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Use of New and Light Materials in Automotive Engineering for Towing System

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Featured Application: The motor vehicle industry is undergoing continuous action to reduce the weight of transport means. To achieve this, one important method is to use new and composite materials and aluminum alloys for various parts of the vehicle. Towing systems represent one of these very important components, for which alternative materials are being studied to replace steel. The presented conclusions are practically useful and can be used by towing system manufacturers.

Abstract: Towing systems are an important component in the automobile industry, having to meet specific quality and resistance conditions. In most cases, the towbar is made of steel. Decreases in vehicle weight and manufacturing price mean that, in this field, research is also being conducted in order to replace the materials that make up the towbar and replace the steel with composite materials or aluminum alloys. In this paper, research was performed on towing systems built from other materials, and the obtained results were compared with those of steel systems. Theoretical calculations and experimental results made it possible to obtain a database and recommendations for the use of new and composite materials. The experimental tests validated the theoretical results obtained. Five towing systems made of different materials were studied. The results of the research are emphasized through recommendations regarding the manufacturing of towing systems.

Keywords: towbar; towball; towing system; safety; car; finite element method

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1. Introduction

In the automotive industry, the share of steel in manufacturing has continuously decreased in the last 50 years, with countless components being replaced by other metallic, plastic, or composite materials. Plastics and composite materials have now, in some cases, made up half of a vehicle's weight.

The most commonly used nowadays are composite materials. According to one study [1], the largest amounts of composite materials are used in the automotive and civil construction industries, using about 31% worldwide of the entire amount of composites manufactured for automotive engineering. Traditional metallic materials are increasingly being replaced by polymeric composite materials, with automobiles now containing up to 50% composite parts. In addition to the advantages of the low specific mass and high strength of composite materials, their tendencies to decrease life span and increase the number of vehicles impose good recycling capabilities on these materials; thus, revolutions in manufacturing technologies appear, developing modern production lines. Currently, plastic materials represent approximately 10% of the total mass of a motor vehicle, and this percentage is on an upward trend [2].

Composite materials present a whole series of advantages that recommend the replacement of classic materials. Their high ratio between strength and weight, dimensional stability over time, resistance to corrosion and against chemical agents, and good processing capacity are just some of the exceptional characteristics of composites; they can successfully replace the most used metals in the industry—steel and aluminum. The disadvantages of composites are that they have a higher price than metals, are easily flammable, their resins emit toxic fumes, and they are harder to recycle than metals.

New and composite materials are also based on new manufacturing processes, among which, additive manufacturing (AM) can currently be distinguished, which is based on a new philosophy of the incremental manufacturing of materials. Additive manufacturing involves layer-by-layer modeling and the consolidation of raw powder material into arbitrary configurations, normally using a computer-controlled laser [3]. Carbon nanotube composites are promising new materials with interesting applications in the automotive industry as well. The properties of these materials, as well as the scale of the dimensions they offer, lead to significant advantages in numerous applications, providing an increased strength, stiffness, impact resistance, and service life. All these advantages are summarized in [4], presenting basic results related to mechanical, electrical, and thermal properties. But nanocomposites have been proven to be a high-performance material. They also possess unusual combinations of properties and, as such, offer unique design possibilities. The growth rate of nanocomposite use is estimated at 25%. They are environmentally friendly and have proven to be extremely useful in the automotive industry [5]. Composites made of epoxy resins reinforced with natural fibers began to be used by car manufacturers in the production of door panels, seats, linings, dashboards, etc. Natural fibers offer advantages such as a low weight, low cost, and recyclability. Among these natural fibers are kenaf hemp, flax, jute, and sisal. However, in order to obtain quality materials, certain technical characteristics must be observed that must be obtained technologically [6]. The fuel savings and improved emissions being pursued in automotive engineering are driving the growing trend of replacing conventional steel and cast iron with composites or Al and Mg in vehicle manufacturing. However, there are technical issues that need to be resolved if this industry is to use lightweight materials. The main problem in need of a solution is the production of these materials at a reasonable price. A cost–benefit study is always necessary, and a study of these aspects is presented in [7,8].

The recycling of composites is another aspect that must be considered when using them. This is difficult due to their inherent heterogeneous nature. However, environmental legislation requires that all materials be properly recovered and recycled. Various technologies have been developed for composites. We list mechanical recycling, thermal recycling, and chemical recycling. Studies on the recycling of composites have proposed efficient separation and recovery technologies [9–11]. Applications of composites and their manufacturing methods are presented in numerous studies [12–14].

After iron, aluminum has become the most widely used metal, and among its countless advantages are the following, which are useful in research:

- It is a light metal, which is why it is used in the naval and aeronautical industry;
- It is a good electrical and thermal conductor, weaker than copper, but much lighter, which is why it is used in the electrical industry;
- It is a ductile and malleable metal, with the possibility of obtaining thin sheets with a thickness of 0.005 mm, which is why it is used in the food and pharmaceutical industries;
- It has a high resistance to corrosion, which is why it is used in corrosive environments.

Pure aluminum has rather poor mechanical properties, and to improve its characteristics, various alloying elements can be added, obtaining aluminum alloys that, depending on their application, have much more effective properties (Table 1).

If between 1990 and 2000, the steel mass of a car was 50–60% of the total mass, according to the automotive research center (CAR), currently, the steel mass of motor vehicles is about 15%, and by 2040, will reach about 5% of the total mass. Today, leading automobile manufacturers frequently use aluminum alloys for most components in their construction. If in the automobile industry, these alloys are used for bodywork elements, wheels, and cables, as well as in the composition of engines and transmissions, in this paper, we will try to use them for components of the towing system, more precisely, to make an alternative towbar to the steel one.

Table 1. The main physical and technological properties of aluminum and its alloys.

Characteristic	Aluminum	Aluminum Alloys
Specific mass, ρ [kg/dm^3]	2.7	2.6–2.85
Mechanical tensile strength, σ_r [MPa]	70–100	150–450
Melting point [°C]	660	570–655
Elongation [%]	20–5	0.5–18
Brinell hardness HB [MPa]	250–400	500–1300

A number of car components are currently manufactured from aluminum or aluminum alloys [15,16].

The range of aluminum applications in the automotive industry is extremely varied. The strategies used for and the possibilities of using cast or forged alloys are analyzed in [17]. The purpose of using aluminum in automotive applications is mainly determined by reducing the weight of automotive components [18–20].

The properties of aluminum are enhanced within aluminum alloys. For example, the AlSi5Cu2Mg alloy has proven to be very suitable for the manufacturing of cylinder head castings for the automotive industry. An evaluation of the influence of Ti addition (0.1; 0.2; and 0.3 wt% Ti) on the properties of the AlSi5Cu2Mg alloy was studied in [21]. Other properties of the alloys used in the automotive industry can be found in [22,23].

Bioinspired lattice structures made of aluminum have an extremely wide range of applications, especially in the aerospace and automotive industries. This is mainly due to their high strength to weight ratio. A comparative study between the theoretically obtained solutions and the experimental results of an aluminum alloy (MLS AlSi10Mg) and magnesium alloy (WE43) additively manufactured by selective laser melting is presented in [24]. Also, a check with the Finite Element Method (FEM) validated the results obtained. Other results on the applications of aluminum alloys in the automotive industry can be found in [25].

The accelerated use of aluminum in industry poses additional problems in terms of recycling the material. Recently, a series of new techniques proposed, including laser-induced breakdown spectroscopy (LIBS) and solid-state recycling, represent new and promising ways to recycle this material. In particular, solid-state recycling by compression and extrusion at ambient temperature can lead to energy savings and minimal metal loss [26].

Car trailers and semi-trailers are very varied and have lots of uses, not just the transporting of goods or people. The roles assigned to the most common trailers are caravan, platform with tarpaulin, platform without tarpaulin, electric current generator, tanker truck, tipper, concrete mixer, refrigerated transport, store, nacelle, animal transport, etc.

Semi-trailers are those that lack a front axle, and during operation, they rest on the rear of the vehicle. For cars, the most common are semi-trailers, with the two-axle trailer most often being found on platforms or where the weight is high, requiring balance when stationary and/or for various reasons.

Due to the regime during the operation of the car–trailer assembly, the coupling between these two vehicles must be very resistant, both to dynamic and static loads, but also to the influence of chemical and meteorological factors. The connection between the motor vehicle and the towed vehicle is made with a complex towing system, with the towbar being among the most important components of this system.

Towing systems for cars are completely different from other systems found on trucks, tractors, etc. In general, car towing systems are similar in shape, but differ dimensionally from car to car, due to body shape gauge, vehicle height, and other reasons, which also differ from car model to car model.

The compositions of towing systems are approximately similar in all car models, but their differences can be as follows: the mounting flanges on the chassis can be of several shapes or be made up of two or more parts, connected to each other either by welding or by nuts and bolts; the distance between the clamping flanges of the hook may vary, depending on the type of towbar; the strength bar can be bent in two or four points, depending on the chassis, to bypass various components of it; and the tow hook can have many shapes, so as not to overlap the rear bumper of the car, also depending on the model of the hook. Most tow hooks are made from a circular bar that is turned and then bent, flattened, and drilled. The towing hook standard stipulates that the ball has a diameter of 50 mm, with the construction of the trailer requiring coupling with an inner radius that allows the hook ball to penetrate and rotate. The most common towbars used on cars are L-shaped.

Designing towbars starts with determining the maximum load that a vehicle can tow, but their sizing must also take into account the rear bumper, which must go around it, so the length L is considered to be the distance between the center of the sphere and the midpoint of the distance between the two holes, while the height H is the distance between the center of the sphere and the axis passing between the two holes. In addition to the mentioned dimensions, it should be specified that these hooks are available with a bending radius R between 25 and 120 mm and a bending angle α with values between 67° and 150°, but also with two bends, both on the inside, or one on the inside and the other on the outside.

The interest shown in the manufacturing and use of towing systems has led to the appearance of studies on these systems. Experiments simulating real operating conditions have been performed and the lifetime of such systems has been determined [27]. The shape of the towbar has become classic. However, minor changes to the shape and dimensions of the hook can bring about major benefits in operation [28]. In the mentioned paper, five parameters were considered as design variables. A new improved design was, thus, obtained with the optimized values determined from the study. The studies dealt with improving the quality of the towbar in passenger cars, taking into account the usefulness of this component [29]. Other aspects of the use of towing systems are described in [30–32], and materials that qualify for the manufacturing of this component are studied in [33,34].

In the framework of this paper, we propose carrying out a study on the towing systems used in cars if alternative materials were used for the manufacturing of the towbar. Along with the steel hook, considered as a control specimen, a composite towing hook and three towing systems with towbars made of aluminum or aluminum alloys are manufactured. Based on these systems, which are calculated with the classical methods, experimental measurements are made and, finally, conclusions are drawn regarding the advantages and disadvantages offered by the different solutions and materials used.

2. Models and Methods

2.1. Presentation of the Analyzed Towing System

The towing system chosen for carrying out the theoretical and experimental research is that used to equip passenger cars (Figure 1). To fix the towing system to the chassis of the car, it is necessary to disassemble the rear bumper and then reassemble it. Fastening the towing system to the vehicle structure is achieved with four M10 x 100 bolts and four M10 nuts. After mounting the cross beam and the bumper, the last operation is to attach the tow hook and electrical connection. The hook is attached with two M12 x 70 screws and two M12 nuts.

For a towbar made of S355J2 steel, the characteristics of the material are as follows: $E = 2.1 \times 10^5$ N/mm^2, $\sigma_e = 355$ N/mm^2 and $\sigma_r = 470$–630 N/mm^2.

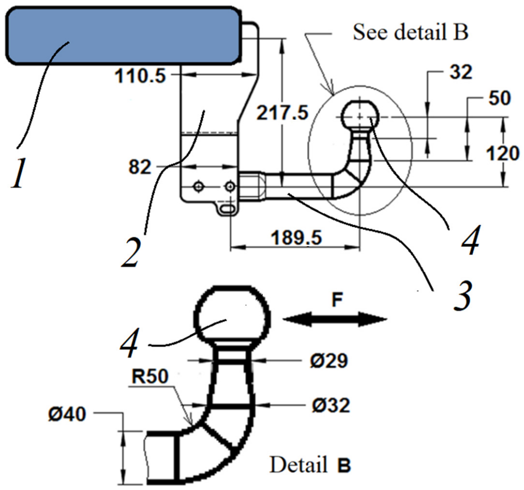


Figure 1. Dimensions of the towing system. 1—car; 2—support; 3—towbar; and 4—ball.

2.2. Classical Calculus Method

For the calculation applying the classic methods from the strength of materials, the considered towing system is presented in Figure 2.

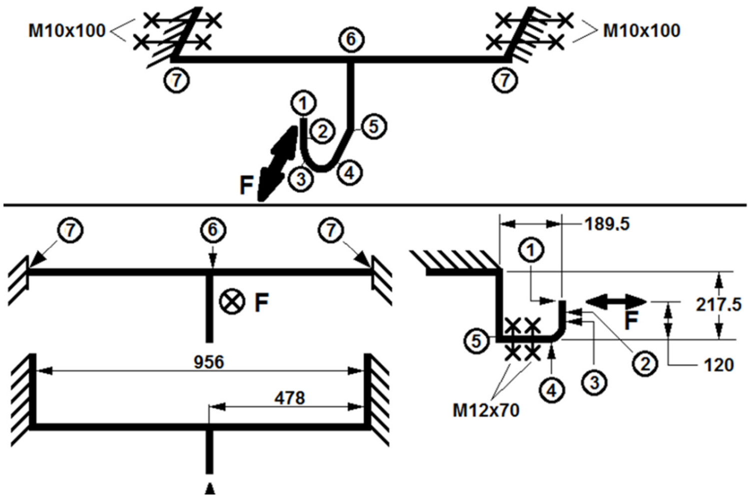


Figure 2. Simplified sketch of the studied towing system. Points 1, 2, ..., 7 are points of interest where the calculations will be made.

The towing system is considered to be fixed to the vehicle chassis by the means of the 4 M10 x 100 bolts. The towing hook is also considered to be fixed to the structure of the towing system due to its attachment by the means of the 2 M12 x 70 bolts. The force F is parallel to the ground and is considered to be directed towards the center of the towbar ball, towards the vehicle (Figure 3). This force comes from the mechanical connection between the trailer and the pulling vehicle, and the value of the maximum force is calculated during sudden braking, depending on the mass of the trailer and the deceleration value of the vehicle–trailer combination. The mass of the trailer is of interest, because during braking, the trailer tends to push the vehicle due to inertia if the trailer is not equipped with its own braking system. A similar force occurs when the vehicle accelerates, with the trailer tending to hold the vehicle in place and the force being directed in the opposite direction to the direction of motion. The force exerted by the trailer during braking is greater than that when starting, because usually, the deceleration from braking is greater than the acceleration of the vehicle–trailer assembly [35].

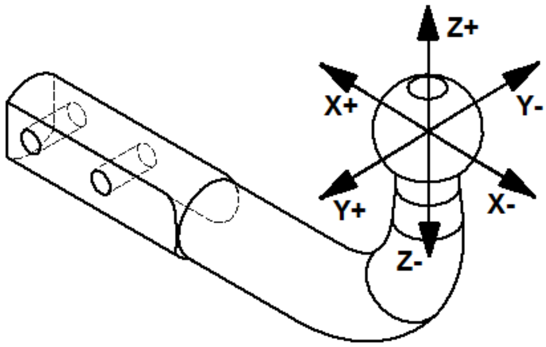


Figure 3. The orientation of force F during the running of the vehicle–trailer assembly.

In reality, the force exerted by the trailer on the towing hook while driving is in all 3 directions, due to the following considerations, as shown in Figure 3:

- The variable angle in the horizontal plane between the longitudinal axes of the vehicle and the trailer, which occurs on roads with curves, introduces forces in the X and Y directions;
- The variable angle in the vertical plane between the longitudinal axes of the motor vehicle and the trailer, when the assembly travels on sloping and ramped roads or bumpy roads, introduces forces in the X and Z directions;
- The most frequent and required direction is the longitudinal X direction, during braking and acceleration.

To determine the value of the maximum force that can act on the hook, the following characteristics are needed.

- The relationship by which the value of the force is determined:

$$F = m_R.a_R \tag{1}$$

where a_R is the deceleration of the total assembly. It is considered to be a trailer with the maximum mass allowed for motor vehicles: m_R = 750 kg.

- Because braking is discussed, it means that there is deceleration, determined by the relationship:

$$a = \frac{\partial v}{\partial t} \Rightarrow a = \frac{\Delta v}{\Delta t} \Rightarrow a = \frac{v_i - v_0}{t_f} = \frac{27.78 - 0}{2.53} = 10.98 \left[\frac{m}{s^2}\right] \tag{2}$$

The technical book of the car does not specify the braking time necessary to determine the acceleration (deceleration), but the braking distance–*sf*, from the initial speed: v_i = 100 km/h = 27.78 m/s to v_0 = 0 km/h = 0 m/s, and s_f = 35.2 m.

- Starting from the displacement relation (in the present case, the braking distance—s_f), the value of the braking time—t_f can be determined:

$$d = \frac{a \cdot t^2}{2} \Rightarrow t_f = \frac{2 \cdot s_f}{v_i - v_0} \Rightarrow t_f = \frac{2 \times 35.2}{27.78 - 0} \Rightarrow t_f = 2.53\ [s] \tag{3}$$

where *sf* = *d* and *tf* = *t*;

The values of deceleration '*a*', braking time 't_f', and braking distance 's_f' are calculated under conditions where the car is braking without the trailer attached (see Equations (4)–(8)). The braking of the vehicle–trailer assembly is carried out over a longer distance, because the tendency of the trailer is to push the vehicle and increase its braking space and time, and the deceleration value is lower, so these parameters are considered proportionally with the mass of the vehicle and the mass of the whole assembly, Equation (4).

$$m_{auto} = 1.933\ kg;\ s_f = 35.2\ m\ ;\ t_f = 2.53\ s\ ;\ \ a = 10.98\ m/s^2 \tag{4}$$

$$m_{ans} = m_{auto} + m_r = 1.933 + 750 = 2683\ [kg] \quad (5)$$

$$s_{f-ans} = \frac{m_{ans} \times s_f}{m_{auto}} = \frac{2.683 \times 35.2}{1.933} = 48.86\ [m] \quad (6)$$

$$t_{f-ans} = \frac{m_{ans} \times t_f}{m_{auto}} = \frac{2.683 \times 2.53}{1.933} = 3.52\ [s] \quad (7)$$

$$a_{ans} = \frac{m_{ans} \times a}{m_{auto}} = \frac{2.683 \times 10.96}{1.933} = 7.9\ [m/s^2] \quad (8)$$

Knowing the deceleration ($a_R = a_{ans} = 7.9$ m/s^2) and the mass of the trailer ($m_R = 750$ kg), using Equation (1), the force value $F \approx 6$ k will be obtained.

The type approval sheet for this towing system specifies the value of the test force at 2×10^6 cycles, $F = 7.26$ kN, 20% higher than the maximum value resulting from the calculations; therefore, for the study to be thorough, the resistance calculations will consider: $F = 7.5$ kN.

2.3. Finite Element Method (FEM)

The Finite Element Method (FEM), applied for more than five decades in the field in its classic form [36], has proven to be an extremely powerful and precise tool for the development of research in the field of vehicle engineering and that of their components [37]. Thus, a study dedicated to the towing system in parallel with the use of FEM is presented in [38]. Various aspects related to the study, design, and manufacturing of these systems can be found in [39–46].

Inventor software developed by the AutoDesk company was used for the modeling and calculation of the stress and strain that appear in the components of the towing system. The elements are modeled individually and then assembled for the whole system. The areas of interest to engineers are at the ends of the beam and at the radius of curvature of the tow hook, on the inside. Therefore, the results obtained with the FEM for these sensitive areas will be followed. The components of the towing system, consisting of the resistance beam and the flanges welded with it, have a simple construction and geometry. Thus, they can be discretized by 2D surfaces or even 1D lines. However, the geometry of the towing hook is complex and contains numerous parameters. Three-dimensional elements will be used for discretization.

The most requested part of the towing system is the hook, which is why it is given special attention in the calculations. The discretization that provided us with the results considered in the paper consists of 54,133 elements that are defined by 86,174 nodes. The force required by the system will be applied in the center of the sphere, in the longitudinal direction of the vehicle, with the direction towards the car. The value of this force acting on the towing system we previously showed to be F = 7.5 kN.

2.4. Experimental Methods of Stresses' Determination

In general, for the determination of mechanical quantities in the laboratory, the classical method used is tensometry [47–53]. Its purpose is to measure the deformations on the surface of a stressed body. In order to obtain useful values and finally determine the stresses, the deformations are measured, and then by calculation applying Hook's Law, the stresses are calculated. In current practice, there are several variants that can be used to measure voltages:

- Electrical tensometry when the technique of measuring non-electric quantities (generally mechanical) is performed with electrical methods. In this way, specific deformations are determined in a first phase, after which, the stresses are calculated;
- Photoelasticity is an optical method that uses the birefringence properties of materials. The method provides information about the voltages in the entire analyzed system. The results obtained are useful and in line with reality, even when there are structures with complex geometry;

- Brittle lacquers—this is based on covering the researched model with a thin layer of brittle lacquer and loading it in order to determine the state of stress. The varnish's resistance to breaking or cracking is lower than the elasticity limit of the studied body. The thickness of the varnish layer is a maximum of 0.15 mm;
- VIC (Video Image Correlation) is a modern and very useful optical method due to the precise results it can provide.

In the present study, photoelasticity is used to determine the stresses in the towing bar.

3. Experimental Study of the Proposed Materials

The material from which towing hooks are currently manufactured is steel. In this paper, the authors propose the use of alternative materials made of aluminum (or aluminum alloys) and fiber composites. In order to perform a comparative evaluation of the proposed materials, samples were made from the three types of materials that were subjected to mechanical tests. Based on these tests, useful conclusions were drawn for the manufacturing of towbars from alternative materials in the automotive industry.

The testing machine used was Lloyd LS Plus 100 (Figure 4) (Lloyd Instruments-AMETEK, Berwyn, PA, USA). The advanced material testing machine LS100Plus incorporates an extensive range of research functions, so it is ideal for performing complex and routine tests in applications of up to 100 kN [54]. The features of the machine are its simplicity of configuration, operation, and maintenance; high precision load measurements; constant maintenance of loads; data sampling rate of 8 kHz; charging speed control; saving of up to 600 test results; 10 programmable settings for testing; pre-loading of samples; multi-stage testing with NEXYGENPlus software; extension resolution of <0.03 microns; display options in several languages; multi-unit display options; updatable Flash; and a wide range of load cells, handles, rods, strain gauges, and temperature chambers.

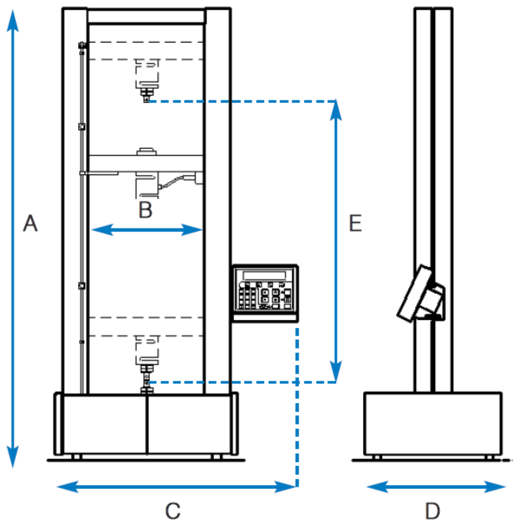


Figure 4. The LS 100 Plus testing machine. A, B, C, D, E represent the characteristic dimensions of the testing machine.

3.1. Materials Used for Specimens

The following were used to carry out the tests in order to compare the behavior of different types of materials:

1. Carbon fiber (CF) with unidirectional fabric + resin type SIKADUR 330 (Sika, Zurich, Switzerland, see [55]);
2. CF with unidirectional fabric + Epoxy L385 resin + 385 hardener (R&G Faserverbundwerkstoffe GmbH, Boeblingen, Germany see [56]);
3. Steel equivalent to that of the towing hook, S355J2, machining by chipping (Shanghai Bozhong Metal Group, Shanghai, China, see [57];
4. 99.7% pure aluminum, gravity casting, AAl [58];

5. Aluminum alloy AlSi10MnMg, pressure casting [58];
6. Aluminum alloy AlSi12Cu1Fe, pressure casting [58].

3.1.1. Specimens Made of Composite Materials

For the production of samples from composite materials, the most advantageous solution in terms of mechanical strength was chosen, namely, CF with unidirectional fabric. It was decided to make two types ofAAmples, both based on CF, but with two different types of resins; the first with the name SIKADUR 330 [56] and the second with the name Epoxy L385 [57], to which hardener 385 was added. The weight of the two mixtures was 60% CF and 40% resin. Both types of composite materials were extremely resistant to mechanical action, but the CF composite material with epoxy resin showed a better elasticity and that with SIKADUR resin was more fragile, a fact also found during the experimental determinations.

From the point of view of sample manufacturing, both types of materials went through the same stages and were also made from 10 layers of CFs at once, going through the following sequence of operations: preparation of the unidirectional CF strips, preparation of the two half-matrices, preparation of the resins, making the mixture between the CF and the two types of resins, adding 4 mm shims to maintain the thickness of the composite plates, closing the mold, maintaining the mixture for 24 h for the rigid formation of the composite plates, releasing the mold, releasing the two composite plates, cutting with a diamond disc and grinding on a grinder with a continuous abrasive belt, and obtaining specimens for tensile tests and bending tests [59].

To improve the mechanical properties of the CF-based composite with SIKADUR resin, the developer of this product proposes a 4 h heat treatment of the polymerized plate in the oven at a temperature of 60 °C, which was applied. The thickness of the plates obtained was not exactly 4 mm, with variable tolerances within ±0.5 mm, which was why, after obtaining the samples, they were measured individually in order to comply with the calculation of breaking stresses. Also, the polymerized plates were cut manually, without a precision automatic machine, so their width differed, which was why the widths of the specimens were measured individually, an action also carried out in order to strictly comply with the calculations.

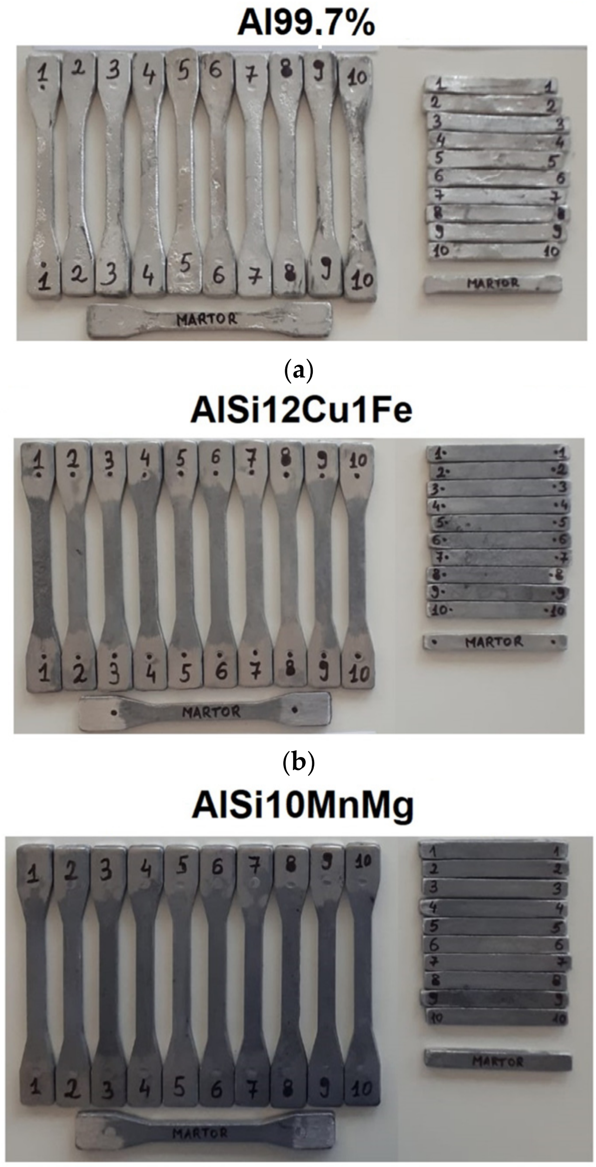
3.1.2. Aluminum and Aluminum-Based Alloys Used

To realize the aluminum-based samples, two types of alloys used in the automotive industry, from which seat belt retractors for cars are made, were chosen. After which, it was also desired to experiment with 99.7% pure aluminum.

The alloy brands used in the manufacturing of the samples were AlSi10MnMg and AlSi12Cu1Fe, known for their high-pressure casting properties, but also for their high resistance to breakage, vibrations, mechanical shocks, and fatigue (Figure 5).

The process of obtaining the samples was performed by casting under pressure in the shell for the samples of aluminum alloys, and for the samples of pure aluminum, this process was conducted by gravity casting in the forming mixture. The pure aluminum samples could not be obtained by pressure casting, because the solidified material of samples made of this material was very soft, and when removing the part from the shell, the eliminators mutilated the material, destroying the samples, which was why it was decided to cast in a mixture.

If the process of casting under pressure in the shell was very stable regarding the final dimensions of a piece, and the proportions of all the samples obtained were identical (regarding the relevance of the strength calculations), the same cannot be said about the gravity casting in the forming mixture. The samples obtained from pure aluminum were measured individually in the section, in order to exactly respect the data entered in the strength calculation. Specimens for bending tests were obtained by cutting and grinding tensile specimens, and the validation of all specimens was performed non-destructively, regarding the level of porosity from the casting process, either by gravity or under pressure.



(**c**)

Figure 5. Tensile and bending specimens, made of (**a**) Al99.7%, (**b**) AlSi12Cu1Fe, and (**c**) AlSi10MnMg.

3.1.3. Steel

The grade of steel used in the manufacturing of the specimens was S355J2. The semi-finished product from which the samples were made was sheet metal with a thickness of 4 mm, cut by laser, and because this process thermally influenced the cutting area, producing a superficial tempering of the sheet, the cutting was made with additions of 5 mm on each side, additions that were later removed on a CNC milling machine to avoid a possible influence on the results of the experimental research on mechanical strength. Analogous for the specimens intended for the bending test, the holes at the ends of the specimens intended for the tensile tests had a purely technological role, to help fix them on the milling device in order to obtain the hourglass-shaped outer outline (Figure 6).

Due to the fact that the final dimensions of the samples were obtained using a high-precision machine, the dimensions of all the samples were constant, and their section was 4×10 mm, which is why it was not necessary to measure each sample.

The specific mass (density, ρ [g/cm^3]) of the materials varied according to the chemical composition of which they were made, and the density values of the materials studied in the present paper are shown in Table 2.

Figure 6. Tensile and bending specimens, made of steel.

Table 2. The density masses of the materials studied in the paper.

Material	Density ρ [g/cm^3]
Steel	7.75–7.85
Carbon Fiber	1.7–1.8
Aluminum/Aluminum alloy	2.6–2.7

It is noted that the material with the highest specific mass was steel, which is why the study of obtaining towing hooks from alternative materials was desired, precisely with the idea of reducing the total mass of the vehicle.

The materials proposed to replace steel have much lower values of this property, with the specific mass of CF composite materials being 20% that of steel and the density of aluminum and aluminum-based alloys being 33% that of steel.

3.2. Comparison of the Results of the Specimens Subjected to Traction

Ten samples were analyzed for each material. The breaking force was determined for each specimen. Calculations were also performed regarding the tensile breaking stress of each type of material (Figure 7).

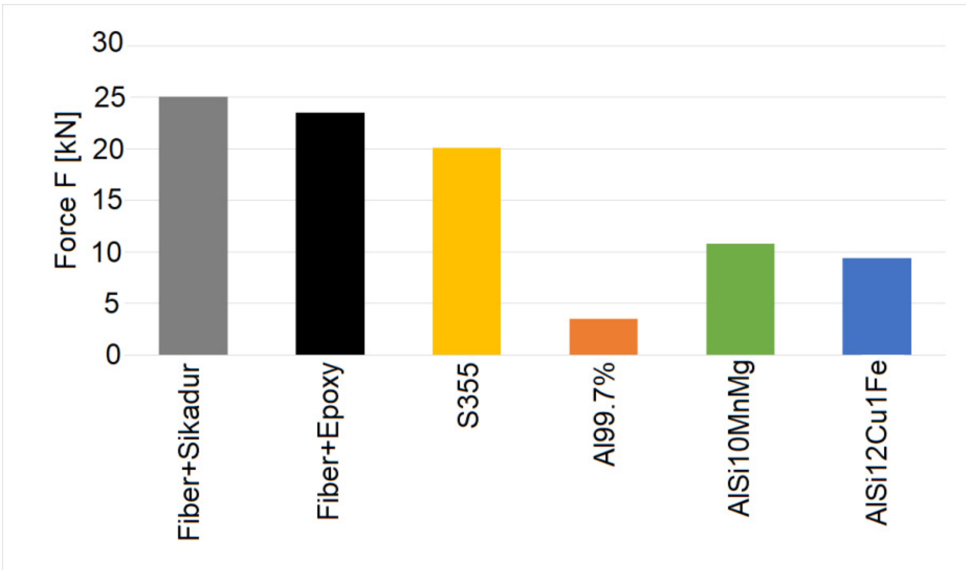


Figure 7. Tensile breaking strength of the specimens.

From Figure 7, it can be seen that the highest breaking forces of the samples were in the cases of those made of CFs and Sikadur-type resin. Equation (9) (see Figure 8) was applied to determine the tensile breaking stress specific to each specimen:

$$\sigma_{tr} = \frac{F}{A_S} = \frac{F}{g \times h} \tag{9}$$

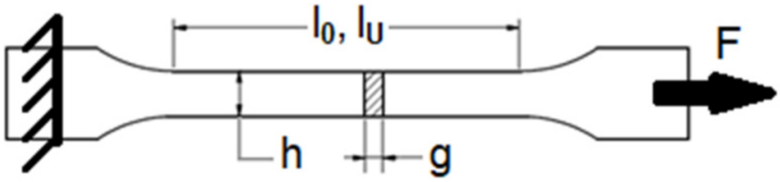


Figure 8. Specimen dimensions.

A stress diagram was made (Figure 9), and it was actually found that the CF samples with epoxy-type resin had the highest breaking resistance.

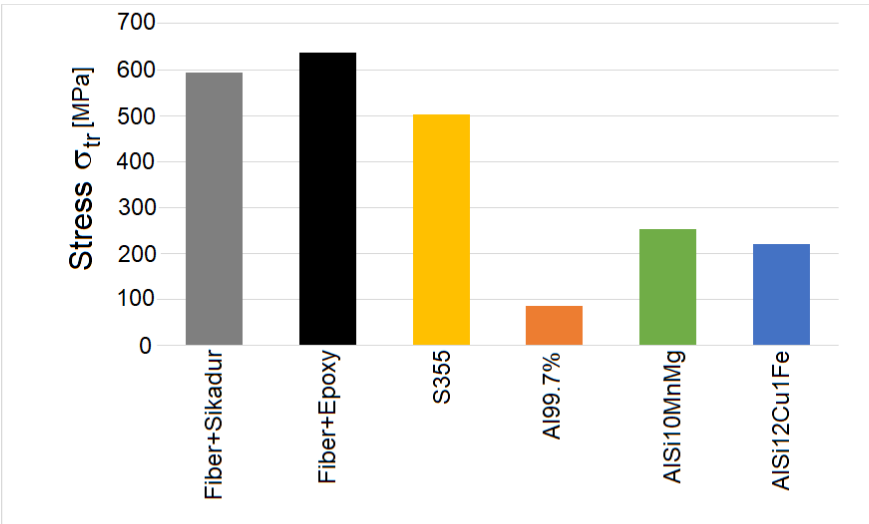


Figure 9. The tensile failure stress of the specimens.

It was found that the samples with the most constant stress behavior were those made of steel, justified by the fact that the homogeneity of this material is very good, and there are a multitude of studies and various theories in this sense. The 99.7% pure aluminum specimens were the least resistant to breaking, being the weakest material in terms of breaking stress. For this reason, they are not even found in the industry of resistance structures. By improving the properties of aluminum by alloying with various chemical elements, it is observed that the alloys gained a high strength compared to that of pure aluminum.

To analyze and compare the state of homogeneity, the graph in Figure 10 was created, based on the data obtained by calculating the variation in the stress field of the samples.

A first positive remark is the fact that the steel samples behaved almost identically, with the variation field being of the order of 7.7%. An unsatisfactory remark is given for the samples made with the other types of materials.

The homogeneity of the samples made of pure aluminum was the most deficient, with a very wide variation field of 68.7%, knowing that aluminum is an unstable material. However, the gravity casting process was also deficient, and the state of tension of the samples made of this material was very unstable. The behavioral variation in these specimens was highly fluctuating, representing a major disadvantage in the industry.

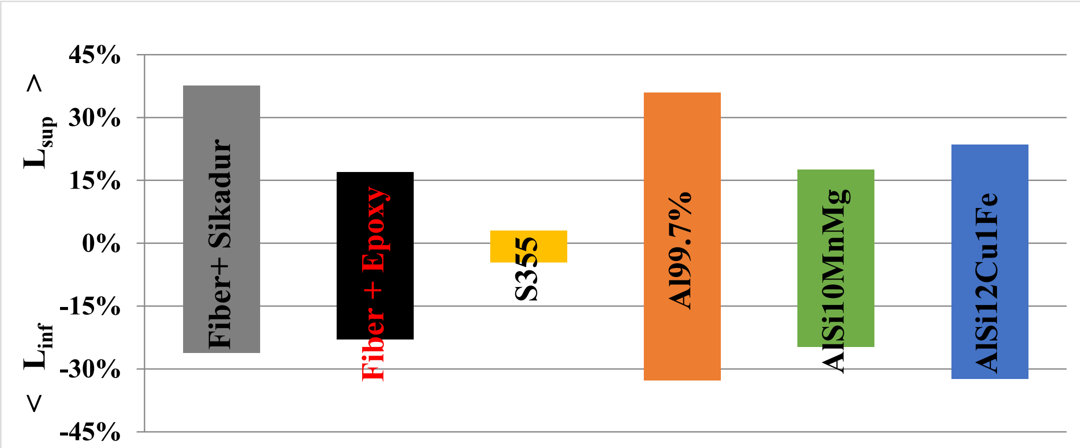


Figure 10. Variation in the tensile stress field on the specimens. *L* represents variation in the values of stress field.

The CF specimens with Sikadur resin behaved similar to the pure aluminum specimens, reaching a field variation of 63.9%.

The CF and epoxy resin specimens showed more advantageous behavior in that the difference between the highest and lowest stresses was closer, with the variation in the stress field being about 40%.

The specimens made of aluminum alloys had a lower stress field variation than those made of pure aluminum and CF with Sikadur resin, the behavior of the AlSi10MnMg alloy was (≈42%), very close to that of CF with epoxy resin, and the variation in the voltage field of the AlSi12Cu1Fe samples was (≈56%) less.

The state of deformation can be considered in two forms:

- Δl, information found in the stress diagram,
- strain ε, information resulting from Equation (10):

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l_U - l_0}{l_0} \tag{10}$$

where l_0 = 70 mm, representing the calculated length of the specimen.

Looking at the deformations occurring after the stresses of different types of materials, as shown in the information attached in Figure 11, the following statements can be made:

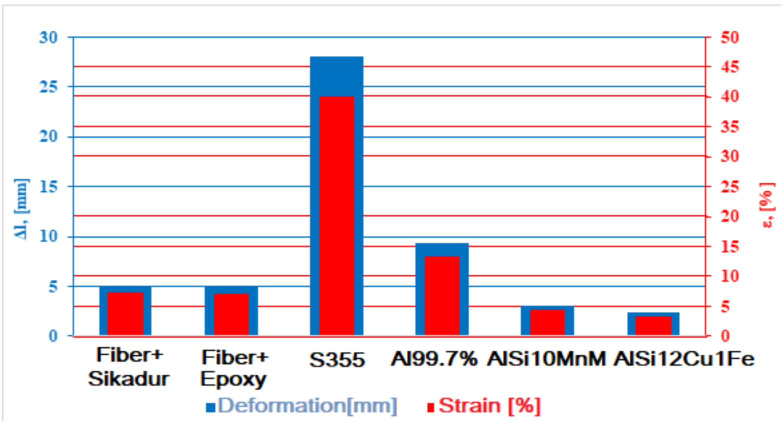


Figure 11. Deformation and strain in specimens in the points of materials failure.

The most elastic material by far was steel, with an elongation of 40%;
The second most elastic material was pure aluminum, with an elongation below 15%;
Both types of composite materials had elongation slightly above 7%;

Aluminum alloys had the lowest elongation, with AlSi10MnMg having 4.5% elongation and AlSi12Cu1Fe having 3.4% elongation.

3.3. Comparison of the Results of the Specimens Subjected to Bending

From Figure 12, it can be seen that the highest breaking force of the samples was in the case of those made of steel.

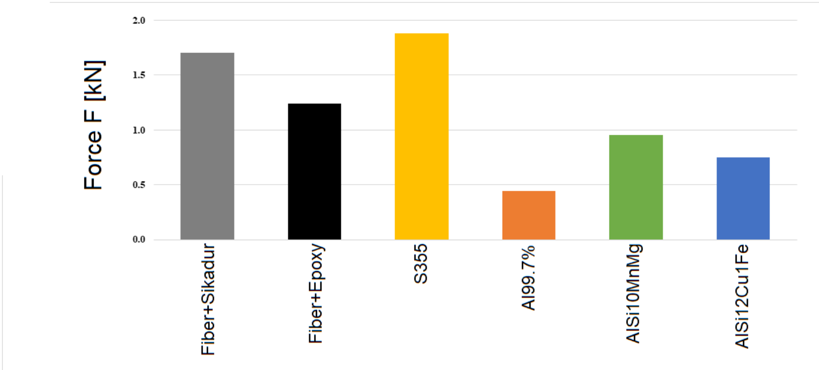


Figure 12. Bending breaking force.

The highest stress occurred halfway between the two supports, at the point where the force acted. The determination of the bending breaking stress for each specimen was carried out by applying Equation (11) of Navier, with the constitutive elements from Figure 13:

$$\sigma_{i2} = \frac{M_i}{W_z} = \frac{\frac{F}{2} \times B_F}{\frac{h \times g^2}{6}} = \frac{\frac{F}{2} \times \frac{l_0}{2}}{\frac{h \times g^2}{6}} = \frac{3F \times l_0}{2h \times g^2} \tag{11}$$

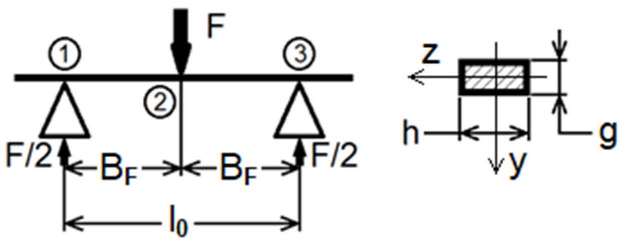


Figure 13. Specimen dimensions.

It was found that the highest bending strength was presented by the steel samples (Figure 14).

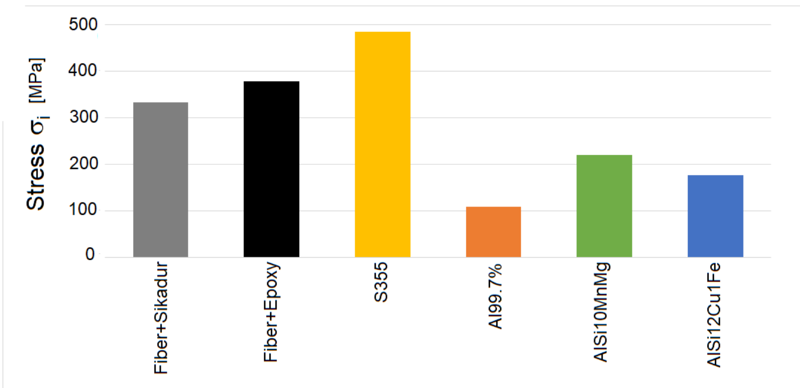


Figure 14. Bending breaking stress.

Pure aluminum had the lowest bending strength, and among the aluminum alloys, AlSi10MnMg showed a better performance than AlSi12Cu1Fe. The 99.7% pure aluminum specimens were the least resistant to breaking, being the weakest material from this point of view.

The state of homogeneity or the variation in the stress field of specimens of the same types of materials can be observed in Figure 15.

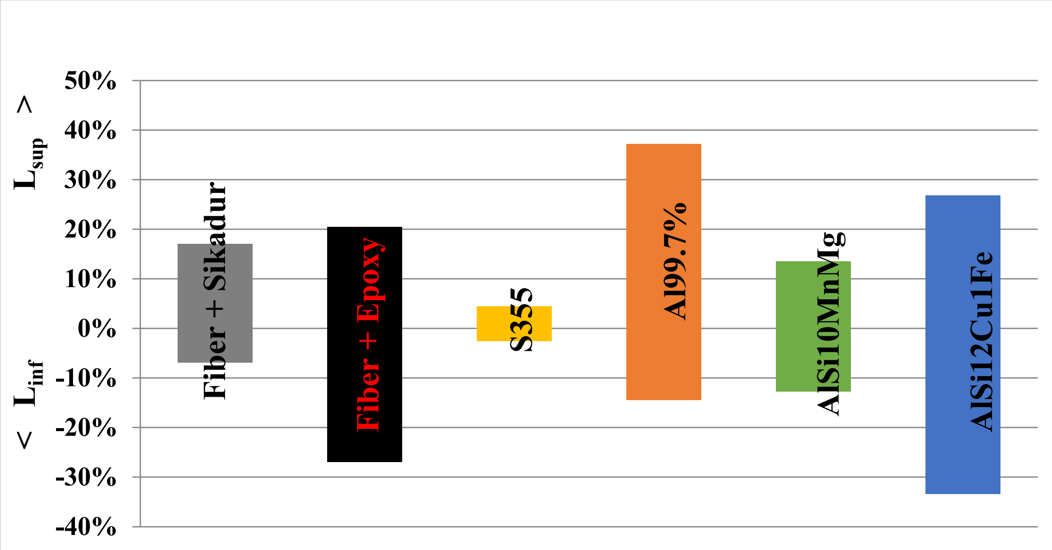


Figure 15. The variation in the stress field at break on the bending specimens.

It is confirmed that the samples made of steel behaved almost identically, with the variation field being in the order of 7%, and the samples made with other types of materials showing very high values of the tension field.

At the opposite pole is the stress field of the specimens made of AlSi12Cu1Fe with 60.3%, pure aluminum with 51.6%, and CF with epoxy resin with 47.5%. The stress state of the specimens made of these materials was very unstable, and the variation in their behaviors in response to the bending stress was very fluctuating. The CF specimens with Sikadur resin showed a better performance than the CF specimens with epoxy resin, and the AlSi10MnMg aluminum alloy specimens showed a better performance than AlSi12Cu1Fe.

The CF and Sikadur-type resin specimens showed a more advantageous behavior, in the sense that the difference between the stresses of the best- and worst-performing specimens was closer to 0%.

However, it is worth noting the behavior of the samples when bending. Those made of pure steel and aluminum tended to be able to deform without limit, without breaking, which is why they had higher elongation coefficients; the samples made of CFs and those of aluminum alloys were completely destroyed, ending up forming two different parts, because the materials are more brittle.

3.4. Discussion

The experimentally obtained values of the specific mechanical characteristics of the compared alternative materials allow the following conclusions to be drawn:

- The tensile strength (breaking strength—σ_r) obtained experimentally was, on average, 620 MPa for the CF samples, compared to 2,700 MPa, the theoretical strength of CF, but these samples had 40% epoxy resin in their composition;
- The tensile strength (breaking strength—σ_r) obtained experimentally was, on average, 240 MPa for the AAl samples, a value found in the range of the theoretical values of the tensile strength specific to aluminum alloys of 150–450 MPa;
- The tensile strength (breaking strength—σ_r) obtained experimentally was, on average, 87 MPa for the pure aluminum samples, a value found in the range of the theoretical values of the tensile strength specific to aluminum of 70–100 MPa;

- The experimentally obtained elongation of the specimens from AAl was 4%, a value that fell within the theoretical range specific to the elongation of AAl of 0.5–18%;
- The experimentally obtained elongation of the pure aluminum samples was 13%, a value that was outside of the theoretical range specific to the elongation of pure aluminum of 20–45%.

Analyzing all the information from the process of testing the specimens, both in tension and in bending, it cannot be stated that a particular type of material had the best-performing properties, with each type having certain more or less important advantages. Table 3 presents a comparative analysis with the advantages and disadvantages of each type of material.

Table 3. The advantages and disadvantages of each type of material.

Material	Advantages	Disadvantages
Steel S355	- The homogeneity of the structure; - Stability of the obtaining process; - Best bending performance; - High traction performance (lower CF).	-The highest specific mass.
Carbon fiber + Sikadur resin	- High tensile performance (lower CF + epoxy); - Above average bending performance; - The lowest specific mass.	- Inhomogeneity of the structure; - Difficult obtainment process.
Carbon fiber + Epoxy resin	- The best traction performance; - High bending performance (lower than S355); - The lowest specific mass.	- Inhomogeneity of the structure; - Difficult obtainment process.
Aluminum 99.7%	- Continuous progress in technologies for obtaining finished products; - Specific mass much lower than S355, but higher than CF.	- The worst traction performance; - The worst bending performance.
Al AlSi10MnMg alloy	- Continuous progress in technologies for obtaining finished products; - Specific mass lower than that of S355; - Superior tensile performance Al99.7% and AlSi12Cu1Fe; - Superior bending performance Al99.7% and AlSi12Cu1Fe.	- Lower traction performance as S355 and CF; - Lower bending performance as S355 and CF; - Higher specific mass F.
Al AlSi12Cu1Fe alloy	- Continuous progress in technologies for obtaining finished products; - Lower specific mass S355; - Superior tensile and bending performance Al99.7%.	- Tensile and bending performance inferior to S355, CF and AlSi10MnMg; - Higher specific mass CF.

4. Study of the Alternative Solution for the Manufacturing of Towbars

4.1. Manufacturing of the Towbars

In order to compare the stresses and deformations through experimental determinations on the towing hooks made of several types of materials, five samples were made: one of steel, one of composites based on CFs with metal inserts, two hooks of two types of aluminum alloys, and one of aluminum with a 99.7% purity. The manufacturing processes were diverse, with several phases and each material using specific technology to obtain the tow hook. The vast majority of towing hooks found in vehicles with a mass of less than 3.5 tons are simple and have low purchase and installation prices.

The manufacturing process used was the classic one, so we will not insist on it.

4.2. Technological Requirements Imposed by Composite Materials

It is known that composite materials are very difficult to recycle, reuse, and remodel, which is why, from the design phase of products made from these types of materials, the exact dimensions must be known and the manufacturing technology must be used correctly. A possible correction of the dimensions or geometric shapes of these landmarks is very difficult or even impossible to achieve after polymerization.

To manufacture the towing hook from composite materials based on CFs, a two-part mold was made, which copied the geometry of the towing hook made of steel (Figure 16). The mold was made of glass fiber polymerized with epoxy resin, with four embedded centering bushings for perfect assembly for the execution of the towing hook.

Figure 16. Carbon fiber towbar mold.

The specimens made with both types of resins showed similar behavior in the tensile and bending tests, but the easy handling of CF mixed with epoxy-type resin (due to its low viscosity) led to the choice of making the towbar from CFs and resin epoxy L385. It should be specified that, in the structure of the CF towing hook, two metal bushings were embedded next to the fixing holes on the chassis to provide resistance both to friction with the screw threads and to the tightening of the flanges on its flattened area. Also, for the benefit of mechanical resistance regarding the tests to which the towing hook was subjected, the CFs in the structure of the towing hook were continuous, with their route being illustrated in Figure 17.

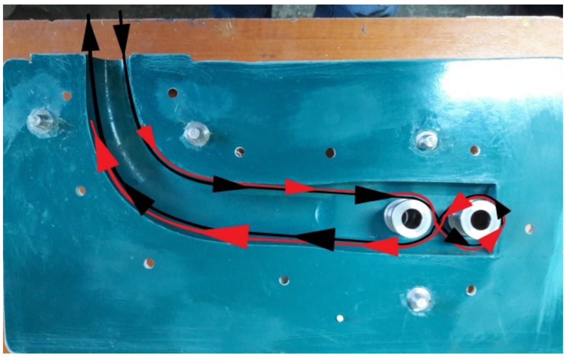


Figure 17. Carbon fiber trail in the towbar.

The functional and overall dimensions of this towbar were obtained by the shape of the mold, which cannot be changed by mechanical actions or other technical solutions, as is the case with the steel towbar, whose shape can be changed by forging.

4.3. Technological Requirements Imposed by Aluminum and Aluminum Alloys

The multiple advantages that silumins offer have attracted interest in making towing hooks from this material. Additionally, in order to highlight the major differences in terms of mechanical tests between the pure aluminum and aluminum, it was decided to make a towing hook with 99.7% aluminum.

Since by comparing the tensile and bending results of the specimens from the two types of alloys, AlSi10MnMg and AlSi12Cu1Fe, different behaviors regarding strength were encountered, it was decided to manufacture the towing hook from both AlSi10MnMg and

AlSi12Cu1Fe, alloys used in the production of automotive equipment (seat belt retractor assembly), as well as in the production of the external components of electric motors.

The process of obtaining the towing hook was conducted by manual gravity casting in classic molding mixture. The realization of the form, with the help of the towing hook made of steel, is presented in Figure 18.

Figure 18. Forming the mold for casting. Left side: The model; Right: The negative.

The hook had a plane of separation between the two half-molds in the middle of it; the supply of material was made through a vertical channel made in the upper half-mold (Figure 19). The final piece is shown in Figure 20.

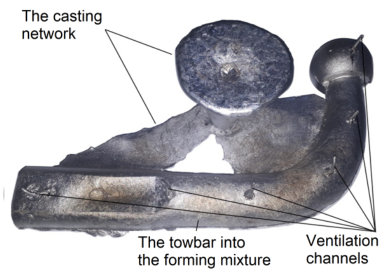


Figure 19. The raw piece.

Figure 20. The aluminum final towbar.

The rough semi-finished product obtained by gravity casting had to be processed through three mechanical processes in order to obtain the towing hook made of aluminum or silumin, namely:

- The removal of the casting network, an operation performed by cutting with a continuous band saw;
- The complete grinding of the burr resulting on the contour of the part (between the separation planes of the forms) and the burr resulting after removing the casting network and the ventilation channels, an operation carried out on a grinder with a continuous abrasive belt;
- Drilling the hook fixing area on the metal frame of the towing system, an operation performed on a conventional milling cutter.

In the end, through the process of gravity casting and related mechanical processing, six towing hooks were obtained, two of each type of aluminum and silicon. To these, the towing hooks made of steel and CFs were added, thus resulting in five types of materials used in the manufacturing of towbars (Figure 21), namely:

1. Steel (S355J2);
2. Carbon fibers;
3. Al99.7% (pure aluminum);
4. AlSi10MnMg;
5. AlSi12Cu1Fe.

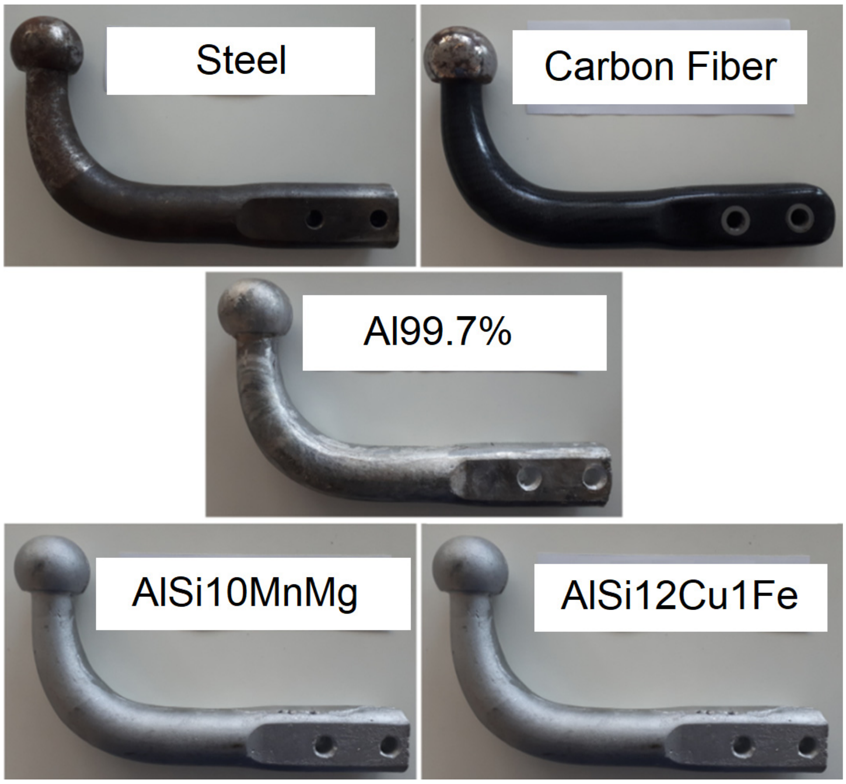


Figure 21. Types of materials used in the manufacturing of towbars.

5. Detailing the Experimental Process for the Five Solutions

We underline that,

- Within the framework of the experimental determinations, the entire towing system will be tested, then, separately, the towing hooks on a traction machine. The braking of the trailer vehicle is simulated by applying a compression force through the test machine. The traction machine used can develop 100 kN;
- Determinations are made by verifying that the samples of the towing hooks can withstand a force greater than or at least equal to 7,500 N. This value we previously obtained in Section 2, resulting from the calculation of the heavy braking of a vehicle with an attached trailer. The trailer will tend to push the vehicle forward.

In Table 4 [35], the results obtained from the experimental determinations are presented, adding the specific mass of the towing hooks.

A comparison between the values obtained by the three methods (two by calculation and one experimental) is made in Table 5.

Obtaining very advantageous results in terms of mechanical strength suggests the idea of oversizing the technical solution, which represents an excess of material and direct costs, but also an additional load on the vehicle, with the repercussion of added energy consumption and an automatic increase in the level of noxes emitted by the thermal engine. Comparing the results obtained by the classic stress determination and FEM, very close similarity in the values is found, which is why the mutual validation of the two methods is considered. It is observed that the maximum stress values are approximately 50% of the elastic limit value (σ_e = 355 MPa) of the material from which the towing system is made, therefore, the technical solution presents a safety factor of two. The system is not undersized or oversized, being considered a reliable system for the manufacturer's requirements. Also, the results obtained indicate that the most requested element in the whole towing assembly is the towing hook, and with good results, but much lower than those in the hook, is the resistance beam.

Table 4. Experimental measurements of towbars.

Material	Maximum Force	Maximum Displacement [mm]	Maximum Stress [MPa]	Specific Mass [Kg/m^3]
Carbon fiber	14.436	27.65	354.36	780
Steel S355	24.724	13.85	606.89	3.400
Aluminum Al99.7	5.134	54.60	71.31	1.050
AlSi10MnMg	8.504	18.80	208.74	1.050
AlSi12Cu1Fe	7.401	15.40	181.67	1.050

Table 5. The critical stresses obtained by the 3 methods.

Method	Area of Interest		
	The Inside of the Radius of Curvature of the Towbar, Σ_{int}	The Outside of the Radius of Curvature of the Towbar, Σ_{ext}	The Ends of the Strenght Beam of the Entire Towing System
	[MPa]	[MPa]	[MPa]
Classical calculus	188	117.04	63.82
FEM	184.9	118.6	63.4
Fotoelasticimetry	164.6	104.4	-

According to the theoretical analysis, the beam is slightly oversized, but it has a square pipe section with a wall thickness of 5 mm for technological reasons due to the integrity of the profile when welding the flanges at its ends and in the center, because in the manufacturing industry of towing systems, profiles with a minimum thickness of 5 mm are used.

Comparing the results obtained by the photoelastic method of stress determination with the other previously mentioned methods, it is found that the latter are lower by approximately 11%. The result obtained by the third method is not considered as unsatisfactory, as the difference is not excessively large, but the photoelastic method is more permissive in this case.

Also, the maximum value obtained for the stress allows us to state that the dimensioning of the towing system is compliant, being neither too high nor too low. An under-dimensioning of the proposed technical solution can lead to the premature destruction of the system, with the related risks, and over-dimensioning leads to high costs and additional energy consumption required to propel the vehicle.

Even though the photoelastic method obtained lower stress values compared to previous calculation methods, it provided a special view on the stress dispersion in the transition zone between the cylindrical volume of the material and the volume of the material determined by the geometry of the torus sector and regions of the towing hook, where it is observed that the line of the neutral axis moves to the inside of the radius of curvature (the axis of the centers of gravity of the cross-sections does not coincide with the neutral axis). The displacement of the neutral axis is according to the theory of a curved bar with a large curvature, the theory of E. Winkler. This theory has been used for bending stress distributions that are hyperbolic, passing through 0 on the axis of the center of curvature. Another meaning of neutral axis displacement is that the stress inside the radius of curvature is greater than the stress outside the radius of curvature (stress concentration effect). Also, regarding the behavior of the samples, it can be said that those from CF and AAl are very brittle, with very low elongation coefficients, and their characteristic curves almost linear compared to that of the steel and pure aluminum samples.

A major disadvantage in the behavior of these samples is their lack of homogeneity, and there are considerable differences between the samples of the same type with the exception of those from S355; with a well-documented preparation of the acquisition processes, much more satisfactory results could be obtained in this regard.

Analyzing the behavior of the samples, there was interest in making towing hooks from CF mixed with epoxy resin, AlSi10MnMg alloy (with this material showing better performances than that of AlSi12Cu1Fe), but out of the desire to confirm, a hook was also made from the second type of AAl, and, of course, they were compared with a hook made of S355 steel.

Considering the interest in studying the behavior of a towing hook with extreme displacement, without breaking and without imposing material damage hazards on the mechanical strength testing machine, it was decided to make a pure aluminum towing hook (Al99.7%), as it has been observed that these are very malleable and do not break.

Calculations showed that the minimum force acting on the towing hook must be 7.5 kN to validate the required strength of the hook during car braking.

By far the best strength was shown by the steel towbar, but the CF towbar showed very advantageous behavior, with the breaking force being almost double the breaking force required for product validation. The AAl towbars came very close to the validation limit, with the AlSi10MnMg one passing the test and slightly exceeding the required force, while the other was more deficient, as were the specimens in that alloy, failing the test but being very close to the limit.

In terms of sphere displacements, the most advantageous behavior was shown by the steel hook with the smallest displacement, with the CF towing hook having the most generous deflection. The unsatisfactory aspects presented by the towing hooks in AAl are due to the low plasticity it has, with the material being very fragile, and the breakage was sudden.

If, so far, only superlatives have been said about the behavior of the steel towbar, the advantages of alternative materials that surpass S355 should be highlighted.

When the strength of a hook is related to its mass (in the case of the same material), the material's performance indices are obtained, showing that the model made of CF is 2.5 times more efficient than S355, with AlSi10MnMg being 11% more efficient and AlSi12Cu1Fe being 3% below the performance of steel. These indices provide the satisfaction of research in the field of alternative materials for the manufacturing of towing hooks. Certainly, if the manufacturing processes for the production of both CF and AAl towbars were improved, to achieve more homogeneous designs, a better performance would be achieved even compared to steel.

To obtain more advantageous results for the components made of AAl, there are several ways, either through thermal treatments, where recrystallizations will be obtained in the structure of the material in order to improve the plasticity properties or by reducing the silicon content for better plasticity. On the other hand, silicon helps the metal bath to be more fluid, which is why the level of the chemical composition of the alloy should not be lowered too much.

Annealing thermal treatments to eliminate internal stresses in aluminum-based structures, stresses resulting from solidification after the casting process, can considerably improve the mechanical properties of aluminum alloy or pure aluminum components.

6. Shape Optimization of the Towbar

Following the results obtained in the previous sections, a more advantageous concept solution is proposed in terms of reducing the stresses in the critical area of the towing hook by changing its section geometry, keeping the same cross-sectional area for comparison (as an optimization element), but also the same volume of material corresponding to the reference towing hook.

A trapezoidal section can lead to a stress reduction of at least 25% compared to that obtained with a circular section hook (Figure 22).

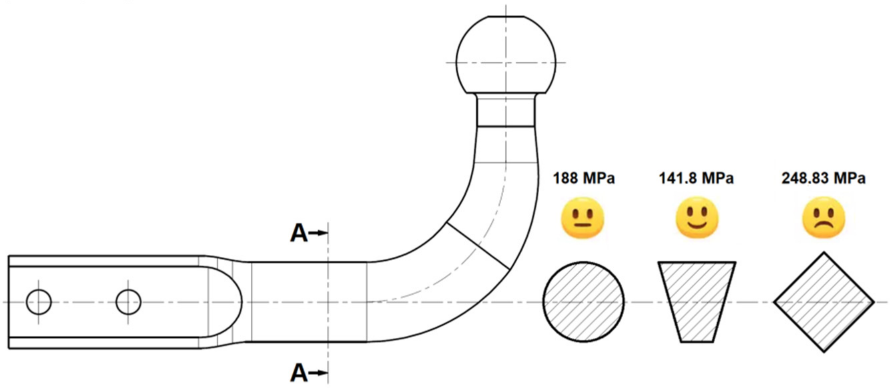


Figure 22. Proposals for towbar optimization.

Regarding the solution, a square section and bending radius after an edge can lead to an excessively high stress increase, even 1.5 times the stress value in the reference hook.

Regarding the improvement of the mechanical characteristics of aluminum-based components, this can be achieved by applying different thermal treatments. The stress relief annealing heat treatment consists of heating the blanks in the furnace to high temperatures for each type of material, then maintaining at this temperature and cooling them slowly at the same time as the furnace. This process can be successfully carried out in electric hearth furnaces, as well as belt furnaces. After the applied thermal treatment, semi-finished products are produced with superior mechanical properties.

Looking at the testing of the entire towing system, following theoretical analyses based on the strength of materials, but also with FEM, it is concluded that the highest stress in the system occurs inside the radius of curvature of the towing hook, therefore, the experiment focuses on the state of stress and strain that occur in the mentioned area.

The requirements for the structure of the towbar are complex, as follows: bending along the entire length of the towbar from the ball to the farthest hook fixing hole, and compression and tension due to bending and compression.

Presenting the current situation, where the tow hooks are of similar design, it can be said that the steel tow hook is that with the highest mechanical strength, the CF hook is stronger than the siluminium ones, and the hook made of pure aluminum presents the weakest mechanical characteristics in terms of strength.

On the other hand, looking at the situation in terms of the specific mass of each type of towing hook, it can be said that the most disadvantageous hook is the steel one, and the product with the lowest mass is that made of CFs. Aluminum and silumin hooks have a mass closer to that of a CF hook and very far from that of a steel hook.

By relating each of the values of the actuation forces on the hooks to the values corresponding to the specific masses of each hook, a comparison index is obtained. Higher index values represent a better performance for the hook made of that material. From this point of view, the best-performing hook is by far the CF hook, the silumin hooks have a similar performance to steel (AlSi10MnMg is slightly better performing, AlSi12Cu1Fe is worse performing), and the Al99.7% hook showed a weak performance.

Regarding the physical appearance of the hooks after testing, disregarding the actuation forces, it can be said that the pure steel and aluminum products are the most advantageous because they did not break, but only deformed plastically. The CF towbar did not break into multiple components, but was completely damaged, breaking the connection between the metal inserts and the CF. Aluminum alloy components are also at a disadvantage in this regard because they broke, forming two independent parts, and the automotive industry does not allow this type of behavior. To reduce the discomfort created by the breaking of the towing hooks in the locks, studies could be carried out on alloying with other chemical elements to decrease the brittleness of the material.

7. Conclusions

Comparing the behavior of the steel towbar tested individually with that tested in the towing system as a whole, very interesting results are observed. The torsion of the strength beam of the towing assembly facilitates and helps the towing hook to suffer less tilt, so testing the towing hook as a whole is of great importance and brings a greater guarantee of the deformation mode.

Comparatively analyzing the chemical composition of the two types of aluminum alloys, but especially the admissible field of tolerances for each alloying element, it is observed that the AlSi10MnMg brand alloy is more restrictive, with admissible limits in a very low tolerance field. For this reason, the development of the AlSi10MnMg alloy involves certain additional costs, primarily due to the need to use a larger amount of pure aluminum as a raw material.

The alloy brand AlSi12Cu1Fe has a more generous tolerance field of elements, therefore, its development is mainly carried out from the waste of other alloy brands, which is why its manufacturing costs are lower than those for the development of the AlSi10MnMg alloy.

Concluding on the commercialization of aluminum alloys, AlSi10MnMg will be commercially available at a higher price than AlSi12Cu1Fe, but offers more advantageous properties.

Based on the results obtained in the work, it can be concluded that other materials besides steel can be used for the manufacturing of towing systems for cars. Composite materials or composite alloys can be used if it is found that they present economic or other advantages, and from a mechanical point of view, these materials can ensure the strength of the assembly.

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