presented in the discussion section.

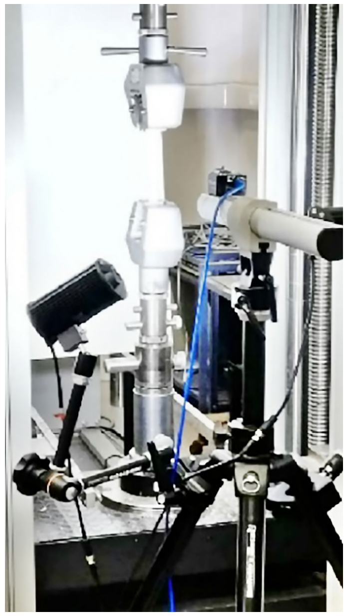

Figure 6. Material tensile test equipment

2.2. Shear test

Shear test is performed to determine the material shear modulus. The shear modulus (G [MPa] or [GPa]) is one of the elasticity indices of the material that shows the relationship between shear stress and shear strain. The principle of this test is to perform a set of defined displacements on a V-notch specimen in order to obtain the highest shear state in the center of the specimen. These displacements are achieved through the relative motion of the movable handle relative to the fixed handle. Plane shear tests are performed on a single-sided GFRP composite material using the Iosipescu shear test according to the standart ASTM D5379/D5379M-19 (Figure 7) (Khashaba *et al.* 2013). It consists of a straight beam with two sharp, 90° grooves made at the edges of medium-length specimens. Applying two pairs of forces generating two opposite moments of action in section ab, a pure and uniform state of shear stress is formed between the roots of the incision. Moreover, the behaviour of nonlinear materials can be investigated using the Iosipescu test method (Odegard, Kumosa 2000).

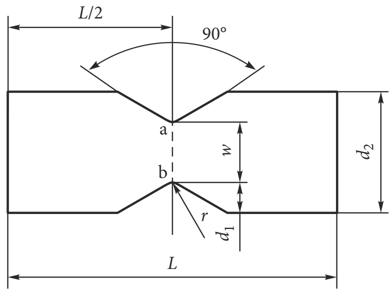

Figure 7. Shear test specimen layout: d_1 = 20.0 mm; d_2 = 4.0 mm; h = 4.0 mm; L = 76.0 mm; r = 1.3 mm; w = 12.0 mm (ASTM D5379/D5379M-19)

The shear test must follow the following procedure:

- the specimen is prepared according to the standard;
- connection of the strain gauge to both the controller and the mounting at +45 and –45° to the loading axis of the specimen. Zero the force reading;
- the specimen is placed on a test rig and it is checked that the notch alignment tool is pulled up into the notch. Gently tighten the left side of the jaw, then gently tighten the right side of the jaw. It must be checked that the specimen is fixed in the center of the reinforcement and that it touches the upper and lower jaws of the handle on both sides while still being held at the rear;
- the specimen is stretched at a constant tensile speed until break (ASTM D5379/D5379M-19).

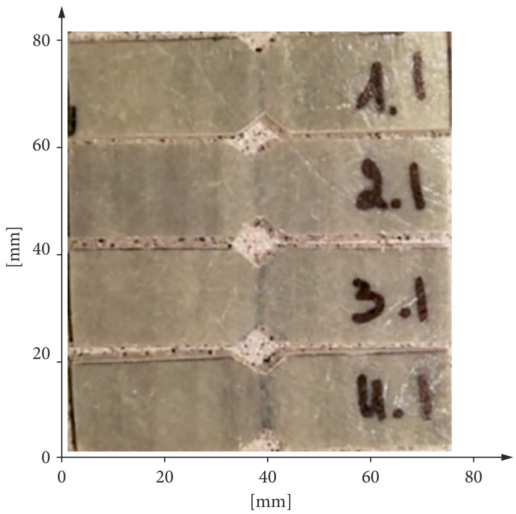

Figure 8. Prepared fiber glass material specimens

There were prepared 8 specimens for this test: 4 specimens with tow orientations of 0 and 4 specimens with tow orientations of 90° (Figures 8 and 9). All specimens thickness is 3 mm. The flat specimen has two identical V-notches symmetrically arranged at the center line in the middle. When the specimen is loaded towards the shear, there is an almost uniform, pure shear stress in the test compartment (between the grooves). The actual stress distribution depends on the properties of the material and the orientation of the fiber.

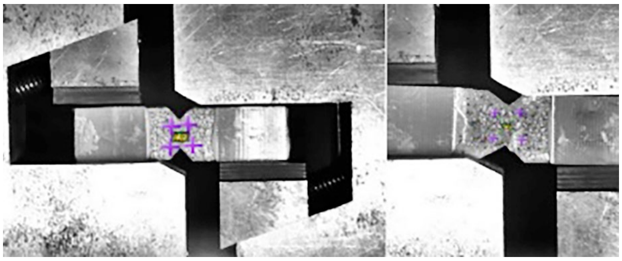

Figure 9. Fiber glass material specimens shear testing

The Iosipescu shear test is relatively easy to use, requiring only small amounts of material. Specimens do not require elaborate fabrication steps and are easy to install in the test fixture. Modulus determination is relatively straight forward once the small strain gauges are applied in the center of the specimen. In addition, the measurement of shear strength needs additional care as for some composite materials and for some directions, the failure is initiated by localized tensile stresses rather than shear stress (MS 2004).

2.3. Strength comparison of different materials according to tensile and quasi-static crushing test

Steel and aluminium are usual materials used in bus safety frames. Meanwhile, fiberglass composite is not used in the bus safety construction. So, after determining the mechanical properties of the pultruded glass fiber composite material, the strength of this material is also compared with other materials: steel and aluminium.

For tensile test, all specimens were prepared according to the standard ISO 527-2:2012 (all specimens are the same size). The purpose of these three different materials tensile test is to obtain and compare the strength, elasticity and ductility of the materials, i.e. indicators, which, from an engineering point of view, adequately reflect the most important mechanical properties of the material. Steel specimens were prepared of steel S235 (density – 7800 kg/m^3, Poisson's ratio – 0.3, shear module – 77 GPa), aluminium specimens were prepared of aluminium alloy (Al–Zn–Mg) (density – 2700 kg/m^3, Poisson's ratio – 0.32, shear module – 26 GPa) (Engineering ToolBox 2005). All specimens thickness is 3 mm.

Specimens were tested on a *Zwick Z250* material test machine with a central ball lead screw.

The results of the tensile tests of the different materials are presented in the discussion section.

For quasi-static crushing test, all specimens were made of three different materials (aluminium, steel, GFRP). For the most accurate results, all specimens were made of 40×40×2 tubes. All specimens were 80 mm long. This test is performed because it differs from tensile in the directions of the forces acting. Up to the limit of proportionality – the resistance of materials to both tensile and compressive is almost the same. Exceeding the elastic limit increases the transverse deformation, so the specimen resists it not only due to the reinforcement of the material but also due to the increased cross section of the specimen.

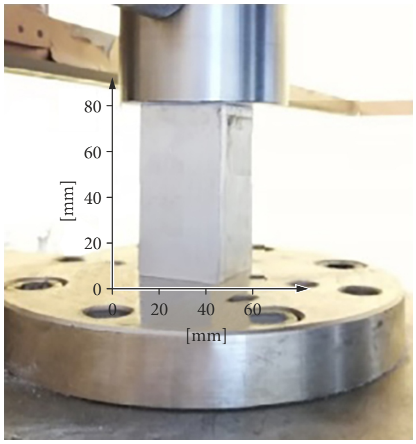

Figure 10. Quasi-static crushing testing

The test was performed on a *Tira 2300* test machine. Figure 10 shows the test set-up with the specimen before the quasi-static compression test. This quasi-static crush test was performed under the recommended test control conditions for composite materials. A test specimen attached to the clamp support was placed on a lower steel plate. This lower steel plate, which remains stationary during the crushing test, was connected to the load cell. During the quasi-static crush test, the upper steel plate attached to the transverse head moves down to the specimen and the compression process begins. The transverse head velocity was 1 mm/s, which corresponds to a compression rate of 0.01133 s^{-1}. At the start of the crushing test, the crushing load, transverse head velocity, and crosshead displacement was recorded and output to a data file.

The specimens were tested until disintegration.

Test results, load data were collected. The load deformation response of the steel, aluminium, and GFRP tube specimens, together with the corresponding deformation pictures under quasi-static lateral compressive loading, are presented in the discussion section.

3. Discussion of results

Based on material properties tests and material comparisons, we can say that fiberglass composite material properties are no worse than steel and it is better than aluminium.

The mechanical properties of the fiber glass composite material were determined by tensile and shear tests. Experimentally determined material parameters are shown in Table.

When comparing experimentally the numerical value of the Poisson's ratio of the composite material (when the fiber is oriented in the crosswise direction) with the numerical value of steel or aluminium, we see that the fiberglass composite material is not as compressible as steel or aluminium, but this difference is very minimal. However, it is very different when the fiber in the composite material is oriented longitudinally. In this case, the values of the Poisson's ratio differ about 10 times (Figure 11).

Such a large difference in the Poisson's ratio longitudinal and crosswise the fibers is due to the large difference in modulus of elasticity between epoxy resin (*E* = 3.3 GPa) and glass fibers (*E* = 70 GPa). In determining the Poisson's ratio, the transverse deformations along the GFRP fiber are determined by the properties of the glass fiber and the transverse deformations of the GFRP fiber are determined by the properties of the epoxy resin. The standard deviation of these values is: crosswise (Poisson's ratio – 0.012), longitudinal (Poisson's ratio – 0.001).

Thus, in order to have a construction, which is made of composite materials will have sufficient strength, it is necessary to evaluate the possible directions of loading and to select the fiber oriented in the right direction.

The tensile force-elongation graphs (Figure 12) shows the main experimental data used to determine the modulus of elasticity of a material, as well as the axial stiffness of the material. When the strength limit is reached, the material breaks. The standard deviation of these values is: crosswise (tensile force – 2.182 kN), longitudinal (tensile force – 0.569 kN). According to the graphs, it can also be seen that at the beginning of the test there was a slight slippage from the grips or at the beginning of the test the grips were not fully compressed (displacement from 0 to ~1.8 mm). This stretch was not evaluated when calculating the modulus of elasticity.

Figure 13 shows the deformation graphs obtained from the force-elongation graphs. In graphs, we see linear material behaviour before reaching the breaking stress, i.e. they have a clearly fragile structure. In addition, from these graphs we see that this material has no plasticity. Each curve shows the maximum stress, which is assumed to be the tensile strength of the material, which is 350 MPa when the fiber is oriented longitudinally and 45 MPa when the fiber is oriented crosswise. The difference in stress values between the longitudinally and crosswise oriented fibers can be explained in the same way as for the Poisson's ratio. The standard deviation of these values is: crosswise (stress – 2.06 MPa), longitudinal (stress – 15.90 MPa). From these stress-strain graphs, the elasticity modulus *E* of the material can be determined by the equation and the calculated values are shown in Table.

$$E = \sigma \cdot \varepsilon,$$

where: *E* is elasticity modulus [MPa]; σ is the uniaxial stress [Pa]; ε is the strain [mm].

Comparing the tensile test results (Figure 14) obtained from tests with three different materials (during the tensile tests, the fiberglass material collapsed to a load of 1200 N, a load of steel of nearly 800 N and a load of 500 N of aluminium) we can say that the glass fiber composite material is strong enough when the fiber is oriented along the tensile force.

a) b)

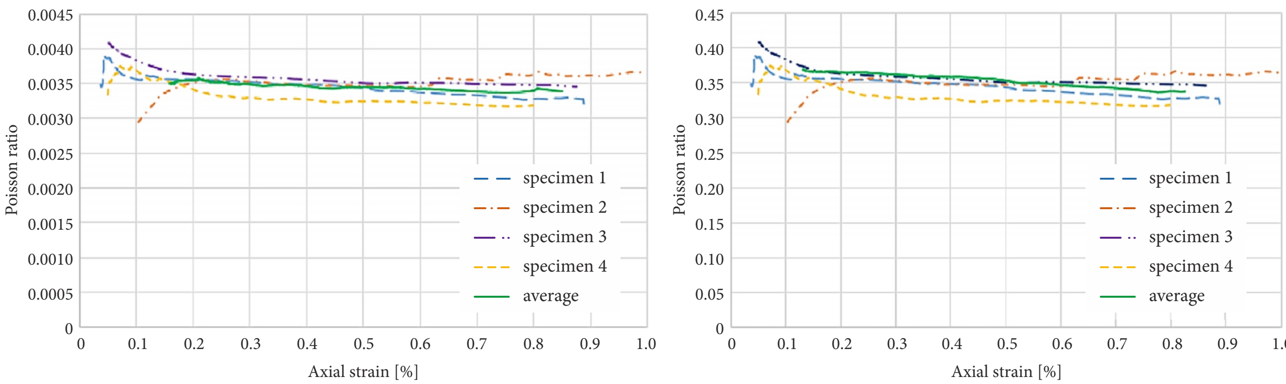

Figure 11. Poisson's ratio vs axial strain curves: a – longitudinal; b – crosswise

a) b)

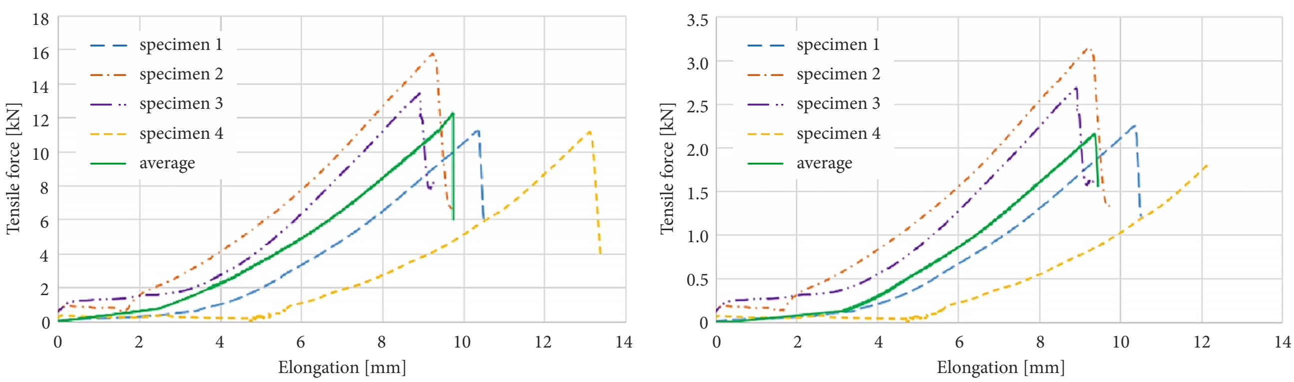

Figure 12. Force vs displacement curves: a – longitudinal; b – crosswise

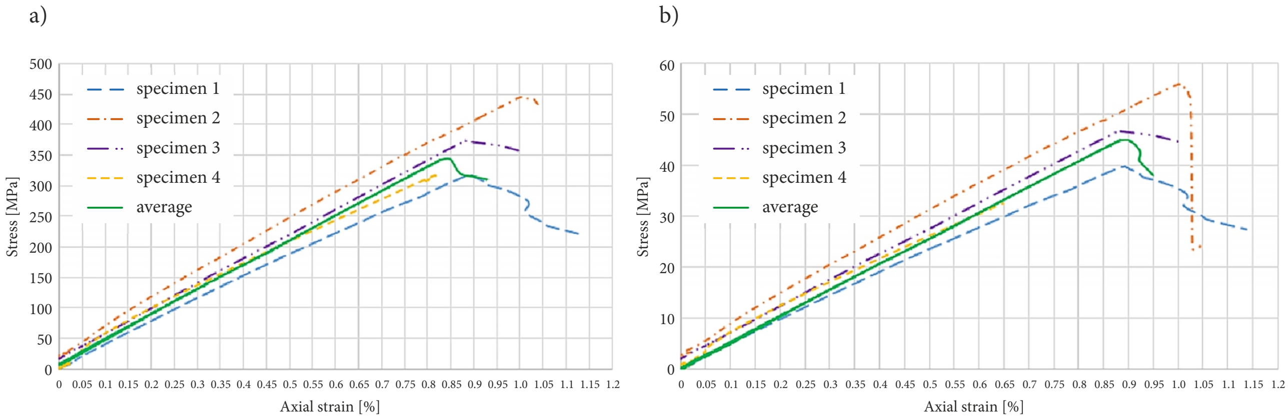

Figure 13. Tension stress vs strain curves: a – longitudinal; b – crosswise

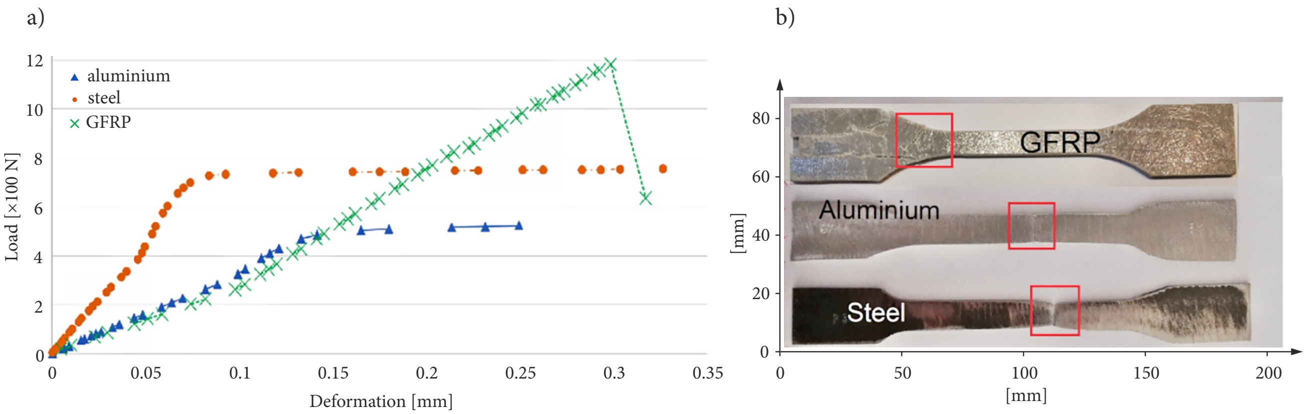

Figure 14. Tensile test results (a) and observed tensile failure modes (b) in tested materials

Table. Mechanical properties of pultruded glass fiber (GFRP) composite material

Property	Directionality	
	longitudinal	crosswise
Density [kg/m^3]	2000	
Tensile ultimate strength [MPa]	364	
Compressive ultimate strength [MPa]	364	
Young's modulus [MPa]	39000	4875
Poisson's ratio [–]	0.035	0.335
Shear modulus [MPa]	3358	3342

Comparing quasi-static crushing test results, it showed that the fiberglass composite material starts to break down during the crushing test (during the crushing test, was found that the fiberglass composite was withstand 10 kN load, steel – 11 kN load and aluminium – 7.8 kN load). During the crushing test, the fiberglass did not deform plastically as steel or aluminium. When it reached the limit of his strength, it broke and began to crumble.

The crushing test photographs (Figure 15) also show that the steel and aluminium have plastic deformations. GFRP has no plastic deformation, it has broken and started to crumble.

Also comparing the weight of the material, this composite material is 6 times lighter than steel. This material seems to have only positive properties. However, its uses in frame construction is limited, since only straight tubes can be produced by pultrusion, and they have lower shear and elastic modulus compared to steel (as determined by shear tests, the shear modulus of the composite material is significantly lower than both steel and aluminium). In order to increase the shear modulus of the composite material, its composition can be modified. Composite material properties can be changed by changing the reinforcing material or matrix (filler). It can also be changed by changing the fiber arrangement.

Using fiberglass tubes in the bus frame construction would solve the problem of weight loss for both large and medium sized buses, which is very sensitive. This type of vehicle has to stop very often at passenger boarding and alighting stops. The heavier the vehicle and the more frequently it has to stop and start again, it increases fuel consumption and emissions significantly. Reducing vehicle weight would proportionally reduce bus exploitation costs.

Based on the results of tensile tests of the composite material and its comparison with steel and aluminium, it can be stated that this material is strong enough and can be used in the construction of a bus safety frame. In addition, after crushing tests and finding that the compos-

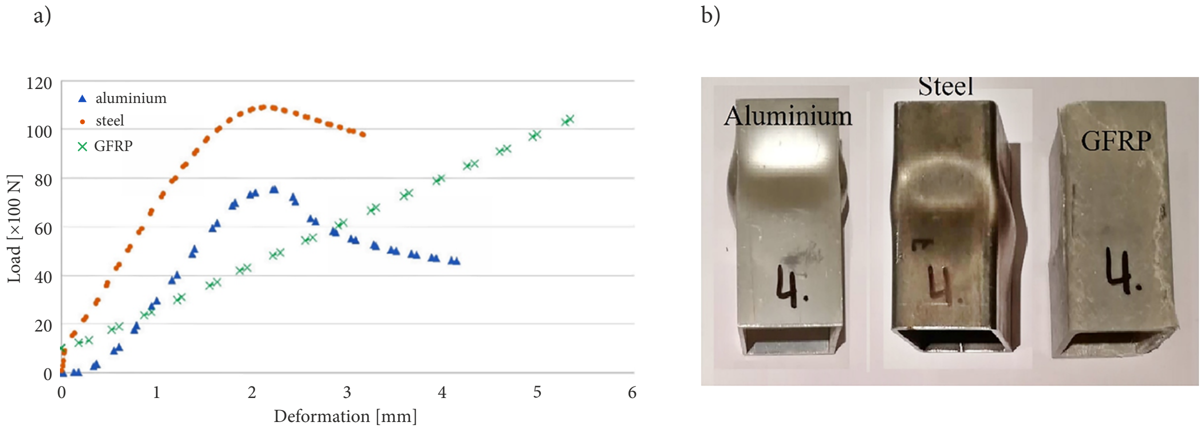

Figure 15. Quasi-static crushing test: a – results; b – failure modes in tested materials

ite material breaks and begins to crumble when a certain load is reached, we can conclude that it cannot be used in the construction of the safety frame in places where it would be directly affected by forces caused by the accident. Therefore, the safety construction of a bus using composite tubes should be designed in such a way that the main energy released during the accident is absorbed by the steel.

Due to the chosen method of production of the composite material, which is pultrusion, the profiles produced can only be straight, which limits their applications in the construction of the bus safety frame.

However, another relevant problem that may limit the use of a composite tube in construction is its connection to steel. In this case, adhesive joints could be used for the connection to the steel. Such a joint would be classified as elastic joints. The advantages thereof are better load distribution – greater driving comfort is likely and the likelihood of cyclic fatigue is minimal. Its disadvantages – due to the high body elasticity, it is difficult to ensure the functionality of precision body units, passenger and emergency doors, side and rear boot lids. The operation of these nodes is subject to quite high technical requirements.

Conclusions

From the results of the tensile test, it can be stated that composite material strength yield is 11% less than steel strength yield and it is 40% more than aluminium strength yield. From the tensile test, we can also see that the composite material deforms, according to the linear dependence, until it reaches the breaking stress. What is more, we see that this material breaks brittle and it has no plastic deformations.

Composite material Poisson's ratio longitudinal fiber direction is 0.035, crosswise fiber direction – 0.335. Therefore, composite material is not as uncompressed as these other material in crosswise direction, but it is more compressed on longitudinal direction than aluminium or steel. An average value and a deviation of only 3.4% were also derived.

Tensile comparison test of different materials shows that composite material withstands 1.5 times more force than steel and about 2.3 times more force than aluminium.

Crushing comparison test of different materials shows that the maximum crushing load is maintained by steel, followed by composite material and aluminium. Moreover, aluminium and steel were plastically deformed, composite material disintegrated and began to crumble.

Composite material shear modulus longitudinal fiber direction is 3358 MPa, crosswise fiber direction – 3342 MPa. Shear modulus on both fiber direction is almost the same. However, composite material shear modulus is about 21 times less than steel shear modulus. Crushing tests also confirmed this.

The large difference between the modulus of elasticity, the Poisson's ratio and the shear modulus in a composite material with anisotropic properties depends on the direction in which the glass fiber (the modulus of elasticity of the fiber is 21 times higher than the modulus of elasticity of the resin).

Replacing steel tubes in a bus safety frame construction with pultruded fiberglass composite material tubes we reduce the weight of the bus structure while maintaining sufficient structural strength. The weight of the fiberglass composite material is 4 times less than that of steel. Reducing vehicle weight is one way to reduce fuel and CO_2 emissions. In this way making vehicles more environmentally friendly.

Using glass fiber tubes produced by pultrusion, which, due to the production technology, can only be produced with a straight profile, the possibilities of its use in the construction of the safety frame of a bus are limited. However, despite this these tubes could be use on the roof or side. This would change the position of the center of gravity – the vertical position of the center of gravity would move closer to the ground. This ensures greater stability of the vehicle.

In addition, the failure properties of composite materials are completely different from those of steel or aluminium (large fragmentation of materials and large changes in the cross-sectional geometry of the tubes during deformation) they cannot be used in areas of the structure that may experience direct impact during an auto accident.

Author contributions

Tautvydas Pravilonis was responsible for literature analysis, experimental tests, preparation of graphs and tables.

Edgar Sokolovskij was responsible for data analysis and improvement.

Tautvydas Pravilonis and Edgar Sokolovskij were responsible for writing all chapters, interpreting the obtained results and formulating conclusions.

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