Mateusz Sowa, Bartłomiej Urbański, Kamila Stopińska

Passive Safety in Sports Cars – Safety Cells

Abstract: The safety cell (depending on its producer also referred to as *safety cage*, *roll cage* or *crash box*) is an indispensable sports car element tasked with limiting results of a potential car crash. The aforesaid structure should be characterised by the highest possible and repeatable workmanship, providing strength assumed at the design stage. The collaboration of the Łukasiewicz Research Network – Upper Silesian Institute of Technology, Welding Research Centre and of the Polish Automobile and Motorcycle Federation (i.e. the institution supervising motor racing in Poland) enabled the implementation of the Certification Procedure for Safety Cages in accordance with the Homologation Regulations for Safety Cages of Federation Internationale de l'Automobile. The article discusses conclusions concerning tests performed within the Certification Procedure for Safety Cages, rescue aspects concerning the safety cell design and further research trends.

Keywords: Automotive, Passive Safety, Safety Cell, Testing of Welded Joints

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Introduction

As a sport event controlled by Fédération Internationale de l'Automobile (FIA), motor racing requires the use of special racing or rally cars. Because of its extreme nature, the sport is characterised by a high accident rate resulting from exceeding safety thresholds, which, in turn, is the consequence of the maximum exploitation of car performance aimed to cover a given distance within the shortest possible time.

In 2015, the FIA implemented a *World Accident Database*, where all fatal accidents taking place in races or rallies are documented [9]. Information contained in the above-named database is used by working groups and the FIA's Safety Department to draw accident-related conclusions and develop new solutions aimed at increasing contestants' safety. The activity of the FIA and their local representatives (ASN) dedicated to improving motor racing safety has brought measurable results as the number of fatalities between the year 2000 and 2022 fell from between 60 and 70 to 40 [6]. The FIA is currently implementing programme *Vision 0*, aimed at the elimination of fatal accidents in motor racing [6].

During crashes, motor racing contestants are protected by many systems, including those improving passive safety. One of the more important of the aforementioned systems is the safety cell (also referred to as safety cage, roll cage or crash box) [22]. This article discusses safety cells, their production and the supervision of the manufacturing process as well as rescue issues following car crashes.

Passive safety in cars

The design of today's cars is the outcome of cooperation involving many engineers representing various industries. Sports vehicle complexity combines aspects of mechanics, industrial design, ergonomics, production technology and safety engineering (being the most important factor in terms of human health and safety) [13]. The present-day form of car bodies, which has evolved for more than 100 years, includes the aspect of passive

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mgr inż. Mateusz Sowa – Łukasiewicz – Górnośląski Instytut Technologiczny, Centrum Spawalnictwa (Łukasiewicz Research Network – Upper Silesian Institute of Technology, Welding Research Centre);

mgr inż. Bartłomiej Urbański – Politechnika Śląska w Gliwicach, Katedra Techniki Cieplnej (Silesian University of Technology, Department of Thermal Technology); Polski Związek Motorowy (Polish Automobile and Motorcycle Federation);

lek. Kamila Stopińska – Śląski Uniwersytet Medyczny w Katowicach, Wydział Nauk Medycznych w Zabrzu (Medical University of Silesia in Katowice; Faculty of Medical Sciences in Zabrze)

safety, i.e. the one aimed to minimise the consequences of defects or accidents [12]. Initially, little emphasis was given to driving comfort and safety, with the running gear and drive systems being the primary subjects under consideration. Cadillac was the first automotive company to use bumpers, made of flat bars and tasked with protecting the frame and the wheels of the vehicle. It was only in 1928 that the Budd company from Philadelphia started making entirely metallic bodies composed of drawpieces joined using welding methods [14]. That important step aimed to increase car passengers' safety and, consequently, contributed to the development of resistance welding techniques used in the joining of car body sheets [18]. In the 1930s, the Citroen company developed an integral car bodywork, implemented in models 11 and 15.

Other important steps were made by the Mercedes-Benz company, which enriched the structure of model W187 with rigid bumpers joined by means of elastic elements [14] and by providing model W111 with crumple zones. An immense increase in the scale of production seen in the 1950s, combined with the reduction of manufacturing costs, made cars more available for many people. However, the aforesaid fact increased traffic intensity and led to increasingly many collisions and accidents. The ever increasing number of cars on the roads entailed a growing interest in car safety features. The 1960s saw the creation of a new engineering sector, i.e. safety engineering. Its first and major accomplishment was the creation of an experimental safety car (in the USA). One of the major assumptions was the protection of passengers during an impact with a barrier when travelling at a speed of 80 km/h. The bumper was to absorb impact energy at a speed of up to 16 km/h [13, 14].

In addition to the application of bumpers, an increase in structural energy consumption involved the use of other elements tasked with the absorption of energy during collisions. One of the two solutions was the implementation of hydraulic shock absorbers, whereas the other one consisted in the application of thin-walled structures undergoing destruction when exposed to force. The 1973 oil crisis led to the use of bumpers made of polyurethane foam, aimed to reduce the vehicle weight and, at the same time, fuel consumption [13, 14].

In addition to ensuring passengers' safety, the present-day car body is also a load-carrying structure, composed of front and rear panels which, during collisions, undergo significant deformations as they absorb impact energy. The passenger part is reinforced with non-deformable beams aimed to provide maximum safety during an accident. In cases of side impacts, safety is provided by a rigid central pillar. In turn, bumper beams are tasked with the uniform distribution of forces onto the longitudinal beams of the vehicle (during a collision). The petrol tank is usually located in the zone being at the lowest risk of deformations during an impact (i.e. in the lower part of the car) and is additionally encased by the floor panel and rigid thresholds. Although car bodywork deformation characteristics are generally complex, the most typical types of deformation include crushing in the horizontal and vertical planes, torsion and bending. To ensure the distribution of forces, it is necessary for elements to have specific structural features. As regards the safety of passengers and goods inside a vehicle, the use of elements characterised by reduced rigidity (in order to absorb energy) and of rigid elements (constituting the safety cell) is of key importance in terms of vehicle behaviour during a collision. An example of a bodywork structure (including the safety cell) made of thin-walled elements is the bodywork of Audi A8, presented in Figure 1.

In terms of safety, the gradation of bodywork rigidity is very important in relation to the reduction of accelerations and inertial forces in the passenger compartment [10]. Examples of the aforesaid zones along with materials used in BMW cars are presented in Figure 2.

There are also other, less standard, bodywork concepts as the one applied in in BMW Z8 Roadster, developed using an innovative *Space Frame* technology. The space framework is made of extruded aluminium sections riveted or welded to bodywork panels. The crucial structures include stringers and the central tunnel joined to make a Y-like shape. The central segment of the floor is designed in a manner ensuring the absorption of impact energy. In addition, impact energy at a speed of up to 25 km/h is absorbed by easily exchangeable bolted elements of the body. A similar solution, referred to as *Audi Space Frame*, has been used in many models, e.g. Audi A2, A8 and R8. The load-bearing structure is made of aluminium bars and cast nodal modules. The front pillars have various cross-sections, whereas the beams are characterised by the variable cross-sectional shape along their entire length. Such a solution made it possible to reduce the weight of the structure by

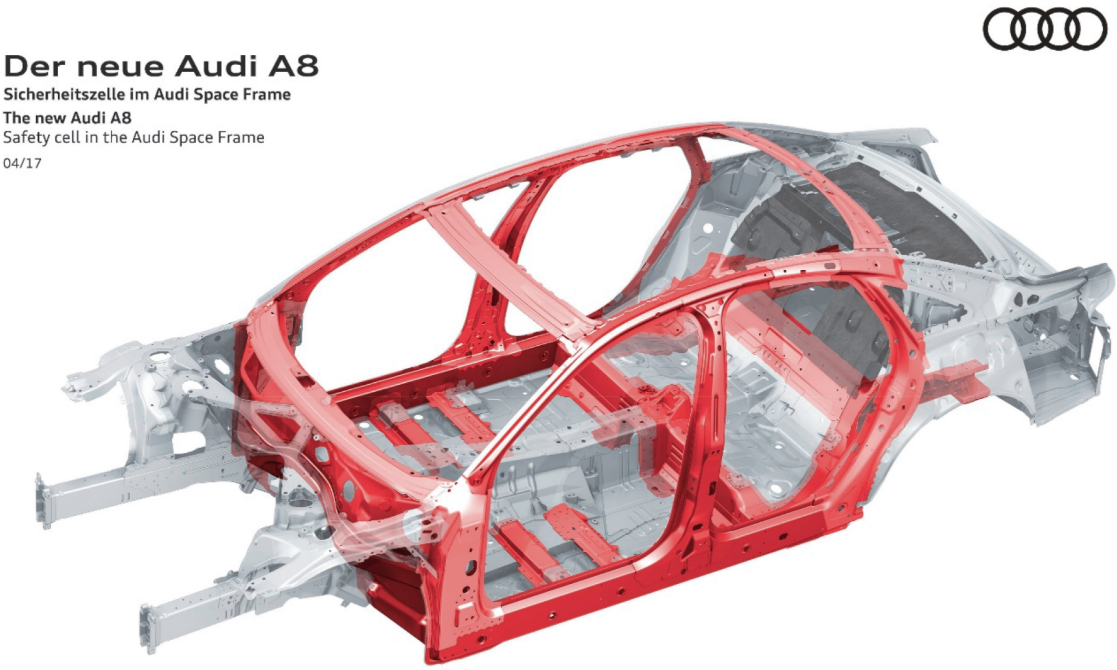

Fig. 1. Safety cell in the Audi Space Frame [3]

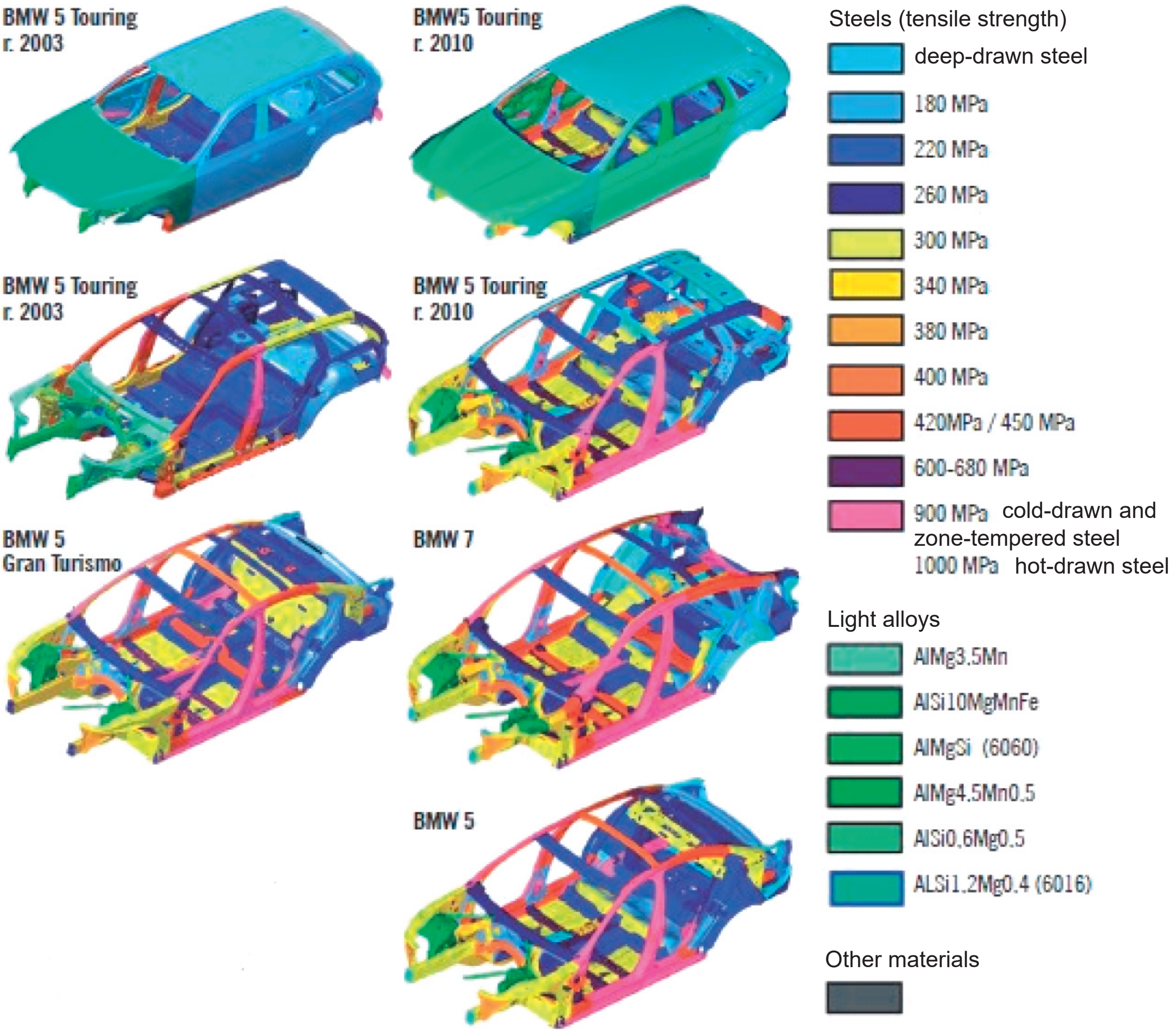

Fig. 2. Crumple zones and their materials in BMW cars [17]

approximately 40% (if compared with steel panelling) without compromising rigidity during collisions. In addition, the bodywork of model R8 is partly made carbon fibre-reinforced plastic (see Fig. 3).

The structure applied in Mercedes-Benz Class C (W203) enables the absorption of asymmetric impact energy by both front stringers. By means of a beam located in the rear axle, forces transferred by the stringers are dissipated in the central tunnel, thresholds and in the body shell. The front and rear segments are composed of bolted modules (referred to by the company as the *crash box*) made of high-strength steel. Another innovative solution is a bodywork designed by the Volkswagen company, where the flat floor is made of a previously bent aluminium sheet with expanded texture. Such an approach enabled the obtainment of a structure which is by 50% more rigid and by 30% lighter than that made of previously used components. During a collision, the floor structure undergoes controlled buckling. Another solution used in today's vehicles is the so-called sandwich structure, composed of thin-walled multi-chamber elements. Such a solution is applied in, e.g. Mercedes-Benz A-class limousine (W168), the safety cell of which is made of high-strength steel sections characterised by significantly higher rigidity than other bodywork elements and joined with less rigid elements constituting a multilayer structure. The above-presented bodywork enables the design of crumple zones [13].

Passive safety in motor racing

Bodyworks of sports cars are divided into two primary types. Bodies of Group 1 sports cars are based on mass-produced cars, appropriately reinforced for motor racing. In turn, bodyworks of Group 2 sports cars, dedicated to motor racing or rallying, have the form of monocoques made of carbon fibre (in Formula 1 or World Endurance Championship) or space tubular structures (used in Group T cars and, since 2022, in Rally 1 cars) [5]. This article discusses safety cells used both in Group 1 and (some) Group 2 cars [8].

Safety cells belong to some of the most important elements directly affecting the safety of motor racing contestants. By increasing bodywork rigidity, the aforesaid structures provide better control of the vehicle when taking corners and constitute one of the key vehicle elements responsible for passive safety, by reducing the effect of bodywork deformation during a collision. The safety cell is a space tubular structure connected with the car bodywork and, during impacts or overturns, tasked with the uniform distribution of impact forces among individual elements of the structure. In other words, the safety cell should absorb impact energy and protect both the driver and the co-driver. An exemplary safety cell installed in Group 1 car bodywork is presented in Figure 4.

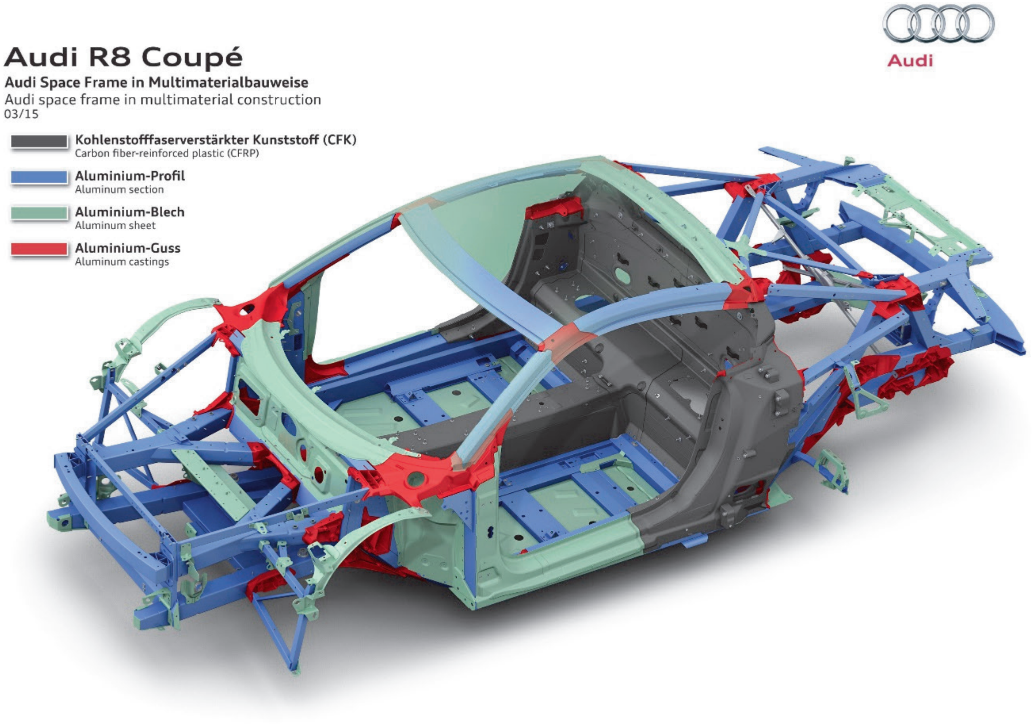

Fig. 3. Multimaterial Audi Space Frame [2]

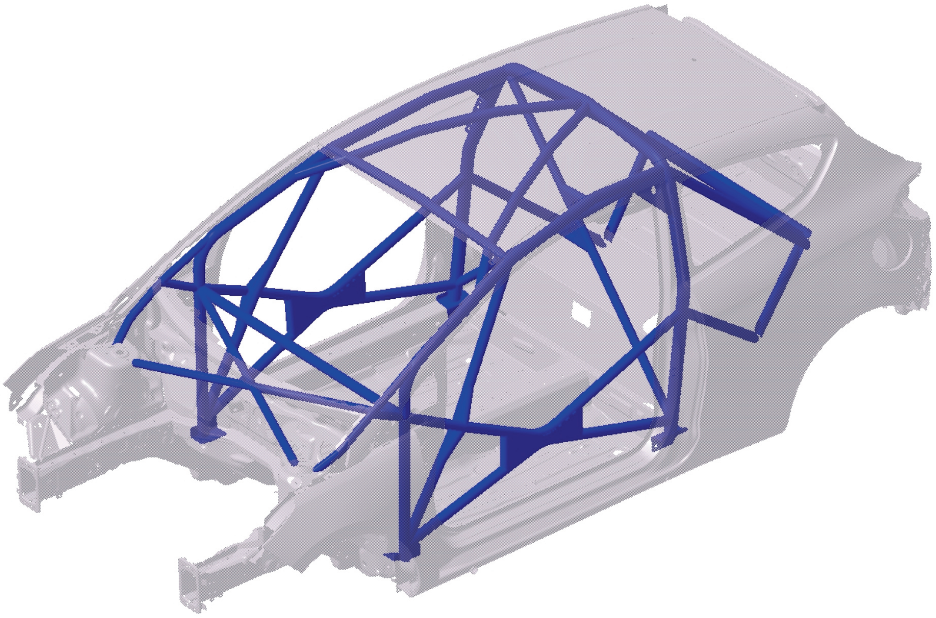

Fig. 4. Safety cell mounted in the rally car bodywork (materials by courtesy of M-Sport Poland Sp. z o.o.)

Safety cells were used in sports cars as early as in the 1960s [21], with their structure and materials evolving nearly every season. Issues concerning the safety cell structure are well-known and have been analysed in many scientific articles and subject to research by FIA, yet many authors claim that the effect resulting from the correlation between the workmanship of the safety cell and its effectiveness during an accident has not been sufficiently documented. The discrepancy between the assumed and the actual strength of the safety cell is of key importance as regards the protection of contestants during an accident. For this reason, the FIA along with ASNs have been gradually supervising manufacturers of safety cells through certification.

The article aims to demonstrate the key importance of not only the structure of safety cells but also the proper technology of their fabrication as well as to discuss the Certification Procedure for Safety Cages implemented by the Polish Automobile and Motorcycle Federation (FIA's ASN, i.e. national sporting authority, in Poland) in collaboration with the Łukasiewicz Research Network – Upper Silesian Institute of Technology, Welding Research Centre in Gliwice.

Certification Procedure for Safety Cages with Respect to Welding Engineering

The process of constructing a safety cell starts with a design developed by its producer in accordance with the FIA's Homologation Regulations for Safety Cages and a national document resulting from the former at the national level, i.e. the PZM's Certification Regulations for Safety Cages. The FIA's Homologation Regulations for Safety Cages specify structural requirements and safety cell strength tests related to the group and weight of the car (stipulated in regulations). Strength tests can involve an actual safety cell mounted on a testing stand or computer-aided simulations performed by FIA's authorised bodies. The PZM's Certification Regulations for Safety Cages define the process of certification along with requirements to be satisfied by the producer. The above-named process consists of the following steps [20]:

1. Initial verification of an application submitted by the producer.
2. Submission (by the producer) of evidence for the conformity of a designed safety cell with the FIA's Homologation Regulations for Safety Cages.
3. Joint audit performed by the Polish Automobile and Motorcycle Federation and an authorised body (i.e. Łukasiewicz Research Network – Upper Silesian Institute of Technology, Welding Research Centre) on the producer's premises.

In addition to the foregoing, the procedure imposes many other responsibilities on the producer, e.g. documentation of materials and production enabling, among other things, the association of a given safety cell with a related material inspection certificate. Each safety cell is also provided with a producer's data plate and a FIA's seal sticker (enabling identification and preventing forgery).

In terms of issues discussed in the article, the most interesting is the third step of the above-named procedure, i.e. an audit performed on the manufacturer's premises. During such an audit, representatives of the Polish Automobile and Motorcycle Federation verify the conformity of submitted safety cell-related documentation with the actual state as well as evaluate producer's preparation for the fabrication of safety cells. In turn, a representative of the Łukasiewicz Research Network – Upper Silesian Institute of Technology, Welding Research Centre is responsible for supervising the pre-weld preparation of elements and the welding process itself. The elements are subjected to tests and their result, if positive, constitutes the basis for the fabrication of a given safety cell by the manufacturer.

Taking into account aspects connected with workmanship and the selection of appropriate technology, the participation of an independent research body, i.e. the Łukasiewicz Research Network – Upper Silesian Institute of Technology, Welding Research Centre from Gliwice, is of key importance. The body is responsible for the welding-related part of the Certification Procedure for Safety Cages, consisting in the performance of welding procedure qualification as well as the performance of tensile tests involving tubular cruciform joints.

Welding procedure qualification for forked joints

The identification of manufacturer's technological potential and, consequently, the quality of products manufactured by the producer of safety cells necessitated the performance of a welding procedure qualification for forked joints (reflecting actual conditions present in safety cell structures). Test joints were prepared in accordance with the schematic diagram presented in Figure 5.

Areas sampled for specimens subjected to macroscopic tests are presented in Figure 6.

The scope of the tests in the welding procedure qualification included the following tests:

1. visual tests consisting in the visual assessment of a given weld by an authorised specialist. The above-named tests, constituting the primary form of the non-destructive verification of the quality of welded joints, are performed in accordance with the requirements contained in the ISO 17640 standard (classification of joint quality level is based on the PN-EN ISO 5817 standard);

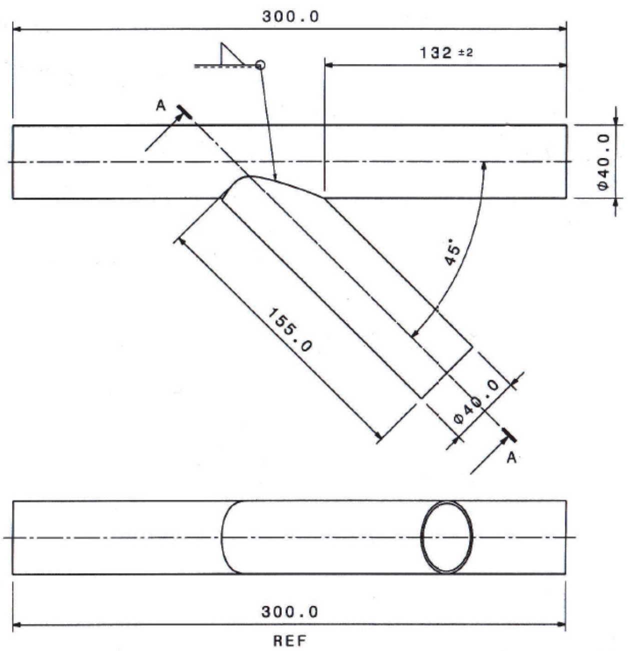

Fig. 5. Preparation of elements subjected to the tests

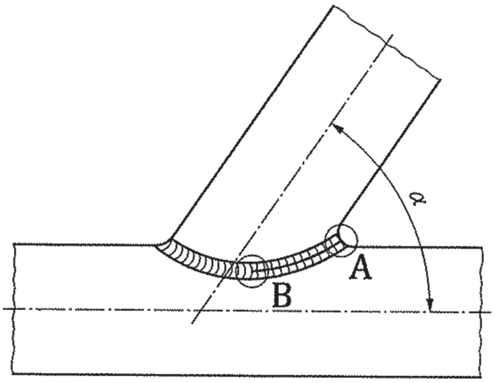

Fig. 6. Area sampled for specimens subjected to the macroscopic tests [1]; in test results the specimen sampled from area A was designated as specimen no. 1, whereas that sampled from area B was designated as specimen no. 2

2. penetrant tests – performed (in accordance with the PN-EN ISO 3452-1 standard) to detect surface cracks;
3. macroscopic metallographic tests – consisting in the observation of an appropriately prepared metallographic specimen (on the cross-section of the joint, in the area specified in the PN-EN ISO 15614-1 standard). The procedure was performed in accordance with the requirements of the PN-EN ISO 17639 standard;
4. hardness measurements – involving the cross-section of the joint, particularly important as regards the welding of high-strength materials, due to higher contents of alloying elements (primarily carbon). Excessively high hardness in the heat affected zone (HAZ) may

lead to brittle cracking during a collision. The measurements involved the performance of Vickers hardness tests (HV10) in accordance with the PN-EN ISO 9015-1 standard.

Static tensile test

In order to determine the strength of a welded joint it was necessary to perform an additional test, necessitating the making of cruciform joints by the producer. The joints were subjected to static tensile tests, performed in accordance with the requirements of the PN-EN ISO 4136 standard; the cruciform joint itself is not subject to welding procedure qualification. Figure 7 presents the pre-test preparation of tubes.

Test results

Presented below are test results performed in accordance with the PZM's Certification Procedure for Safety Cages. Case no. 1 concerned a manufacturer of safety cells evaluated positively. The performance of the procedure did not entail changes in the welding technology or the process applied by the manufacturer. Cases nos. 2 and 3 concerned manufacturers, whose products contained welding imperfections (identified in macroscopic metallographic tests) resulting in the reduced tensile strength of cruciform joints. All of the test joints were made of seamless tubes (cold drawn steel E355 +N in accordance with the PN-EN ISO 10305-1 standard). Only after correcting welding process parameters or changing some aspects of pre-weld preparation of elements it was possible to obtain joints satisfying both quality and strength-related criteria. The test results concerning case no. 2 and case no. 3 were compared in relation to the initial and the target technology (i.e. following the implementation of technological changes).

Case no. 1

Macroscopic metallographic test results

The results of the macroscopic metallographic tests concerning case no. 1 are presented in Figures 8 and 9.

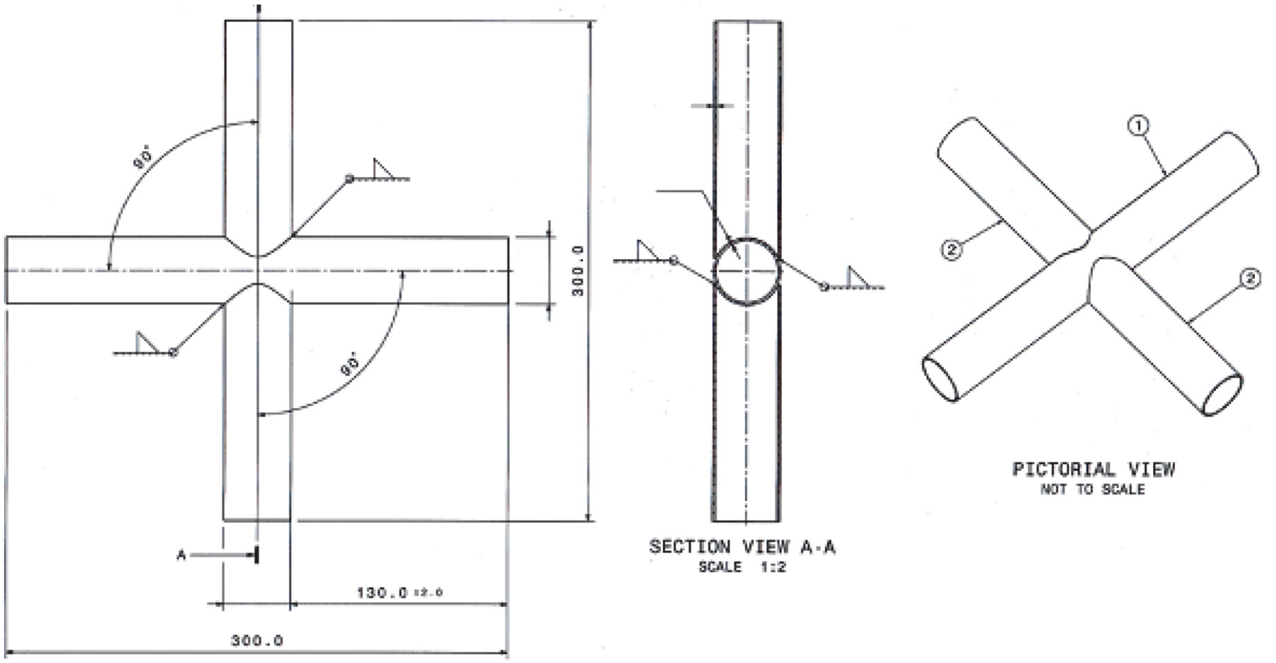

Fig. 7. Preparation of the joint for the tensile test

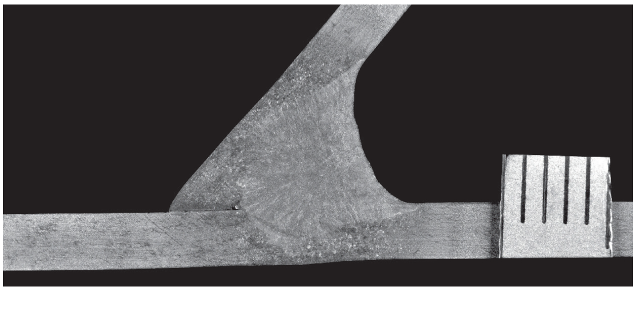

Fig. 8. Macrostructure of specimen no. 1 (sampled from area A, in accordance with Fig. 6)

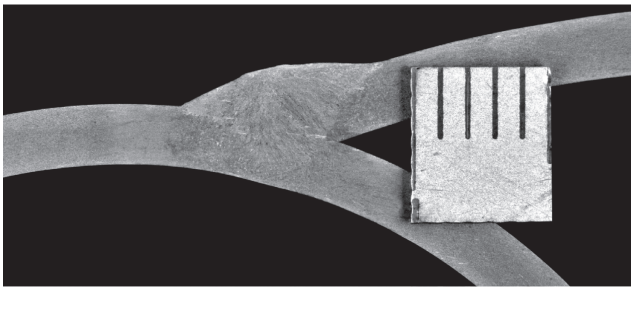

Fig. 9. Macrostructure of specimen no. 2 (sampled from area B, in accordance with Fig. 6)

Tensile test results concerning tubular cruciform joints

The tensile tests were performed using an MTS Criterion C45 testing machine. The test results are presented in Table 1.

Neither the macroscopic metallographic test results nor the static tensile test results revealed the presence of welding imperfections. The strength of the cruciform joint satisfied the criterion of the minimum strength of the base material (amounting to 490 MPa in accordance with the PN-EN 10305-1 standard). The specimen ruptured in the base material, which indicated the proper workmanship of the welded joint (procedure-related criterion).


Fig. 10. Welded joint after the tensile test

Table 1. Tensile test results concerning the tubular cruciform joint made of steel E355+N

Designation	S_o, mm^2	F_m, kN	R_m, MPa	Remarks
Case no. 1	181.4	102.0	562.1	Rupture outside the weld

Case no. 2

Macroscopic metallographic test results

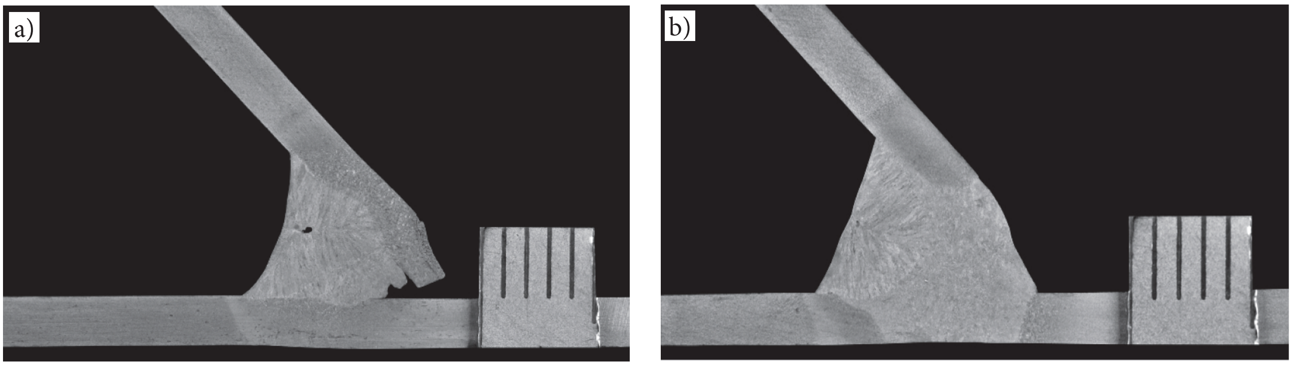

Fig. 11. Macrostructure of specimen no. 1 (sampled from area A, in accordance with Fig. 6); a) result obtained using the manufacturer's technology; b) result obtained after technological changes

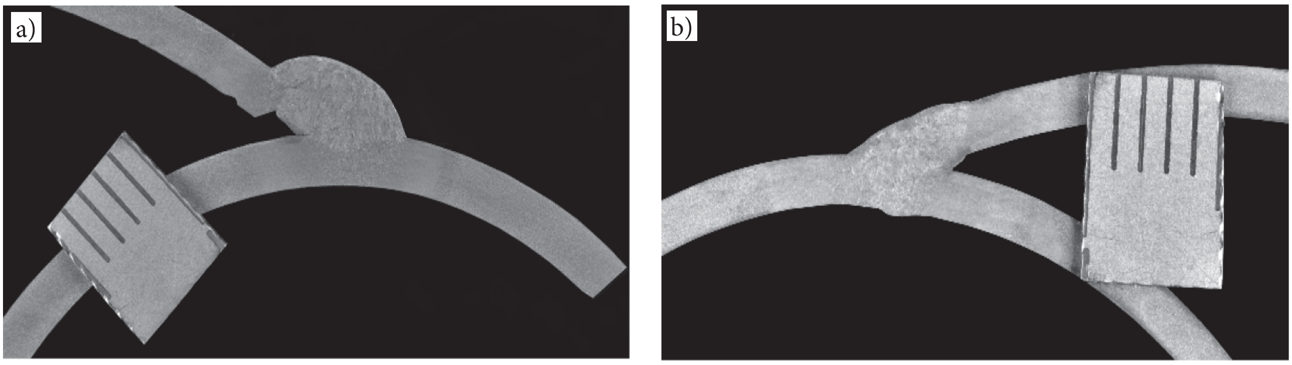

Fig. 12. Macrostructure of specimen no. 2 (sampled from area B, in accordance with Fig. 6); a) result obtained using the manufacturer's technology; b) result obtained after technological changes

Strength test results

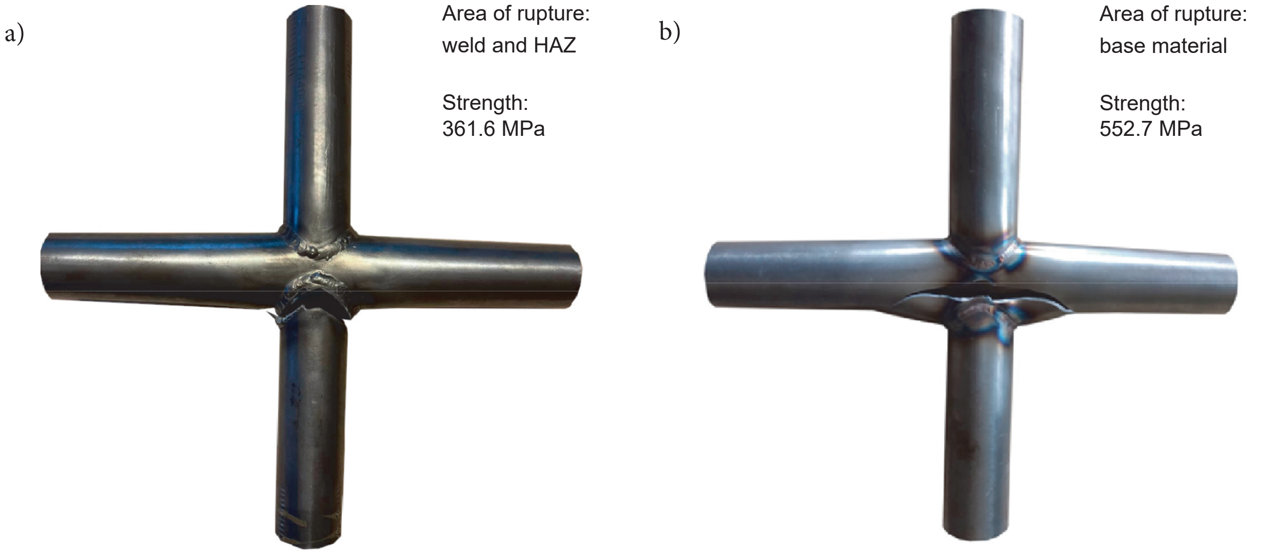

Fig. 13. Welded joints made of steel E355 + N after the tensile test, along with the obtained tensile strength value; a) result obtained using the manufacturer’s technology; b) result obtained after technological changes

Case no. 3

Macroscopic metallographic test results

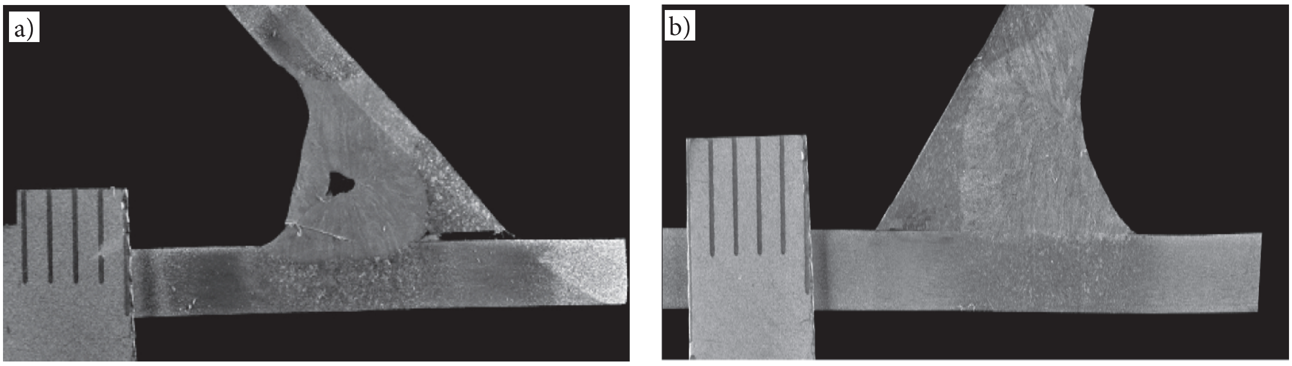

Fig. 14. Macrostructure of specimen no. 1 (sampled from area A, in accordance with Fig. 6); a) result obtained using the manufacturer’s technology; b) result obtained after technological changes

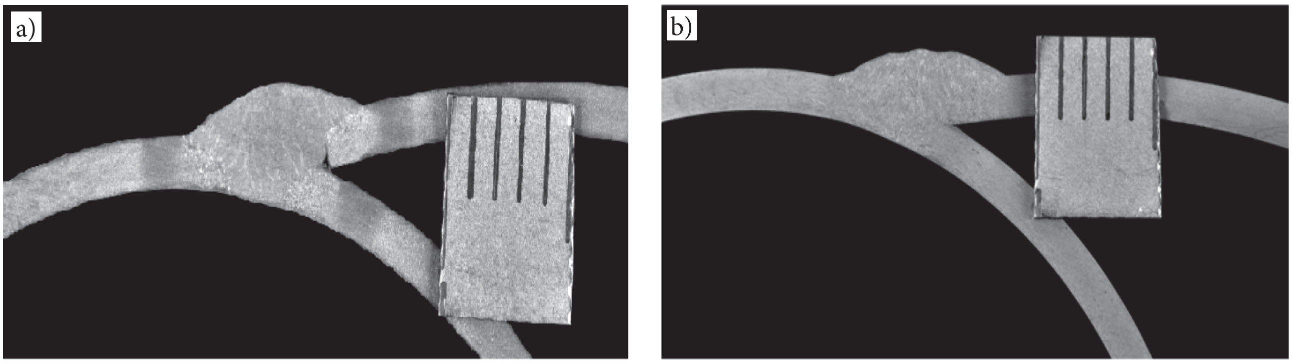

Fig. 15. Macrostructure of specimen no. 2 (sampled from area B, in accordance with Fig. 6); a) result obtained using the manufacturer’s technology; b) result obtained after technological changes

Strength test results

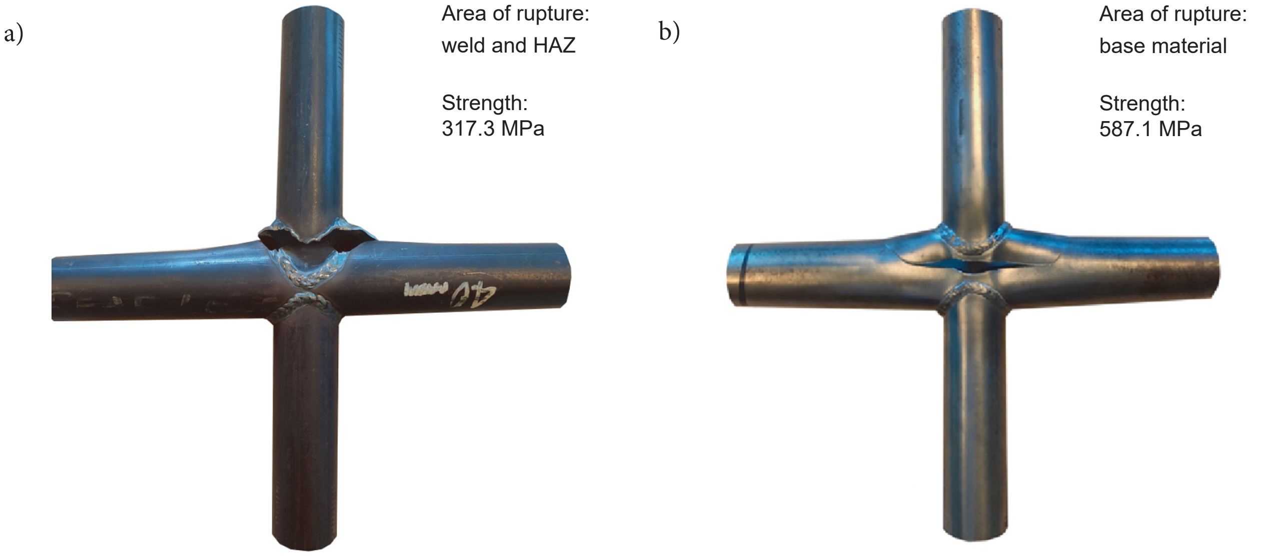

Fig. 16. Welded joints made of steel E355 + N after the tensile test, along with the obtained tensile strength value; on the left: result obtained using the manufacturer's technology; on the right: result obtained after technological changes

Discussion and conclusions

Welding aspect

The above-presented test results revealed that an appropriate manufacturing technology and the workmanship of safety cells play a crucial role in obtaining the previously assumed strength of the structure. In comparison with reference publications, the article-related research work involved the performance of destructive and strength tests of selected safety cell elements [19, 23]. It was demonstrated that the verification of the quality of welded joints (based on the Certification Procedure for Safety Cages) followed by their correction (in terms of appropriate penetration) resulted in a significant increase in the strength of welded joints made by producers. The foregoing was important because of the fact that the safety cell constitutes a key passive safety feature in the sports car, protecting contestants during an accident. The discrepancy between the strength of the safety cell assumed in the design and the actual one poses a significant threat to contestants as, in extreme cases, such a structure would fail to provide expected protection. For this reason, it is necessary to ensure appropriate and independent supervision over manufacturers of safety cells. The implemented procedure is a compromise between the scope of tests and possibilities of safety cell producers.

However, it should be noted that the above-presented procedure does not reflect stresses accompanying car crashes as the static comparison of the strength of safety cell structures does not reflect circumstances of actual accidents. For instance, the notch (having the form of the lack of penetration (of the weld)) would probably trigger the propagation induced by dynamic loads affecting the structure. Such an effect would be even more intense in cases of materials characterised by higher contents of carbon, chromium and molybdenum. In addition, the effect would be intensified by the presence of bainite and brittle martensite in the HAZ.

In order to determine how welding imperfections affect (reduce) the effective absorption of kinetic energy by safety cells it would be necessary to develop a dynamic test affecting a selected fragment of a given safety cell. Such a test should involve the destruction of elements in several configurations of impact energy and the angle of force application. Further tests concerning safety cell structures should include the comparison of the strength of elements made of high-strength steels (e.g. heat-treated steel T45, cold-formed welded steel Docol R8 and chromium-molybdenum steel 25CrMo4) followed by the identification of their ability to absorb energy (based on destructive tests dedicated to such structures). It would also be recommendable to perform tests of safety cells made of composites because carbon fibres could be better structural materials than steels [23].

Additional emphasis should be given to the selection of materials and technologies used for joining the former. It should be noted that a safety cell made of alloy steel and containing improperly made welded joins could be characterised by inferior mechanical properties than those of unalloyed steel, yet made using a properly selected welding technology [18]. It might be interesting how, in terms of strength, the aforesaid cases would differ from each other. A valuable result of such tests could constitute a recommendation related to safety cells structures, particularly as regards manufacturers not subject to certification and supervision by the FIA or the PZM.

Also, it would be beneficial to start analysing all accidents (not only fatal ones) for safety cell protective effectiveness. An example of such a good idea could be the recent implementation of accident recorders (by FIA), useful in the aforesaid analyses. An additional advantage of such the aforesaid solution is the low purchase cost of accident recorders [7].

Data obtained from accident recorders combined with doctors' and biomedical engineering specialists' knowledge of contestants' injuries could help draw conclusions concerning specific accidents and contribute to the development of regulations aimed at the further improvement of passive safety. Such activities have already been undertaken by the FIA, yet, in the opinion of the authors of this article, attention should be paid not only to contests organised by the FIA but also to national and local events organised by ASNs. Obviously, developmental studies concerning safety cell structures and other systems used in sports cars should also focus on the maximisation of absorbed energy. Such an approach, also applied in mass-produced cars and providing the best protection of car drivers and passengers, will necessitate the analysis of the entire sports car bodywork with the safety cell (and not only of the safety cell structure alone) and the development of guidelines concerning the most effective absorption of energy. The aforesaid types of bodywork have already been implemented in selected FIA's groups (e.g. Rally1) [4].

Rescue aspect

It should be assumed that each damage to the safety cell implies a serious accident [1]. For this reason, another important issue related to safety cells is the post-accident handling of casualties. On one hand, the safety cell helps limit accident-related effects, yet, on the other, the very same cell makes it more difficult for rescue teams to access an injured person [1]. Presently, related regulations contain requirements concerning the minimum size of the door, yet they vary depending on types of competitions and groups of vehicles [8].

Easy access to an injured contestant is particularly important if the accident is serious and accompanied by another danger (e.g. fire). The quick diagnosis of any life-threatening injury combined with fast prioritisation of urgent treatment procedures constitute the biggest challenges for medical rescue teams handling patients after motor racing accidents. To meet the above-named challenges, the treatment of severely injured patients should follow an appropriately structured medical protocol [11, 15]. Treating badly injured patients is usually performed in accordance with the ABCDE concept (A – airway, B – breathing, C – circulation, D – disability (i.e. disturbed awareness assessment) and E – exposure (of the patient)), constituting the clearly-specified basis for the prioritisation and sequencing of actions. The immobilisation of the spinal cord is performed primarily to prevent or minimise its secondary damage induced by injuries leading to spinal instability [16]. In terms of motor racing-related injuries, it is particularly component E in the ABCDE conceptual scheme that undergoes various modification. The uncovering and examination of other areas of the body, the palpable assessment of the abdominal cavity condition (tenderness, painfulness, peritoneal symptoms, peristalsis, etc.), the presence of pulse on inguinal arteries, symmetry, limb assessment (oedema, varices, post-thrombotic changes etc.) are impeded by the limited access to the casualty ("imposed" by the structural elements of the safety cell). For the above-presented reasons, guidelines concerning safety cells and car seats should emphasize the necessity of maximising the access to a person injured in an accident.

Safety cells also pose a challenge when it is necessary to cut through the tubes damaged in an accident. It is very important to prevent potential injuries which could be caused by releasing residual stresses when cutting individual elements [1]. It is crucial that rescue teams active at all levels of a given sport event should be aware of the presence of the above-named stresses. Such awareness helps protect rescue team members from injuries and prevent further injuries affecting the casualty. It is necessary that the FIA and ASNs should cooperate with rescue teams, particularly at the local level.

Concluding remarks

1. The above-presented test results revealed that the Certification Procedure for Safety Cages positively affected the quality of manufactured products. After related technological changes, the strength of joints increased by 85% and 52% respectively in relation to that of the joints welded by producers before the modifications performed in accordance with the guidelines specified in the Certification Procedure for Safety Cages.
2. The primary factor affecting the static strength of safety cells is the proper penetration of the weld in the forked (cruciform) joint. The above-presented conclusion is based on the macroscopic metallographic test results and their comparison with the static strength of the cruciform joints welded using a given welding technology.
3. The appropriate adjustment of technological welding conditions confirmed by a related welding procedure qualification record (WPQR) enables the obtainment of welded joints representing required quality, thus significantly increasing the absorbability of kinetic energy by the safety cell structure.

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