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Design and Optimization of the Training Device for the Employment of Hydraulic Rescue Tools in Traffic Accidents

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Abstract: This paper is concerned with the design and structural optimization of a training device for operators of a hydraulic rescue tool employed during traffic accidents, in conjunction with the improvement of the technical procedures used in such situations. Changes in the design process and subsequent production in the motor industry frequently result in an increased impact resistance of the used structural components. This applies, also, to extrication works and frequently used technical equipment. This paper presents its findings on the design process for the prototype of a training device designed for the extrication cutting drill with the assistance of a hydraulic rescue tool. The primary part of the research was dedicated to structural optimization; therefore, parameter dimensioning of the training device's prototype was implemented. The device's mechanical resistance, sturdiness, and stability during the implementation of hydraulic tools were also taken into account. A secondary part of this research comprised experimental results aimed at assessing the time needed to cut through the structural parts of a vehicle—pillars "A" and "B"—while using a hydraulic rescue tool. The structural design of the pillars of selected mid-range vehicles, according to their year of manufacture, was employed. The experiment showed that the newer the vehicle, the higher the cutting resistance of the pillars (predominantly "B"-type pillars). The results revealed that the cutting-work drill contributes to the reduction in the actual cutting time. Furthermore, the identification of the optimal place for cutting and the cutting angle led to more efficient extrication processes that can be applied during rescue works resulting from traffic accidents.

Keywords: design; optimization; beam element; FEM analysis; training device prototype; hydraulic rescue tools; firefighters' units; experiment

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1. Introduction

Land transport involves complex systems. Therefore, it is vital to combine multiple areas and processes that can provide the required transport services and safe environments for land transport users. Increasingly, mobility has become a topic of great interest [1]. However, the steep rise in mobility has had several negative impacts affecting society, e.g., an increasing number of traffic accidents, the severity of such accidents, and increasing numbers of injured individuals, as well as material and environmental damage [1,2]. The European Commission's White Paper, Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system, contains a list of initiatives. With respect to transport safety, the primary responsibilities are set out in the White Paper's Objective 1.4.—Acting on transport safety: saving thousands of lives [2–4]. Transport safety involves not only the harmonization and development of new intelligent vehicle technologies and transport systems but also the introduction of comprehensive measures addressing the origins of traffic accidents and the coordination and employment of individual rescue services and methods.

Current progress in vehicle development encompasses additional new challenges in the practical knowledge and required skills of emergency rescue service units. One of the contemporary tasks when dealing with traffic accidents is increasing the efficiency of the rescue response via regular training and the practice-oriented education of units that are employed during traffic accidents. The technical equipment used by rescue services requires particular attention, particularly in light of the continuing development of alternative fuel vehicles and improvements in safety parameters and in the passive safety components of a vehicle.

In the past decade, we have witnessed significant changes in the motor industry, notably in regard to passive and active safety and preferred drives, together with the materials used. Generally, an automobile's body accounts for 40% of the overall weight of the vehicle [5]. The inclusion of progressive high-strength and ultra-high-strength steels that enable a reduction in overall vehicle weight and increase the mechanical resistance of load-bearing vehicle structures has increased. As a result, the level of passive safety during traffic accidents has increased. The behavior of vehicles during collisions has been discussed by several independent institutions, including the European New Car Assessment Programme (the Euro NCAP), the National Highway Traffic Safety Administration (the NHTSA), and the Institute for Highway Safety (the IIHS). These institutions test the influence of dynamic phenomena, including crash tests, with the aims of assessing the safety of a rescue crew during various operations and evaluating the passive safety of vehicles [6–9].

These tests are concerned with the parameters of so-called crumple zones and the identification of the critical spots of a vehicle's self-supporting body.

Issues regarding the performance efficiency of hydraulic rescue tools, the methods of their application, and, most importantly, the identification of suitable locations for cutting specific constituents of a vehicle's body are being brought to the forefront, primarily with regard to the construction materials that are currently utilized and further requirements concerning the dimensioning of vehicle components. Moreover, there is a direct relationship between these issues and the time required for the procedures for rescuing individuals from crashed vehicles, as well as the efficiency of selected rescue technologies [10–12].

Based on the statistical data [13–16], the rescue tools that are predominantly employed for traffic accidents—mostly for rescuing individuals—consist of hydraulic tools that are used for cutting, spreading, or a combination of cutting and ductility/pressure. The changes in the construction and material composition of vehicles have brought about a need to adjust the procedures of rescue services. The main cause of this reality is the improved properties of the materials used in modern vehicles, which cannot be deformed by the employed hydraulic tools (either by spreading or cutting), due to their higher resistance. Thus, there is a growing need for modification of the technical means available to rescue teams, together with a need for expanded education and training of firefighters' units.

The quick and efficient implementation of extrication processes resulting from traffic accidents is increasingly problematic and time-consuming. The selected combination of intervention tactics with the equipment and skills in handling the available tools and techniques is the main issue. In [17], Rom Duckworth, a specialized Connecticut emergency responder, emphasized that focusing on each detail of extrication tools and optimal rescue tactics borders on impossibility. As a result, the excessive focus on the technical aspects (tools and technologies) can lead to a situation where the technically proficient rescuers do not possess an understanding of how their actions influence the overall operations and efficiency of the emergency response. On the other hand, the excessive focus on the intervention tactics can result in a situation where, despite the suitable tactics chosen by the commander of the firefighter unit, the crew does not have sufficient training to fulfil those procedures. In conclusion, it is necessary to find a balance between the tactical training and technical skills of the emergency response team [17–19].

The intervening fire units have a unique nature of work. As a result, their attention during rescue works needs to be divided between their own health and safety, as well as the health and safety of all people that can be influenced by their actions, or lack thereof [20–22]. As part of his study [23], Brian Marcinek points out the risks posed by extrication tools. The author states that such risks are stemming from the fact that in the vast majority of situations considered, the overall risk is determined by a number of relevant foreseeable risks (those set by the construction and technical characteristics of extrication devices, the danger of the addressed situation, and its development after the utilization of said devices). In his final report [24], aimed at the evaluation of the extrication tools' capability in relation to high-strength materials found in vehicles, Merrifield explained that a successful emergency rescue response is only possible with well-coordinated teamwork and appropriate material and technical provision. He further states that when rescuing people in traffic accidents, the most common situations require the cutting of "A" and "B" pillars. He refers to those as the extrication cutting zones [24–26].

Based on the abovementioned facts, it can be concluded that the rescue service emergency responses which employ hydraulic rescue tools are relatively numerous. Therefore, not only up-to-date technological equipment but also the regular and purpose-driven training of emergency response units as well as individuals play a vital role in the efficient and safe extrication of people trapped in vehicles during traffic accidents.

The purpose of this article is to present the results from the process of design and structural optimization of the training device prototype's parameters, designed for cutting work training, which employs the hydraulic rescue tool, together with the results concerning the efficiency and safety of emergency rescue activities necessary in traffic accidents. The primary objective is the structural design and parameter optimization of a simple training device with regard to the mechanical resistance of its components, the sturdiness of the design, and the device's stability during its employment. The secondary objective is the testing of the designed training device prototype, with the aim to train future operators of the hydraulic rescue tool and to improve the efficiency of the technical procedures used in traffic accidents during extrications. The final set objective of the implemented experiments was to assess the dependence of the time needed to cut the structural parts of the car—"A" and "B" pillars (mid-range vehicles, variable age structure)—with the use of a hydraulic rescue tool (cutting angle, perpendicular to the longitudinal axis of the pillar) on the construction design of said pillars.

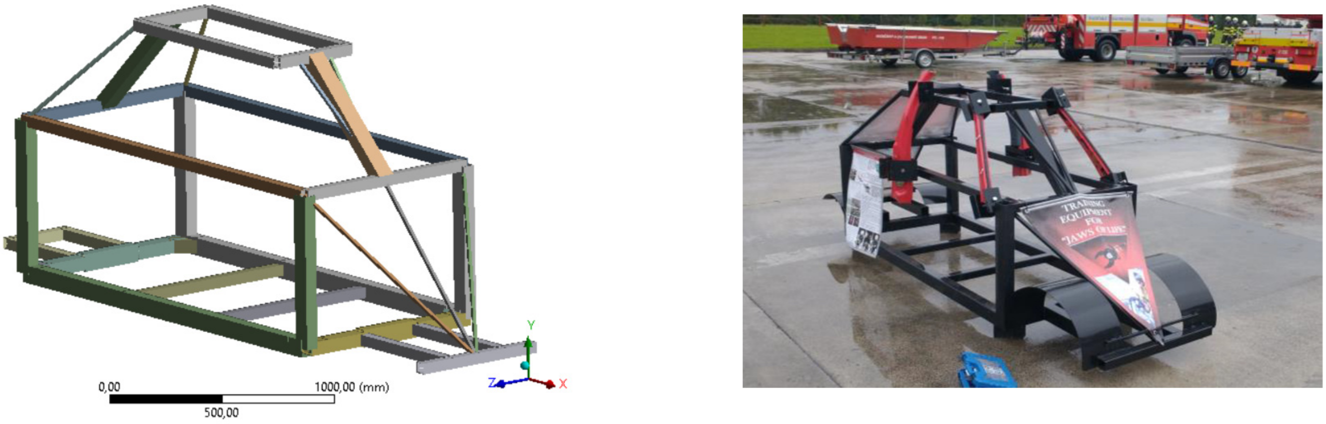
2. Materials and Methods

New technologies and materials currently employed in the motor industry frequently bear the responsibility of causing a paradox of safety in contrast with accessibility. In other words, the vehicle is constructed with the aim of protecting its passengers in case of an accident; however, it is this improved level of safety that can prove to be problematic to the emergency response team. The pillars of older vehicles are made of rolled sheets with reinforcements on both ends and a single metal thickness in the middle. Newer vehicles tend to have much broader pillars, frequently with reinforced steel insertions. From the perspective of the emergency response units, this can significantly impact the cutting works and the overall duration of the rescue [27–29].

2.1. Conceptual Design and Construction of the Prototype Training Device

When dealing with the issue of quality improvement of firefighting units in the field of extrications caused by traffic accidents, a conceptual design of a training device (Figure 1a) was created with the subsequent construction of its prototype (Figure 1b). The primary purpose of its construction was first and foremost to enable the training of cutting, which employs the hydraulic rescue tool. The device is designed to cut the specific construction parts of the vehicle (type "A" and "B" pillars). However, it is also suitable for experimental procedures in the area of emergency response activities.

The construction of the training device is self-supporting and made of steel. Its primary specialization is to mount a specific construction part of a vehicle, type "A" or type "B" pillars. The training device enables the replacement of pillars specific for different types of vehicles through an original solution of their mounting on its load-bearing structure. The purpose of its employment is the study and training of cutting works which utilize hydraulic rescue tools. This device can increase the efficiency and safety of cutting works and enables the objective resistance assessment of various materials used in the construction parts of vehicles, as well as the experimentation with impediments and circumstances influencing the cutting process, the identification of the most suitable location for cutting, and the elimination of torsion during the cutting, as well as additional factors.



(**a**) (**b**)

Figure 1. (**a**) FEM training device model; (**b**) training device prototype.

A substantial part of the research presented in this paper is comprised of the structural optimization of the training device, with the aim to ensure its sufficient sturdiness and stability during cutting operations training. Nowadays, the parameter optimization of technical construction and their individual structural components is viewed as a necessary tool in the development and design of new technical systems, as well as in the innovation of the existing equipment [30].

When optimizing constructions, machines, etc., the objective is conventionally a reduction in weight and material savings, optimal dimensions, and the shape of the technical system components, most frequently in order to increase the component's reliability or to reduce production costs, etc. [31].

Generally, the optimal solution is viewed as the best solution in terms of selected criterion that, under certain restrictive circumstances, leads to an extreme of the target function. The target function for technical systems optimization is most commonly the price, construction weight, shape of the selected components, maximum permissible deformations, maximum voltage, the required stability of the construction, or prescribed values of its various frequencies [31,32].

The target function is expressed either explicitly or implicitly, always by the means of optimization (design) variables, i.e., parameters that change their values during optimization and gradually converge to the optimal solution. Design variables can represent thickness, lengths, material properties, etc. [32]. Fundamentally, these variables can be divided into sizing variables which change only the size parameters of the construction without affecting its geometry, and shape variables which affect the shape of the construction or its individual components.

Optimization tasks frequently contain requirements which must be met in the design. Such restrictions in the mathematical notation of the model optimization represent constraining (secondary) conditions. They can be noted in the form of equations or inequalities, and they can be related to weight, maximum voltage, deformations, or prescribed frequencies.

The target function and secondary conditions of the specific problem have been formulated based on engineering practice requirements in a way that extremizes (maximizes or minimizes), e.g., the production costs, weight, technological complexity, stability, or other operating parameters.

2.2. Parameter Optimization of the Training Device Construction

In addition to the basic conditions (dimension optimization of the sections used, the mounting method of the sample pillar to the structure, etc.), the structural design of the training device also follows the condition of the sufficient sturdiness of the whole construction to eliminate the possible slipping of the device with regard to the surface area. One of the key conditions the designed construction is required to fulfil is its mobility, i.e., the possibility to move it in accordance with the requirements of the training purposes. The mounting of the device on the surface area is thus not solved by a fixed attachment. In order to ensure that the body of the device is not in direct contact with the ground and thus exposed to a more corrosive environment, feet made of rectangular sections are placed horizontally in the end corners.

Due to this fact, the marginal optimization condition was a sufficiently large friction force component in the place where the feet touch the ground. Construction is considered to be in motion if the limit adhesive force is exceeded at three of the four points of contact, resulting in a subsequent slip.

Specific force–friction effects occur in the area of body contact. Frictional effects always have the nature of resistances. Hence, under the relative standstill of the bodies, or in case the bodies are already under relative movement, the frictional force effects act against this relative movement in the common tangent plane of the contact surfaces.

Three possible states of the contact area relative movement can be distinguished:

- State of their relative standstill (adhesive force T_o, Equation (1));
- State at the threshold between their relative standstill and incipient motion (limit adhesive force T_{om}, Equation (2));
- State of their relative movement (force of the shear friction T, formulated by Coulomb's law, Equation (3)).

Real instances prove that in the incipient relative motion of two sturdy bodies, the magnitude of the frictional force effects 20 to 30% more than their already existing motion, and the change is a step change, $f_o > f$ [33].

The constant of proportionality between the magnitude of the corresponding frictional force effect T and the contact force of the bodies N is represented by the friction coefficient:

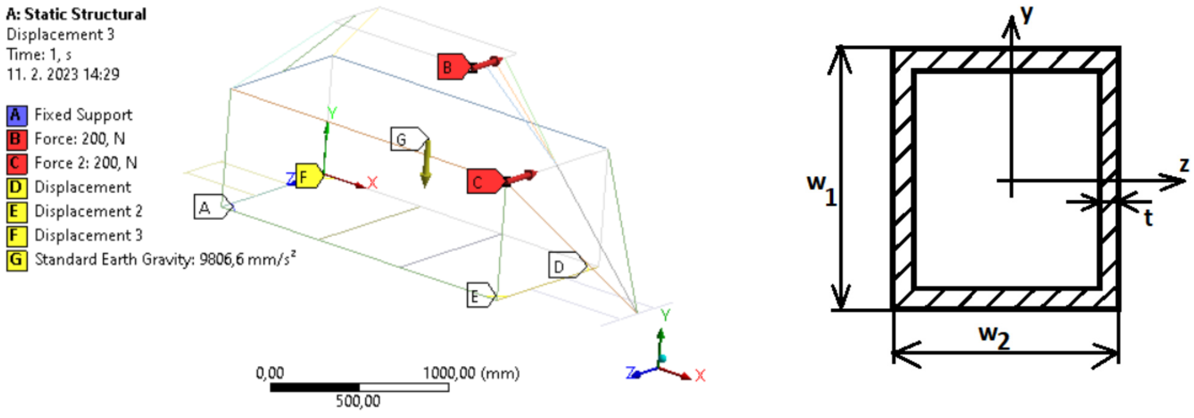
$$T_o \leq f_o \cdot N \tag{1}$$

$$T_{om} = f_o \cdot N \tag{2}$$

$$T = f \cdot N \tag{3}$$

f_o—Adhesion factor (at the adhesion threshold);
f—Shear friction factor.

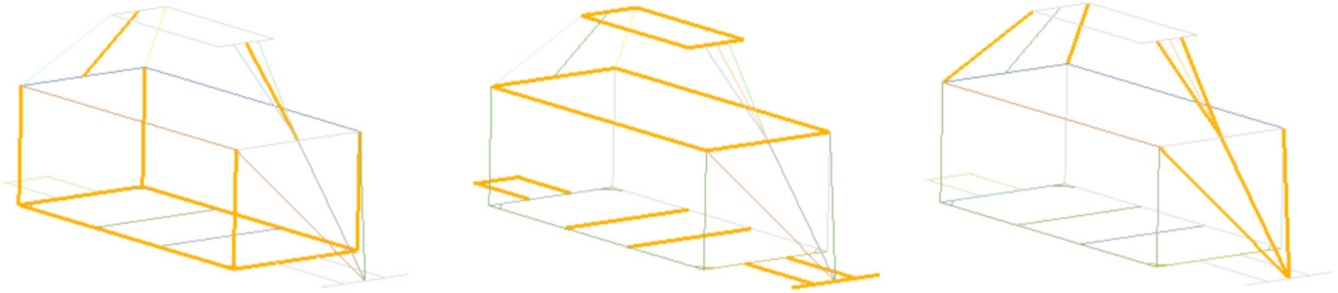
Due to this fact, in the FEM model, Figure 1, the analyzed force components were in the direction perpendicular to the point of device contact with the ground (contact force N) and in the direction of movement (frictional force effect T). Marginal displacement conditions were defined at all contact points of the device legs with the ground, as well as the body's own gravity; Figure 2a. From the measurements during the use of the hydraulic release tool in real conditions, assumptions were made that the maximal force affecting the device during training is 200 [N] + 200 [N] = 400 [N], and the limit position of the applied force is at the location of the mounting of the "A" and "B" pillars. The overall weight of the construction is 114 [kg]. The adhesion factor between the metal construction and concrete base was assumed to be $f_o = 0.27$ $[-]$. The aforesaid parameters enabled us to define the initial assumption for construction optimization, which allowed us to determine the basic dimensions of the test equipment. The finite element model was constructed from beam sections and comprised 6042 Nodes and 3030 Elements.



(**a**) (**b**)

Figure 2. (**a**) Marginal conditions and FEM model load; (**b**) dimension optimization of the sections used.

The test equipment is principally constructed from three basic types of sections (Figure 3). The input values for numerical optimization comprise a set of standardized dimensions of closed thin-walled sections provided by the manufacturers [34].



(**a**) (**b**) (**c**)

Figure 3. (**a**) Profil 1; (**b**) Profil 2; (**c**) Profil 3.

The finite element program for nonlinear analysis software (ADINA) was used as an optimization tool. The predefined combinations of the design variable values W1, W2, and t (Figure 2b) enabled us to carry out several parametric studies. Since Sections 1 and 2 (Figures 2b and 3a,b) serve as the supporting frame of the construction, their dimensions formed the base of the optimized parameters [35]. Section 3 (Figure 3c) was not included in the optimization process, and its dimension was set by a fixed value 15 × 15 × 2 [mm] (Figure 2b), considering that it fulfils only an auxiliary function (fastening of the information poster).

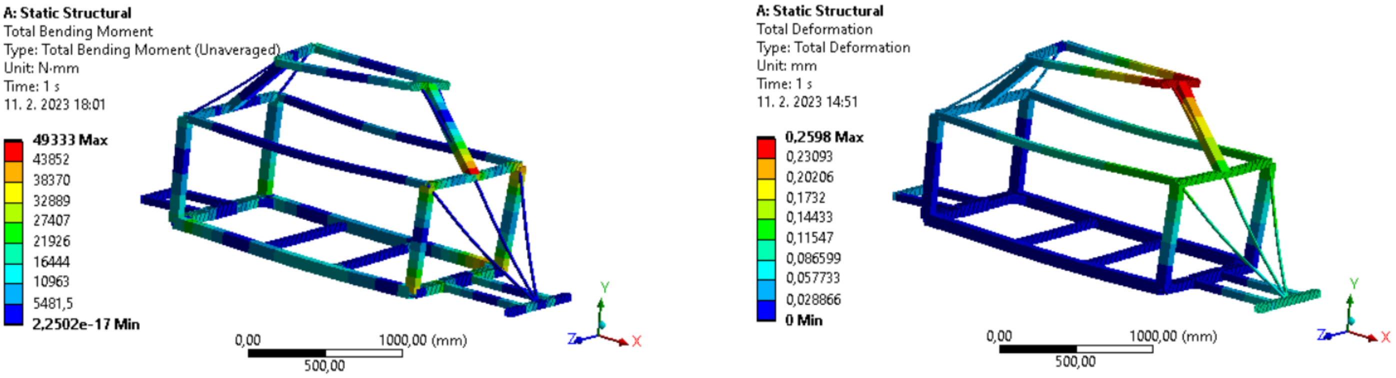
The set of necessary input parameters can be defined within the ANSYS program, or simply by importing the table of values generated in other available spreadsheet software (e.g., Excel). Each time a parametric variable is changed, the ANSYS software automatically responds and creates a new model, defines the loads, and performs a repeated calculation. The obtained numerical results can either be directly subtracted or exported as a table. Using ADINA-PLOT, it is possible to delineate them and then implement post-optimization designs and modifications.

2.3. FEM Analysis Results for Final Dimensions of the Optimized Closed Thin-Walled Sections

The reaction force Y presented the normal force N and the reaction force Z presented the adhesion strength T_o (Figure 2a). In four points of contact with the ground (Figure 2a, A,D,E,F), the fulfillment of the condition of mutual rest was checked in each step of the optimization, whether the frictional forces T_o (Equation (1)) and the subsequent unstable storage were overcome in the given place. The optimization procedure has proven that at the prescribed load (the combined stress stemming from the utilization of the hydraulic tool was taken into account), the set optimization conditions fulfil the following section dimensions:

- Section 1—considered the main section, with an optimization dimension of 60 × 80 × 3 [mm]. Forms the load-bearing part of the construction, i.e., the basic frame.
- Section 2—considered a significant section, with an optimization dimension of 50 × 50 × 2 [mm]. Forms a complementary part of the construction. As a result, the section may be less sturdy, while its components have primarily a support function.
- Section 3—has a fixed dimension of 15 × 15 × 2 [mm] and fulfils only an auxiliary function.

The maximal magnitude of the bending moment occurs in the mounting point of Section 1 and its magnitude is $M_{oMAX} = 49.333$ [N·mm] (Figure 4a). The maximal displacement occurs in the upper part of the construction and its magnitude is 0.2598 [mm] (Figure 4b.)



(**a**) (**b**)

Figure 4. (**a**) Course of the bending moment; (**b**) course of deformations.

When concerning the beam elements, the magnitude of the stress at the analyzed location is determined by the magnitude of the bending moment (Figure 4a).

$$\sigma_{OMAX} = \frac{M_o}{W_{oz}} = \frac{49,333\ [\text{N}\cdot\text{mm}]}{15,632.4\ [\text{mm}^3]} = 3.15\ \left[\text{N}\cdot\text{mm}^{-2}\right] = 3.15\ [\text{MPa}] \tag{4}$$

$$W_{oz} = \frac{I_z}{y_{max}} = \frac{468,972\ [\text{mm}^4]}{30\ [\text{mm}]} = 15,632.4\ \left[\text{mm}^3\right]. \tag{5}$$

Here, W_{oz} represents the section modulus of closed thin-walled horizontally placed Section 1 with dimensions of 80 × 60 × 3 [mm], I_z is the moment of inertia to the axis z, and y_{max} is the section fiber the furthest from the neutral axis.

2.4. Testing of a Prototype Training Device in a Vehicle Body Pillars Cutting Process

The testing of the prototype training device was implemented primarily in order to:

- Verify the selected operating properties of the training device (sturdiness, stability, displacement resistance, etc.);
- Implement the training of cutting works employing the hydraulic rescue tool in practice, with the focus brought to selected structural parts of the vehicles;
- Determine the dependence of the time needed to cut the structural parts of the car, type "A" and "B" pillars (mid-range vehicles, variable age structure).

In addition, the cut-through time of the "A" and "B" pillars of the vehicles with different age structures was monitored simultaneously with the testing of the performance and utility characteristic of the training device and the hydraulic device operator training. A variedness of construction materials, dimensions, and shapes of the vehicle body pillars was related to the given set of samples (Table 1). For the purpose of the experiments, Holmatro hydraulic cutters, model CU 3035 NCT, were used (Figure 5).

Figure 5. Holmatro hydraulic cutters, model CU 3035 NCT [36].

Table 1. Technical parameters Holmatro, CU 3035 NCT [37].

Max. Working Pressure	720 bar
Cutting force	306 kN/31 t
Weight, ready for use	14.8 kg
Dimensions (L × W × H)	700 × 230 × 187 mm
Temperature range	−20 °C–+80 °C

The technical parameters of the rescue tool are listed in Table 1. Hydraulic cutters are designed for emergency rescue work cutting during accidents, e.g., in road and rail transport, in industrial facilities, and on construction sites. The matter of concern is the hydraulic tool powered by a hydraulic pump. The system utilizes mineral oil. The permitted operating pressure is 72 MPa. The tools are equipped with a safety valve preventing excessive pressure in case the oil return to the pump is blocked [36,37].

In order to meet the purpose and objectives of the training device testing, the following tools were utilized during the implemented experimental processes:

- Hydraulic cutters;
- Training device prototype (for type "A" and "B" pillars mounting);
- Steel caliper (to obtain data on sample sizes);
- Tape measure (to measure width and height of samples);
- Digital stopwatch (hydraulic rescue tool activity time measurement);
- Elaborated graphical layout along with a tabular form (for obtained data recording);
- Digital camera (photo documentation of the experiment).

2.5. Conditions and Course of the Experiment

2.5.1. Experimental Samples

The obtained samples constituted of pillars from the vehicle bodies of various brands and types. During the course of the experiments, specifically, the pillars used were of "A" and "B" types (Figure 6), which were mounted on the training device and cut by means of a hydraulic extrication device.

The experimental sample of the type "B" pillar divides the vehicle's body into two and connects the side roof rail with the door sill of the vehicle. This sill is comprised of inner and outer panels, with a reinforcement placed between them [38,39]. Type "B" pillar also contains additional active safety components (air bag, seat belt). However, these elements could act as a hindrance during the cutting. Due to this fact, they had to be removed.

The experimental sample of the type "A" pillar forms a part of the basic car body construction. It is placed between the dash panel under the windscreen and front roof rail, and simultaneously connects the side roof rail of the vehicle [38,40]. In A pillar samples, the cabling and insulating materials were consistently removed.

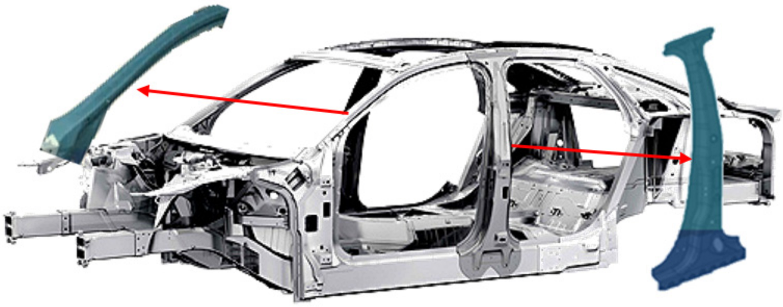


Figure 6. Basic vehicle body construction showing the "A" and "B" pillars [40].

The experimental samples were assessed in terms of the construction material used, along with its mechanical properties (Table 2). Each steel grade falls under a specific categorization in order to meet the functional performance requirements of specific parts of the construction [41,42]. Due to the need to identify the material composition of the pillars, the paper will make use of common denominations covering the low-strength steel (SS), conventional high-strength steel (HSS), high-strength low-alloy steel (HSLA), and advances high-strength steel (AHSS) [43]. Figure 7 shows a spectrum of the steel categories that were used throughout the history of the automotive industry, reflecting the traditional inverse relationship between strength and ductility. At the low end of the strength spectrum are interstitial-free (IF) and mild (MILD) steels, in the middle are the conventional grades of HSS that include interstitial-free, high-strength (IF-HS), isotropic (IS), bake hardenable (BH), and high-strength, low-alloy (HSLA) steels, and at the high end are the AHSS that include dual-phase (DP), complex-phase (CP), transformation-induced plasticity (TRIP), and martensitic (MS) steels. These steels have a very high strength and, except for the MS grade, have a good formability and are being used in many automotive structural applications [43–45].

A total of 18 samples (9 samples for type "A" pillar; 9 samples for type "B" pillar) were applied in the conducted experiment. Due to the fact that these samples were obtained from various types of vehicles, the prerequisite was to analyze them first, specifically in terms of the steel type used in the inner as well as outer side of the pillar. Results have shown that high-strength steels are used for both type "A" and type "B" pillars. The combination of strength and ductility makes them more resistant to deformation and thus improves the parameters of the so-called crumple zones and the identification of the least resistant components of the self-supporting vehicle's construction.

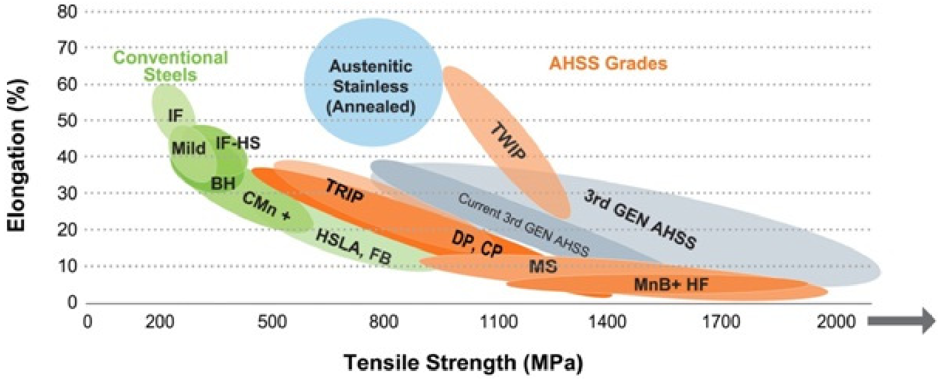


Figure 7. Comparison of conventional low- and high-strength steels used in the motor industry [44].

Table 2. Type "B" pillar sample analysis in terms of the steel type used [46–49].

Sample	Type of Steel—Inner Side	Mechanical Properties—Inner Side	Type of Steel—Outer Side	Mechanical Properties—Outer Side
1	Mild steel	• Tensile Strength max. 200 MPa • Elongation 40–50%	Microalloyed steel	• Tensile Strength 350–550 Mpa • Elongation 20–30%
2	Mild steel	• Tensile Strength max. 200 MPa • Elongation 40–50%	Microalloyed steel	• Tensile strength 350–550 Mpa • Elongation 20–30%
3	Lower-strength steels (interstitial-free and mild steels)	• Tensile Strength 180–260 MPa • Elongation 35–45%	Bake hardenable steels	• Tensile strength 200–300 MPa • Elongation 30–41%
4	Lower-strength steels (interstitial-free and mild steels)	• Tensile Strength 180–260 MPa • Elongation 35–45%	Transformation-induced plasticity steels	• Tensile strength 400–800 MPa • Elongation 20–35%
5	Mild steel	• Tensile Strength max. 200 MPa • Elongation 40–50%	Bake hardenable steels	• Tensile strength 200–300 MPa • Elongation 30–41%
6	Lower-strength steels (interstitial-free and mild steels)	• Tensile Strength 180–260 MPa • Elongation 35–45%	Martensitic stainless steel	• Tensile strength 950–1250 MPa • Elongation 3–7%
7	Lower-strength steels (interstitial-free and mild steels)	• Tensile Strength 180–260 MPa • Elongation 35–45%	Bake hardenable steels	• Tensile strength 200–300 MPa • Elongation 30–41%
8	Lower-strength steels (interstitial-free and mild steels)	• Tensile Strength 180–260 MPa • Elongation 35–45%	Transformation-induced plasticity steels	• Tensile strength 400–800 MPa • Elongation 20–35%
9	Mild steel	• Tensile Strength max. 200 MPa • Elongation 40–50%	Microalloyed steel	• Tensile strength 350–550 Mpa • Elongation 20–30%

2.5.2. Conditions of the Experiment

The implementation of the experiment focused on the prototype testing was conducted in the premises of the Fire Prevention Secondary School in Žilina (Stredná škola požiarnej ochrany v Žiline). A professionally trained member of the Fire and Rescue Corps of the Slovak Republic (hereinafter referred to as the operator) also actively participated in this experiment. The operator was supplied with personal protective equipment used in the routine work, employing hydraulic cutters.

The experiment was conducted under favorable meteorological conditions (air temperature 5–7 °C, no precipitation, wind flow ca. 3 m/s) and lighting conditions (in the time period between 08:00 AM and 02:00 PM).

Furthermore, it observed all predefined rules regarding [50] the safe usage of a training device prototype designed for training aimed at vehicle pillars cutting with the use of hydraulic extrication tools.

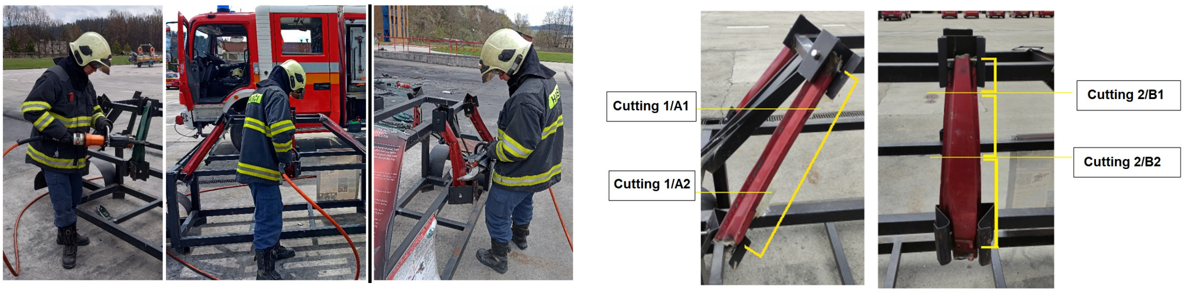
Compliance with the following rules and principles was ensured:

- The operators cannot be positioned between the hydraulic rescue tool and the training device unless the situation demands it;

- It is necessary to affirm that the pillars are sufficiently secured before the actual cutting process;
- Hands should never be placed beyond the grasping area (blades specifically) of any rescue tool;
- When using the hydraulic extrication tools, the working area should span within a radius of at least two meters;
- The hydraulic hoses are never to be under any load as they are highly susceptible to damage. The cutting therefore requires the utmost care;
- It is vital to cover all sharp edges as well as to put any damaged hoses out of service immediately;
- It is necessary to observe the training device's stability;
- The means of communication between the equipment operators and the hydraulic system operators must be established.

2.5.3. The Course of the Experiment

The "A" and "B" samples were mounted on the construction by means of a special clamp. The experiment was preceded by construction examination (placement, visible cracks in welds, excessive deformations) and pillars fastening to ensure the safety of operators and to avoid possible damage of the hydraulic tool. Following the start of the hydraulic system, the operators of the hydraulic extrication cutters approached the construction and started to cut the pillars at predetermined and marked locations (Figure 8).



(**a**) (**b**)

Figure 8. (**a**) Testing of the prototype training device, (**b**) location of designated cutting points.

The cutting of each pillar type was performed at two cutting locations. The overall cutting time of the pillars was recorded from the moment the hydraulic cutter blades were fully opened until the sample was cut, i.e., the hydraulic cutters' blades were fully closed. The time of the cutting process itself was subsequently calculated from the values measured (Tables 3 and 4).

Table 3. Experiment results—cutting process time parameters ("A" pillars, 9 samples, 2 measurements each).

	Cutting 1/A1				Cutting 1/A2			
	Start of Cutting (s)	**End of Cutting (s)**	**Total Time (s)**	**Cutting Time (s)**	**Start of Cutting (s)**	**End of Cutting (s)**	**Total Time (s)**	**Cutting Time (s)**
Sample 1	2.27	7.22	9.48	4.95	3.01	7.14	10.15	4.13
Sample 2	2.51	6.17	8.68	3.67	2.02	6.16	8.19	4.14
Sample 3	2.31	6.80	9.11	4.49	1.56	6.26	7.82	4.70
Sample 4	3.49	8.48	11.98	4.99	2.30	7.10	9.40	4.80
Sample 5	5.06	9.24	14.30	4.18	4.48	7.82	12.30	3.34
Sample 6	2.22	6.55	8.77	4.33	2.01	6.71	8.72	4.71
Sample 7	2.98	8.47	11.45	5.49	2.75	5.07	7.82	2.32
Sample 8	3.56	8.31	11.87	4.75	2.96	8.04	10.99	5.08
Sample 9	3.86	8.30	12.15	4.44	3.19	7.91	11.09	4.72
Average	*3.14*	*7.73*	*10.87*	*4.59*	*2.70*	*6.91*	*9.61*	*4.22*

Table 4. Experiment results—cutting process time parameters (“B” pillars, 9 samples, 2 measurements each).

	Cutting 2/B1				**Cutting 2/B2**			
Sample	**Start of Cutting (s)**	**End of Cutting (s)**	**Total Time (s)**	**Cutting Time (s)**	**Start of Cutting (s)**	**End of Cutting (s)**	**Total Time (s)**	**Cutting Time (s)**
Sample 1	1.90	15.53	17.42	13.63	2.50	16.42	18.92	13.93
Sample 2	1.95	7.67	9.62	5.72	2.80	8.49	11.29	5.69
Sample 3	2.68	6.70	9.37	4.02	2.90	18.32	21.23	15.42
Sample 4	3.68	7.65	11.32	3.97	2.28	6.10	8.38	3.81
Sample 5	3.55	12.44	10.99	3.89	2.67	9.07	11.74	6.40
Sample 6	1.90	19.54	11.45	7.64	2.23	16.85	19.08	14.62
Sample 7	2.04	22.57	24.61	20.54 (no-cut)	1.53	27.23	28.76	25.70
Sample 8	2.06	15.12	17.18	13.07	2.10	15.38	17.48	13.29
Sample 9	1.59	13.63	15.22	12.04	1.37	13.65	15.02	12.28
Average	*2.37*	*13.43*	*14.13*	*9.39*	*2.26*	*14.61*	*16.88*	*12.35*

2.5.4. Fastening Testing and Measurement of “A” Pillar Samples

The construction of the prototype training device is primarily focused on the specific structural parts of the vehicle, i.e., type “A” and type “B” pillars. An original and relatively simple solution enables sample fastening as well as its subsequent replacement for another sample. The experiment implementation also tested the fastening of “A” pillars to the load-bearing part of the construction. The main issue observed was their resistance to the implemented cutting procedures.

The cutting process was performed in two locations: cutting 1/A1—cut at the upper section of the pillar A, approximately 10 cm from its top edge; measurement 1/A2—cut at the lower section of the pillar, approximately 10 cm from the dash panel below the windscreen of the vehicle. The aforementioned locations were chosen with regard to the handling possibilities concerning the equipment operation, and considering that the material properties along the entire length of the A pillar remained the same. The results of the experiment—that being the assessment of the dependence of the cutting time of the individual samples—are recorded in Table 3.

The measurement results do not show any significant time difference between the samples. None of the type A sample caused any problem during the cutting process. It may therefore be assumed that, generally, the given type of pillar does not prove problematic for the hydraulic tools. The structure of material used for type A pillars is not the same as for type B pillars. The thickness of the material used is always lesser for type A, which was also proven by the experiment; the time required to cut through the sample was shorter.

2.5.5. Fastening Testing and Measurement of “B” Pillar Samples

The construction of the prototype training device is also equipped with fastenings for pillars at the rear of the front door, referred to as the type “B” pillars. The purpose of this pillar is to provide protection in case of side impacts. Its controlled deformation in such impacts is required particularly in order to ensure the highest possible protection of the vehicle’s passengers. As a consequence, they are supplemented by various reinforcements of square-, circular-, or bar-shaped steel sections. Standard “B” pillars come in a variety of shapes and material structures. As opposed to “A” pillars, their specificity lies precisely in the combination of different materials. Here, the tensile strength ranges between 800 and 1600 MPa [51,52], which was also manifested in the implementation of the experiment. The pillars were mounted through the use of special fastenings and their resistance to the cutting effect caused by the hydraulic rescue tools was observed once more. The cutting process was performed in two locations: cutting 2/B1—cut at the upper section of the pillar, approximately 10 cm from its top edge; measurement 2/B2—cut at the lower section of the pillar, approximately 20 cm from the sill of the vehicle. The aforementioned locations were chosen with regard to operation possibilities concerning the utilization of the equipment, considering that the material properties along the entire length of the "B" pillar remained the same. Conclusive values of the cutting process time duration are shown in Table 4.

The results of the 2/B2 measurement evince a more noticeable difference in the cutting time among individual samples. By way of illustration, it can be stated that sample 7 (Figure 9) failed to be cut during the experiment. This is assignable to the fact that the seat belt fastening was not removed from the inner part of the pillar, which posed another impediment for cutting. The results of the experiments have shown that in terms of the material structure, there is no "ideal" place for pillar cutting. High demands are thus placed not only on the quality and performance of the extrication devices, but also on the skill and training of the operators.

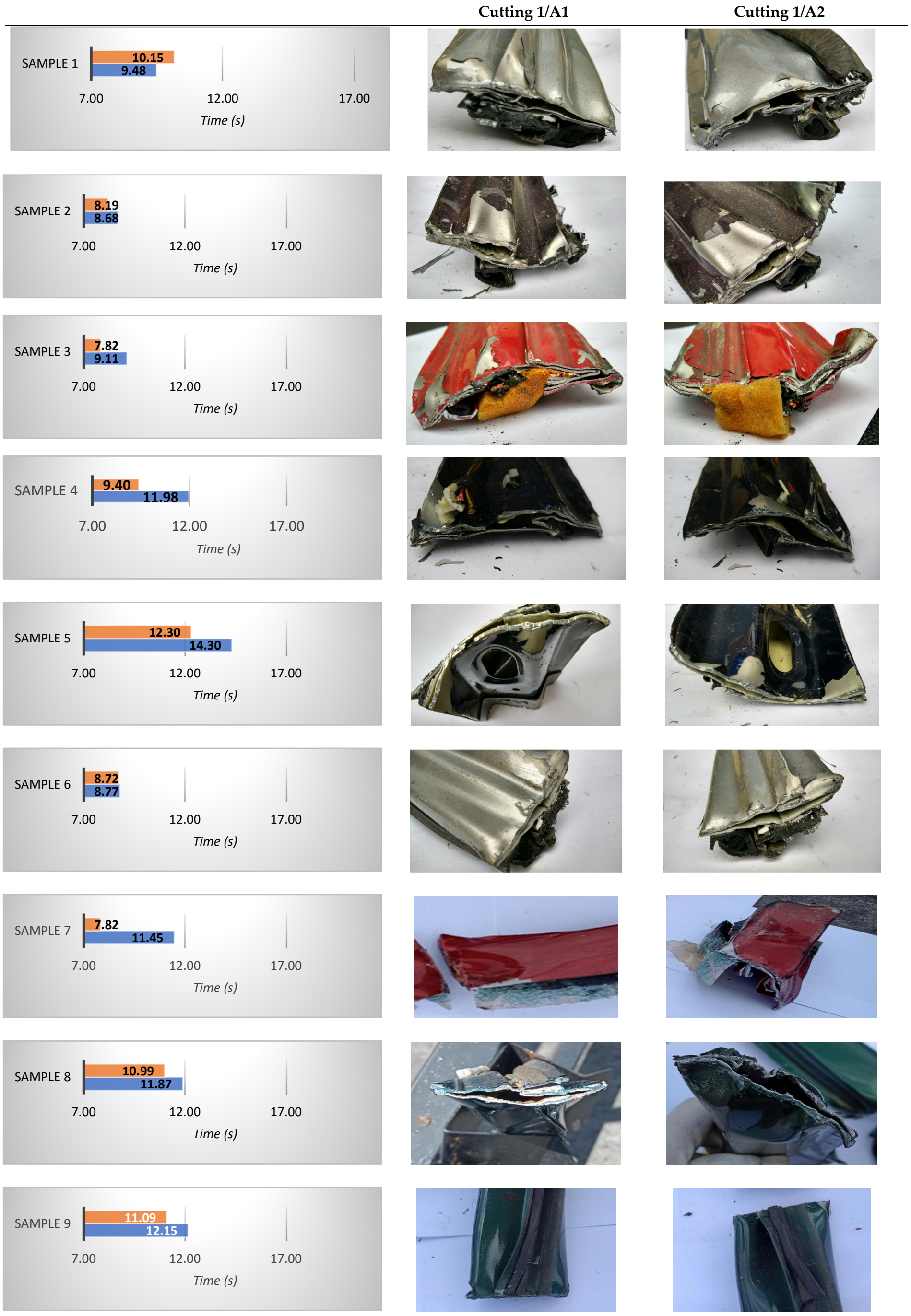


Figure 9. The results of cutting 1/A1 and 1/A2.

3. Results and Discussion

The long-term and manifold employment of the designed device, which is intended for training of the hydraulic rescue tool operators and are utilized during extrications caused by traffic accidents, proved its functionality, mechanical resistance, and spatial stability. The training device was constructed based on the results of parametric optimization. Any minor issues or imperfection found in the process were remedied on an ongoing basis (e.g., minor design modifications or changes in cutting techniques and circumstances). As a consequence, further improvements were made in the construction. The fastening of the individual samples to the load-bearing part of the training device was represented by strength and stability, the influence of the cutting work notwithstanding.

Considering individual samples in terms of assessing the dependence of their cutting time, a conclusion can be made that with regard to the "A" pillar, no significant differences regarding the time duration were identified. The average value of the overall cutting time regarding the 1/A1 and 1/A2 measurements is almost identical, with no significant time differences (Figure 10). This was proven by two executed cuts, approximately 10 cm from the roof and 10 cm from the dash panel under the windscreen. In this specific case, the cutting times varied by ca. one second.

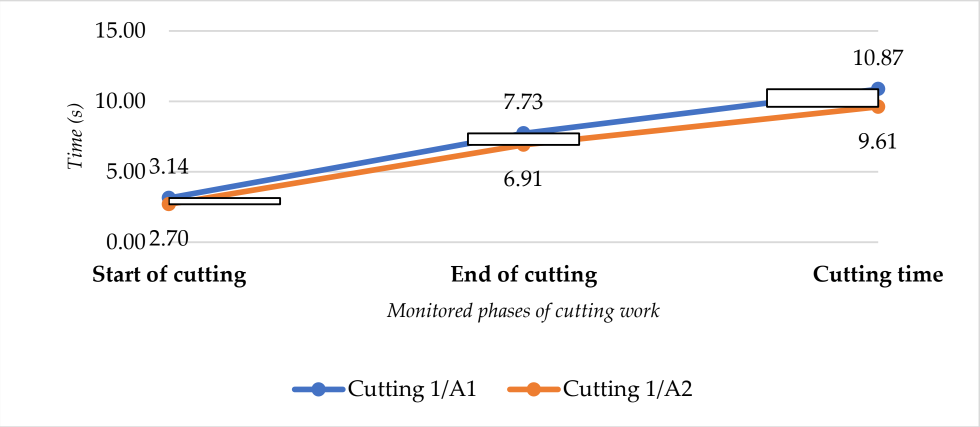


Figure 10. Summary of results (average) for the observed phases concerning the type "A" pillar cutting process.

In the instance of the "B" pillars samples and time of cutting, a more significant time difference can be observed in case of 1/B1 and 1/B2 measurements (Figure 11). This is due to the shape of the "B" pillar and the particular combination of structural steels used. In the motor industry, increased demands are placed on this body component, particularly with regard to the choice of structural material.

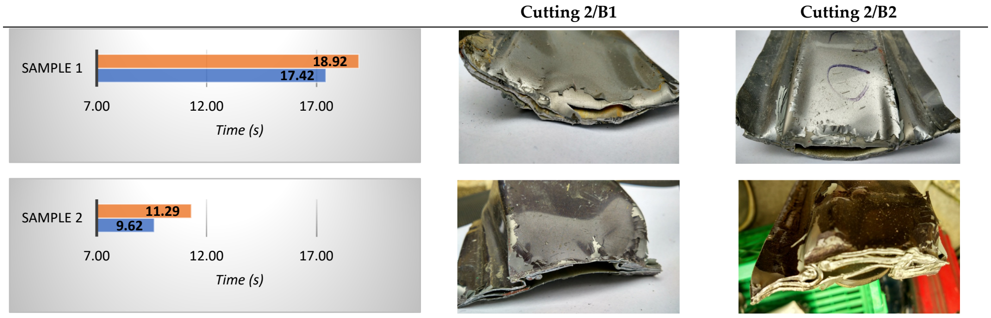


Figure 11. *Cont.*

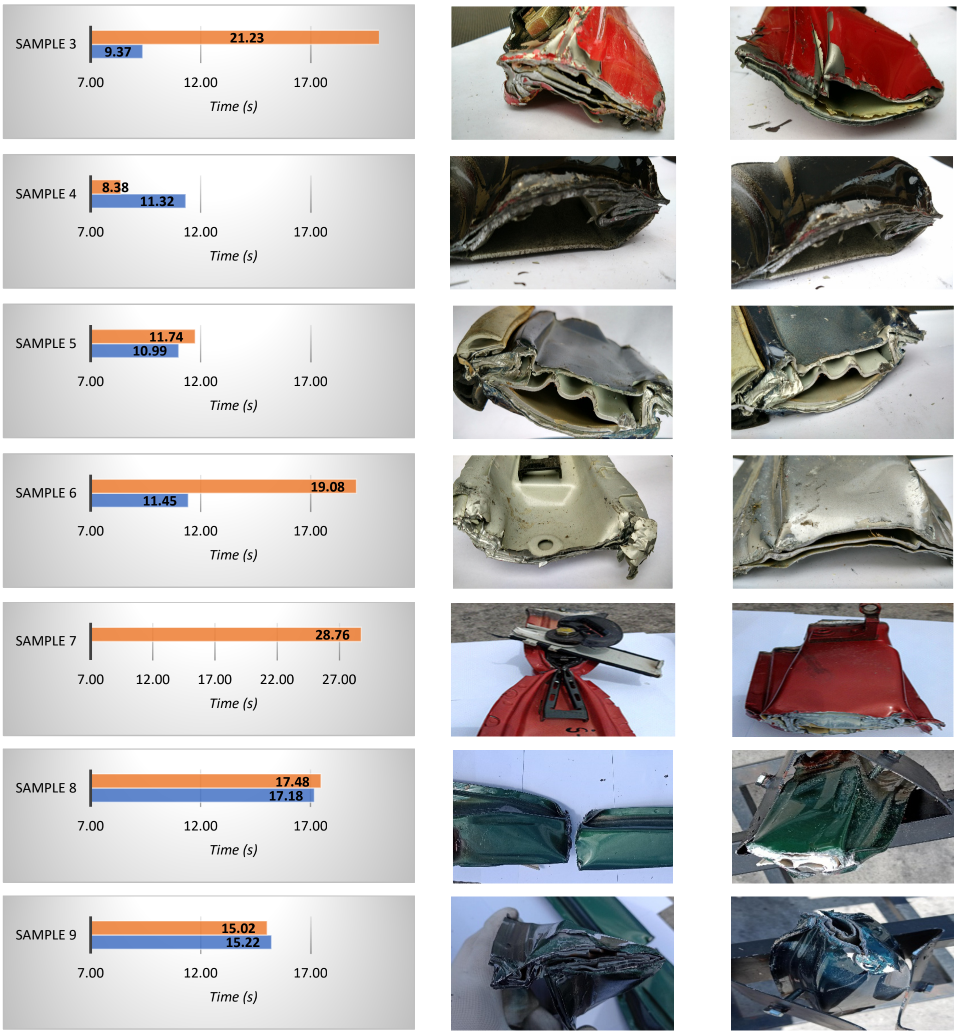


Figure 11. The results of cutting 2/B1 and 2/B2.

Generally, type "B" pillars are made of pressings with a thickness up to 2.8 mm in order to increase the stiffness of the body in a side impact. The results of the average measurement times are shown in Figure 12.

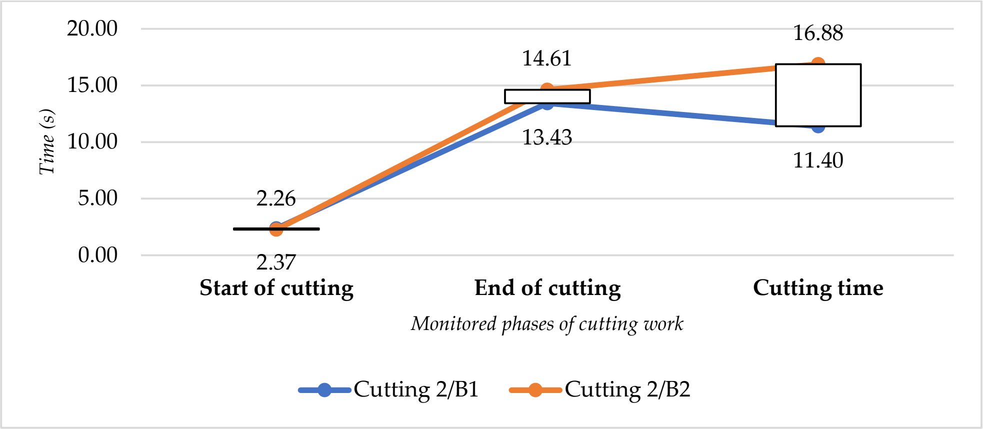


Figure 12. Summary of results (average) for the observed phases concerning the type "B" pillar cutting process.

Judging from the results given so far—particularly the overall time required to cut the vehicle body pillars—it can be determined that the time of the cutting process does not significantly affect the duration of the rescue work. However, a point needs to be made that not only the quality of the hydraulic rescue tool, but also the theoretical preparation concerning the technical rescue and training of the operators, play an important role. In terms of the Fire and Rescue Corps of the Slovak Republic, the most frequently used hydraulic rescue tools rank among the older equipment. Nevertheless, the experiment has proven that it is still serviceable in cutting the low-strength steel found in the older vehicles, or in the "specific, less resistant areas" of newer types of vehicles. The cutting of high-strength and ultra-high-strength steels could prove problematic. In order to maximize the overall efficiency of the extrication device, the identification of the optimal cutting location is needed. The illustration of the locations of various steel types in the respective types of vehicles (as shown in Figure 13) could also prove useful. The ideal cutting location is marked in a green color.

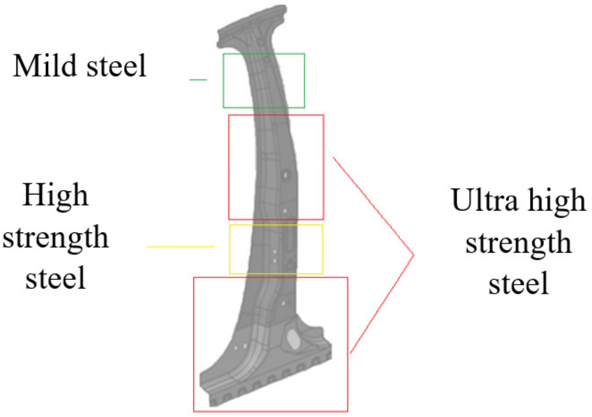


Figure 13. Type "B" pillar material structure and ideal cutting location (green area).

With the choice of the correct emergency rescue tactic, possible errors could be eliminated, and better cutting results with the extrication equipment could be achieved. The cutting process must be preceded by a visual assessment of the pillar structure in order to identify the suitable cutting location. In addition to handling hydraulic extrication tools, firefighting units also need to know the nature of the material with which they will be required to work.

In order to achieve better results of the cutting process, the appropriate cutting angle must be determined (Figure 14). Operators are required to hold the blades of the extrication cutting tool perpendicular to the pillar material so as to minimize the cutting area. Equally important is to monitor the response of the extrication tool with regard to its revolving effect caused by the cutting process, i.e., the rotation of the tool around the cut material. The closer the material is to the point of rotation, the higher the efficiency of the cutting process. When cutting the pillars, it may occur that the extrication tool starts to unbiddenly move sideways around the material that is being cut. In such case, it is necessary to adjust the initial cutting angle and move the extrication tool counter to the direction of unwanted rotation.

Any successful emergency rescue bears a close relation to the knowledge of small details concerning the correct technique of hydraulic rescue tool employment. Interestingly, the identical procedures and techniques applied when working with this device led to different results. The training device presented in this paper is constructed in a way which allows the firefighting units to learn how to properly use the hydraulic rescue tools with regard to blade gripping speed, the determination of the proper cutting angles, as well as suitable cutting locations. The set of this knowledge can significantly influence the speed, safety, and time efficiency of the extrication processes caused by traffic accidents.

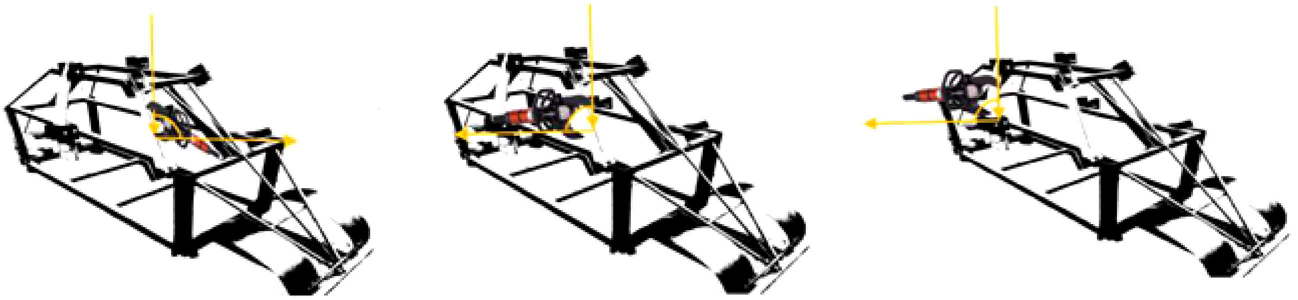

(**a**) (**b**) (**c**)

Figure 14. (**a**,**b**) Type "A" pillar cutting angle; (**c**) type "B" pillar cutting angle.

4. Conclusions

Increasing demands regarding vehicle construction may, in the future, result in a reduction in the efficiency of hydraulic extrication devices employed in traffic accidents. Modern high-strength steel structural reinforcement in the center of each pillar may prove impossible to cut with the help of a hydraulic extrication device; although, when sufficient force is applied, it can be deformed. Reinforcements and new materials present in type "B" pillars can lead to subsequent damage of the hydraulic cutter′s blades.

As part of the experiment carried out on the training facility, we can see the structure and strengthening of the important parts of the "A" and "B" pillar, and at the same time, the effectiveness of the release device. In the case of sample 7, column "B" was not cut. The extrication tool was ineffective in this case due to the operator′s poor evaluation in the initial analysis of the material. The key is to identify the correct cutting site, which is very important in emergency operations and has a significant impact on the success of rescue operations. In this regard, it is therefore important that the firefighter has an overview of the structure of the individual posts. In a real situation of using a rescue tool, in addition to reinforced important structural elements, as pillars "A" and "B", expect the presence of airbags and seat belts. Experience is required, which can also be obtained using training equipment, which allows you to experiment with obstacles and conditions during shearing work. Furthermore, the experiment demonstrated that the rescue tool used, which is the most widespread in the conditions of the Slovak Republic, it is still usable for cutting steel. In the case of older vehicles, we did not notice any problem; the cutting time was the shortest in this case. Cutting newer types of vehicles, especially in places where there is high-strength and ultra-high-strength steel, may already be problematic. Increased cutting time was noted.

The optimized and constructed training device prototype designed by the authors and presented in this paper contributes to the firefighting units′ action readiness and productivity necessary for employment of the hydraulic rescue tools. The most significant impact on the gradual improvement of time needed when performing the extrication operations caused by traffic accidents lies in the understanding of the mechanical properties of the materials used in the construction parts of vehicles, their resistance to the cutting force of hydraulic tools, the correct identification of the optimal cutting location, or the human factor and the development of rescuer′s skills with the extrication devices. Subsequently, the improvement of the training device design can lead not only to future improvement of technical procedures and the development of skills needed during extrications resulting from traffic accidents, but also emphasis on the need for the further development of extrication tools and technologies for their employment in rescue services. There is a constant need to keep pace with the incentives and new challenges that arise from the technical progress of vehicle components and can contribute to escalation in the efficiency and safety of rescue services.

Contradictorily, the improved design translates into paradox of safety in opposition to accessibility during traffic accidents. To put it differently, the very construction that enables the driver to survive the accident may be the same reason why the emergency rescue services cannot extricate him/her from the vehicle.

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