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DECELERATION AND DEFORMATION DURING DYNAMIC LOADING OF MODEL CAR BODY PARTS AFTER POST-ACCIDENT REPAIR

Summary. Absorption of impact energy by the passive safety elements of the vehicle body is the basic feature to ensure conditions of safety for the driver and passengers in transport. The parts especially designed for this objective in the self-supporting car body are longitudinals. Their energy-absorbing features are designed in different ways. Evaluation of the degree to which the vehicle (body) ensures safety during a collision is difficult and expensive. Usually, tests under impact conditions are required. The most advanced and costly are the tests carried out on a complete vehicle (whole real object for tests). Whole vehicle testing can be replaced by testing of individual car body elements (for example longitudinal).

The main aim of this article is to present and compare the results of dynamic studies on model energy-consuming objects (new model longitudinals and model longitudinals repaired with welding methods). For the purpose of this study, models of vehicle passive safety elements (model longitudinals) were designed.

On the basis of the conducted tests, it was found that it is worth considering the replacement of collision tests of the whole vehicle by tests of its individual components. This can be considered a new approach that is not widely used. Currently, most often, crash tests of entire vehicles are conducted (high costs) or computer simulations are performed (often with unsatisfactory accuracy).

1. INTRODUCTION

The considerations presented in this article propose using crash tests of individual components of a vehicle instead of a whole vehicle crash test. This is possible for new and for repaired elements. For the purpose of this study, models of vehicle passive safety elements (models of longitudinals) were designed. There were models of new and repaired parts. Dynamic tests were carried out on a specially designed test stand (speed of the hammer up to 9.7 m/s, impact energy up to 23.6 kJ). This test stand enabled registration of the deceleration during impact and deformation of the tested object (models of longitudinals). Based on the tests, it was found that it is worth considering the substitution of collision tests of the whole vehicle by tests of individual components.

According to the currently valid conception of a safe car body (vehicle body that protects the driver and passengers during an accident.), the vehicle is divided into zones. These zones have different stiffnesses and are supposed to be deformed during a crash. The size of deformation and the character of deformation depend on the kinetic energy of the vehicle at the time of impact. Very important factors are the mass of the vehicle and the velocity of impact. It should be mentioned that all of the vehicle parts absorb the impact energy during their deformation. When parts of car body (for example the bumper and outer fender) deform during collision, they absorb some of the kinetic energy of the vehicle. The difference is in their ability to consume energy [1÷3].

In accordance with the conception of a safety car body, the vehicle body includes crash control zones. In these, zones energy-consuming elements are intentionally placed. They are designed in such a way that during the car crash, deformation and absorption as much of the vehicle's kinetic energy as possible are ensured. The vehicle components included in the crash control zones can be divided into two groups. The first group includes elements that have been deliberately designed and used to absorb impact energy (for example crashboxes). The second group includes elements that, in addition to their basic task, have been designed in a way that ensures that they have energy-consuming properties (for example, longitudinals). The basic elements included in the crash control zones are bumpers and sub-bumper beams, crashboxes, a front partition, longitudinals and the bonnet.

In general, car crash tests are not carried out for vehicles after post-accident repair. Such tests are also not carried out for individual parts of the vehicles supporting the structure (passive safety of the vehicle body).

2. LONGITUDINALS AND THEIR REPAIRS

Despite the rapid development of technology, the maintenance of transport still causes many problems [4÷11]. Still, the most important problem is wearing of parts and components [13, 14]. The issues of road safety, and driver and passenger safety [15÷17], especially in terms of impact energy consumption, are very significant [18÷20]. But that is not all. In recent years, particular attention has been devoted to environmental impact [21, 22].

Longitudinals are the basic energy-absorbing parts in the construction of a self-supporting car body. However, longitudinals in the self-supporting car body can be treated as a remnant from the times when frame constructions predominated. These parts have several important functions. The most important of them are the functions of supporting elements for the engine (or the whole drive unit) as well as the suspension of the vehicle. The longitudinals appear in almost every car body. Because of their shape and characteristic location in the vehicle, they have an additional task - absorbing the kinetic energy during car crash [23÷25]. As research shows, kinetic energy during a car crash is absorbed mainly by longitudinals. For this reason, their role in the passive safety of the car body and whole vehicle safety is very important (Fig. 1). It is especially important for the vehicle for postaccident repair.

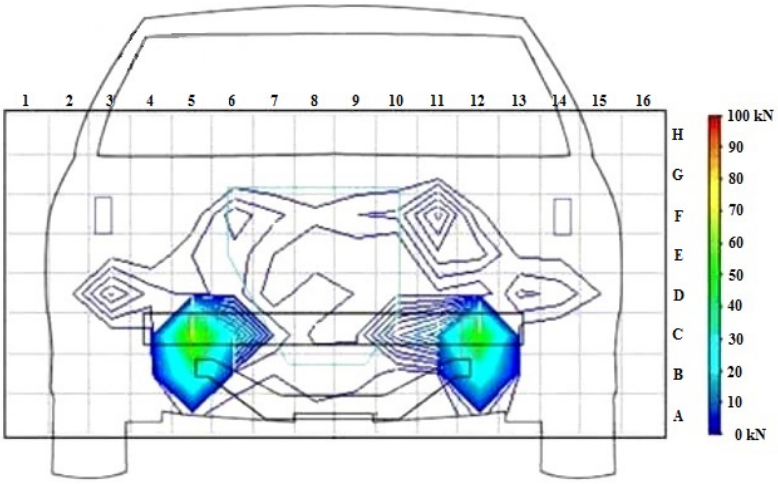

Fig. 1. Results of measurements of the impact force of a passenger car in a rigid barrier at a speed of about 50 km/h in 15 ms of impact [26]

Modern longitudinals as members of the self-supporting car body do not resemble longitudinals from frame structures made as one element. The longitudinals of the currently produced passenger cars generally have a closed cross section. In the simplest constructions, the longitudinal most often consists of two or three parts. However, in more complex constructions, it happens that the longitudinal consists of more main parts. In addition, a series of additional parts may be included in the longitudinal.

During the design of longitudinals, the designer may program the method and course of longitudinal deformation during the collision. It has an effect on the value of deformation of the car body and on the value of deceleration affecting users of the vehicle. Therefore, it also affects the accident course and the health and life of users of the transport. Generally, the designer has to consider three options:

- the shape of the longitudinal and its components,
- the material used for the longitudinal and
- the connections between the longitudinal's individual parts.

The geometrical shapes of the longitudinal ensure the optimal mode and course of deformation and stiffness of all the parts. At specific times, the deformation of the longitudinal will be initiated at the time of impact. This is because holes and ribs have been made in the longitudinal. The number and size of the holes and ribs are strictly defined. The more such elements, the lower the load capacity and stiffness of the longitudinals. The longitudinals of the currently produced passenger cars generally have a closed cross section (Figs. 2 and 3).

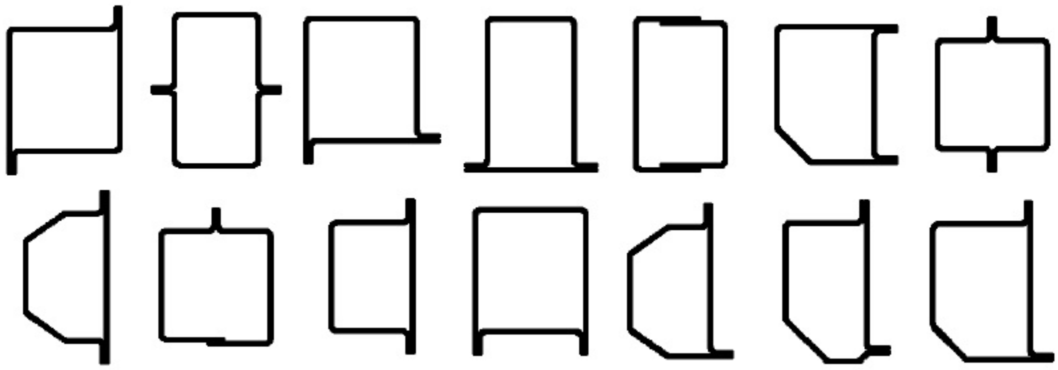

Fig. 2. Examples of different cross-sections of the longitudinals

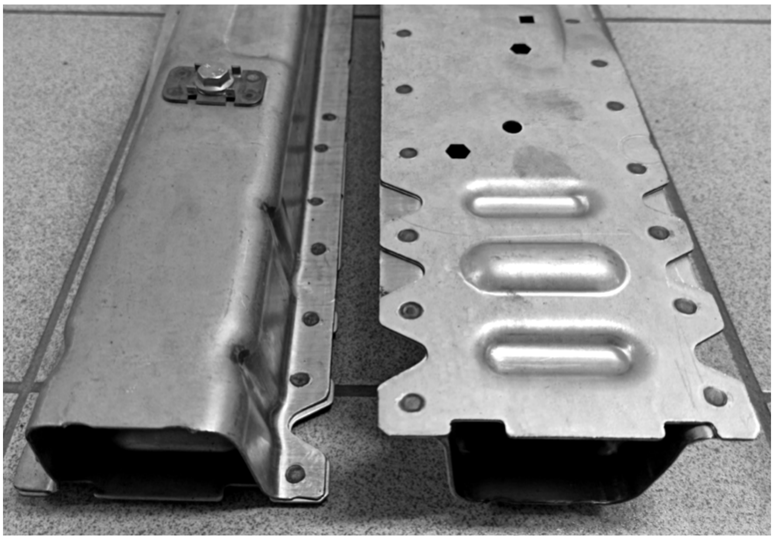

Fig. 3. Example of the front longitudinal from a passenger car

It should be noted that the choice of material also influences the course of deformation and stiffness of longitudinals. This part must have proper load capacity, but at the same time, it must be characterized by proper plastic properties (for example, impact toughness). Currently, commercial passenger vehicles still have car bodies made mainly of steel, but different grades of steel can be used for longitudinals. Generally, the higher the steel strength, the greater the load capacity and rigidity of the longitudinal.

A very important issue in terms of the longitudinals in a self-supporting car body is the connection between components of longitudinals. These connections influence strongly the value of deformation of the car body and the value of deceleration affecting the users of transport. Generally, resistance spot welding is used to connect individual longitudinal components into one functional subassembly, but other welding methods are also used [27÷31]. The smaller the number of individual longitudinal components, the smaller the number of connections required between these components. The smaller the number of connections between individual longitudinal components, the smaller the load capacity and rigidity of the longitudinal.

Generally, repair of the components of the vehicle body (including the longitudinal) can be carried out as repair needed after a road collision or as repair to restore the required technical condition (e.g. corrosion, cracks due to fatigue). However, during post-accident repair of longitudinal, most often, spot resistance welds are replaced with spot welds. These welds are usually made by the MAG welding method (Metal Active Gas) or the MIG welding method (Metal Inert Gas). It involves welding with a consumable electrode in an active or inert shielding gas. Such replacement of a spot resistance weld with a spot weld may cause a change in load capacity and stiffness of the entire longitudinal.

If the load capacity and stiffness are reduced, then, during the next collision, bigger deformation and smaller value of deceleration in relation to the new (unrepaired) longitudinal will develop. If the values of these parameters are increased, then, during the next collision, smaller deformation and higher value of deceleration will occur in relation to the new (unrepaired) longitudinal.

It should be noted that during post-accident repair of longitudinals, other kinds of welds may appear. These are butt welds. An example is the butt weld created when replacing the damaged part of the longitudinal. This configuration of the joint does not exist in new vehicles (Fig. 4). In this case, the repaired longitudinal with the butt weld will always have smaller load capacity and smaller stiffness in comparison to new (unrepaired) longitudinal.

Post-accident repair of longitudinal by replacing the damaged part of the longitudinal is performed when the deformation covers only a part of the longitudinal. This type of repair is possible when the deformation does not exceed the last cutting line determined by the vehicle manufacturer in the repair technology. This repair consists of cutting out a deformed part of the longitudinal and replacing it with a part prepared from the new longitudinal. The joining of individual longitudinal parts is carried out by welding in shielding gases. The butt welds appear in the repaired longitudinal. This type of repair is called repair by replacing the part of damaged longitudinal. If only the longitudinal component is deformed, it can also be repaired. It is possible by replacing the damaged longitudinal component. In this case, original joints (spot resistance welding) are replaced by welded joints (spot welds).

3. INVESTIGATION AND RESULTS

Dynamic testing during investigations has been carried out. Dynamic testing has been done using a special test stand. The main characteristics of the test stand for dynamic testing are shown in Table 1. The test stand is shown in Fig. 5.

The advantages of the designed test stand for dynamic testing are that the velocity of impact can be smoothly adjusted and free fall mass can be gradually changed. In addition, it is possible to study model energy-absorbing elements of the car body as well as elements of the real self-supporting car body.

According to the main assumption of the method of testing, during the impact process, the deceleration of free fall mass and the deformation of the tested element are recorded as a function of time. Time courses of deceleration were obtained using a measuring system with a deceleration sensor. Time courses of deformation were obtained on the basis of determining the regression function, taking into account the results of a frame-by-frame analysis of the movie recorded by a speed camera. All tests were carried out with the maximum values of test stand parameters.

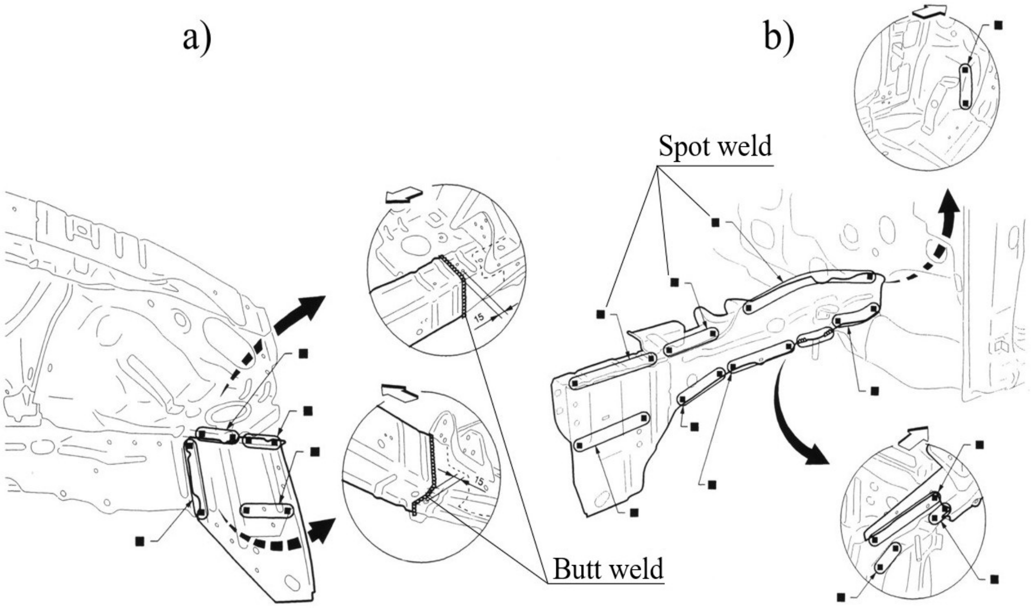

Fig. 4. Manufacturer's recommendations for post-accident repair technology of the front longitudinal: a) by replacing the part of damaged longitudinal and b) by replacing the damaged part of the longitudinal; white arrows indicate the front of the vehicle [32]

Table 1

Characteristics of the test stand for dynamic testing

Hammer mass	up to 500 kg
Impact velocity	up to 9.7 m/s (up to 35 km/h)
Free fall height	up to 4.8 m
Impact energy	up to 23.6 kJ

Model longitudinals were considered for a dynamic investigation. Generally, model longitudinals have 0.5 m length and are composed of two steel parts (Table 2) with a thickness of 3 mm and with a Ω shape. Moreover, model longitudinals have a shape of cross-section similar to that of a rectangle measuring 70 x 90 mm (Fig. 6). Three kinds of model longitudinals for investigations were developed (Fig. 7):

- new (unrepaired) model longitudinals with resistance spot welds (Fig. 7a),
- repaired model longitudinals with spot welds made by the MAG welding method (Fig. 7b) and
- repaired model longitudinals with resistance spot welds and butt weld made by the MAG welding method (Fig. 7c).
- Generally, three types of connections were made in the tested elements: resistance spot welds and welds made with the MAG welding process (spot weld, but weld). To obtain the gradation of the stiffness of the model longitudinal, marginal welds at the end of it were made. The parameters of spot resistance welding are shown in Table 3, while welding parameters in gas shields are shown in Table 4.

Figs. 8÷11 present examples of the results obtained during dynamical testing. The averages and standard deviations were calculated from five tests. These figures illustrate the first phase of the impact (compression). Results were obtained for different kinds of model longitudinal:

- value of deceleration of hammer depending on the time during impact,
- values of the average maximum deceleration of the hammer,
- value of model longitudinal deformation depending on the time during impact and
- values of average maximum deformation of the tested longitudinal.

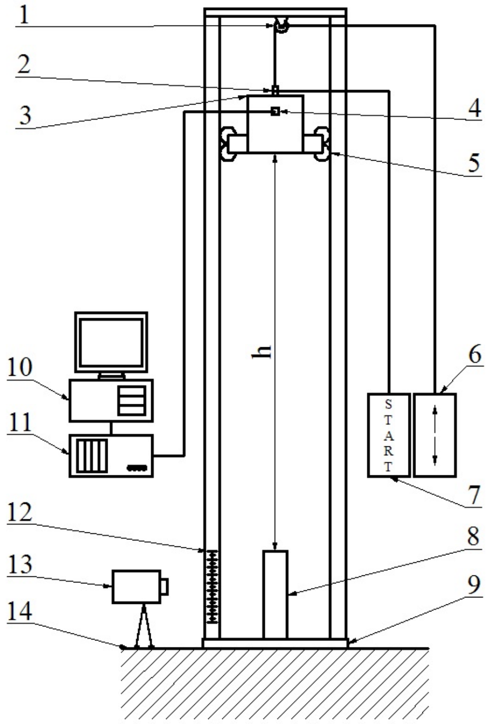

Fig. 5. Schematic diagram of the test stand for dynamic testing of model car body elements, h – height of free fall of the hammer, 1 – hoist, 2 – trigger, 3 – hammer, 4 – deceleration sensor, 5 – guide rollers, 6 – hoist panel, 7 – trigger device, 8 – model longitudinal, 9 – base of test stand, 10 – computer, 11 – device for data acquisition, 12 – graduation, 13 – speed camera and 14 – foundation

Table 2

Chemical composition of the steel from which the model longitudinals were created

Steel grade	Chemical composition, weight %				
S355J2G3	C	Mn	Si	P	S
	0.2	1.45	0.51	maximum 0.035	maximum 0.035

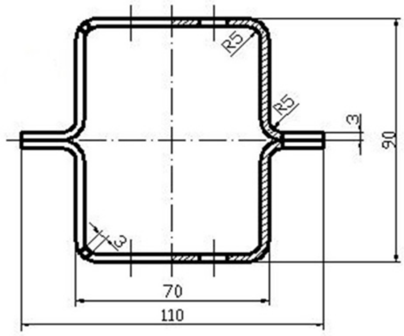

Fig. 6. Half-view and half-section in a plane perpendicular to the axis of the model longitudinal

In the first case, the duration of the impact process (first phase of the impact, which is compression) for the new model longitudinal was about 0.038 s. The maximum value of the deceleration was observed at the beginning of the impact process and, in this case, was about 480 m/s^2. It was the characteristic feature of the time course of the deceleration during impact. This is due to the fact that at the beginning of the impact, the model longitudinal had the highest stiffness. Deceleration increases from zero to the maximum value and, then, the value decreases and increases again to 420 m/s^2. The time course of the deceleration had a specific shape (characteristic changes in the parameter value). This was due to the predetermined deformation type of the model longitudinal during the collision.

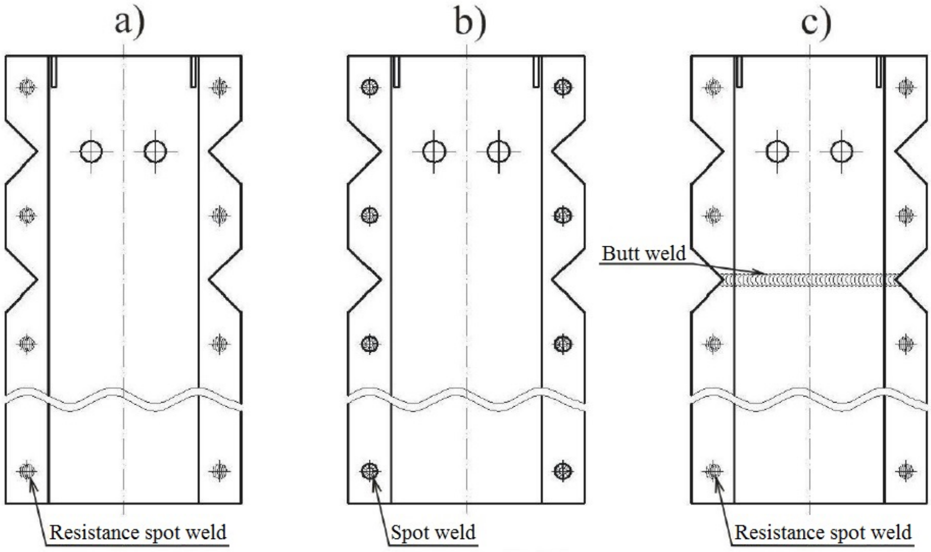

Fig. 7. Model longitudinals used in the investigations: a) new (unrepaired) model longitudinals with spot resistance welds, b) repaired model longitudinals with spot welds made by the MAG welding method and c) repaired model longitudinals with spot resistance welds and butt weld made by the MAG welding method

Table 3

Parameters of resistance spot welding

Diameter of electrodes, mm	Current, kA	The force of electrode pressure, kN	Welding time, s
8.6	18.8	3	0.45

Table 4

MAG welding parameters

Shielding gas	Gas flow rate, dm^3/min	The diameter of the electrode wire, mm	Current, A	Voltage, V	Wire feeding speed, m/min
82% Ar + 18% CO_2	16	0.8	100	20	11

In the second case of change resistance spot welds by spot welds made by the MAG welding process, the duration of the impact process (first phase of the impact) was about 0.034 s. The maximum value of the deceleration was observed at the beginning of the impact process and, in this case,was about 610 m/s^2. Deceleration increases from zero to the maximum value and, then, the value decreases and increases again to 470 m/s^2. In this case, the time course of the deceleration also had a specific shape. The highest value was at the beginning of the impact and, then, the value changes over time.

In the third case, the longitudinal has resistance spot welds and butt weld made by the MAG welding process. The duration of the impact process (first phase of the impact) was about 0.046 s. The maximum value of the deceleration was observed at the beginning of the impact process and, in this case, was about 335 m/s^2. In this case, the time course of the deceleration had a slightly different shape without the characteristic second local maximum. The highest value was obtained at the beginning of the impact and, then, the value changed over time. It should be noted that the standard deviation was comparable in all cases.

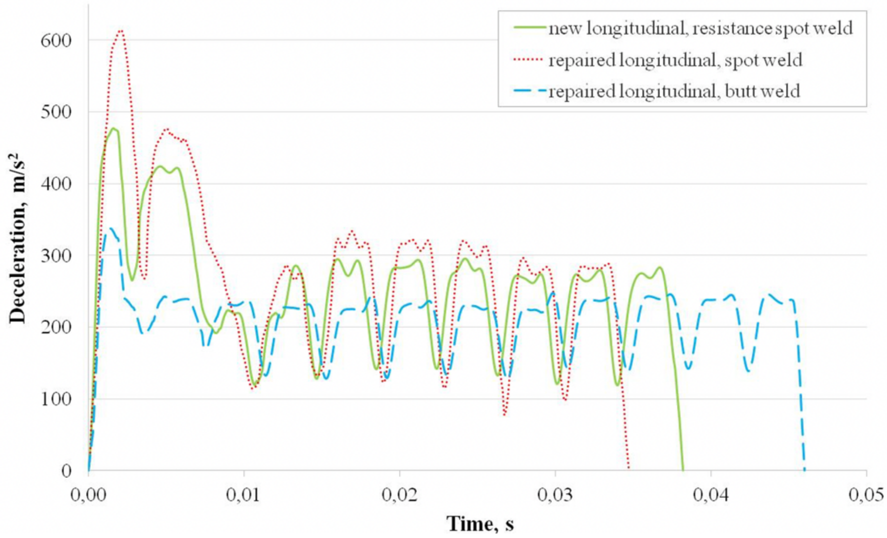

Fig. 8. Value of deceleration of the hammer depending on the time during impact – examples

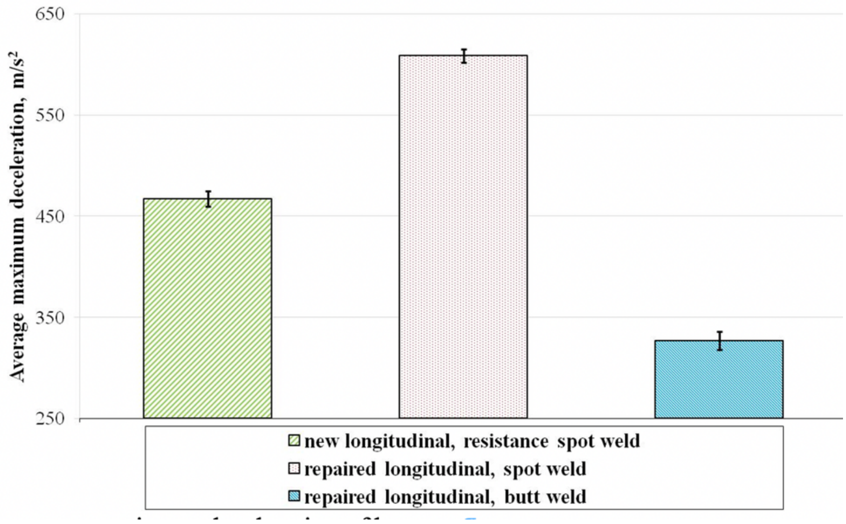

Fig. 9. Values of the average maximum deceleration of hammer

The average maximum deceleration of the hammer in the case of a repaired longitudinal with spot welds made by the MAG welding process was about 30% higher than in the case of new (unrepaired) longitudinals with resistance spot welds. This can be explained by the fact that more force is required to destroy spot welds than resistance spot welds. Moreover, no cracks were observed in the heat-affected zone. Use of spot welds instead of resistance spot welds causes an increase in parameters such as load capacity and stiffness of longitudinal. The average maximum deceleration of hammer in the case of repaired longitudinal with butt welds made by the MAG welding process was about 30% lower than that in case of new (unrepaired) longitudinals with resistance spot welds. This can be explained by the presence of butt weld. The presence of these additional joints causes the appearance of new heat-affected zones. Cracks in the repaired longitudinals in these zones were observed after dynamical tests. Making an additional butt weld leads to a decrease in parameters such as load capacity and stiffness of longitudinal.

The change in the value of model longitudinal deformation depending on the time during impact can be described as a square function. At the beginning of the impact process, the increase in deformation values is clearly greater than that at the end of this process. This is due to the fact that at the beginning of the impact, the hammer has a high velocity and, therefore, high kinetic energy. It should be noted that the presented valued of deformation describes deformation of the tested longitudinal at the end of the first phase of the impact (compression). Therefore, these values are the sum of plastic deformation and elastic deformation. Deformation of the tested longitudinal after the test was smaller because of the disappearance of elastic deformation.

In all cases, the highest values of longitudinal deformation occur at the end of tests. In the first case, for new (unrepaired) model longitudinals with spot resistance welds, the deformation was about 0.088 m. In the second case, for repaired model longitudinals with spot welds made by the MAG welding method, the deformation was about 0.076 m. In the third case, for repaired model longitudinals with resistance spot welds and butt weld made by the MAG welding method, the deformation was about0.116 m. It should be noted that the standard deviation was comparable in the first and the second cases. In the case of repaired model longitudinals with resistance spot welds and butt weld made by the MAG welding process, the standard deviation had the highest value.

It is also worth considering deformation (length reduction) of the longitudinal in relation to its initial length. All model longitudinals had an initial length of 0.5 m. The average deformation of new (unrepaired) longitudinals with resistance spot welds was about 17%. The average deformation of repaired model longitudinals with spot welds made by the MAG welding method was smaller and it is about 15%. However, the average deformation of repaired model longitudinals with resistance spot welds and butt weld made by the MAG welding method was bigger and it was about 23%. However, it must be noted that the differences in the observed deformation values are not very significant. The difference between the highest value (for repaired model longitudinals with resistance spot welds and butt weld made by the MAG welding method) and the lowest value (for repaired model longitudinals with spot welds made by the MAG welding method) is about 0.04 m.

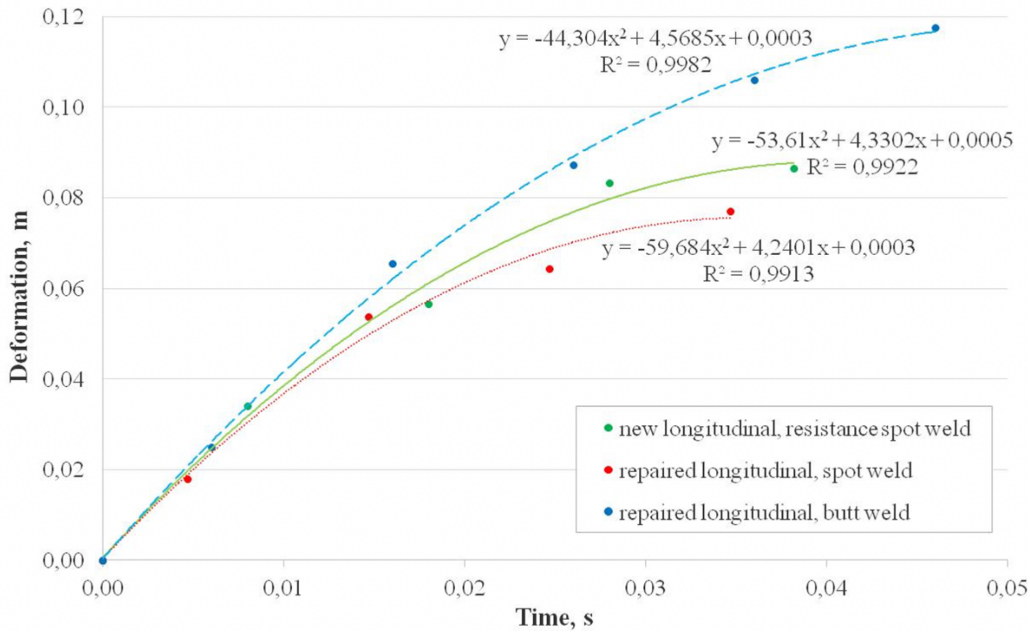

Fig. 10. Value of the model longitudinal deformation depending on the time during impact – examples

The average maximum deformation of longitudinal with spot welds made by the MAG welding process was about 16% lower than in the case of new (unrepaired) longitudinals with resistance spot welds. During testing, some joints between longitudinal parts were damaged. It was observed that resistance spot welds were damaged more often than spot welds. Damage of joints causes stiffness reduction and increase of deformation. The average maximum deformation of repaired longitudinal with butt welds made by the MAG welding process was about 32% higher than that in the case of new (unrepaired) longitudinals with resistance spot welds. This can be explained by the presence of butt weld. The presence of this additional joint caused the appearance of new heat-affected zones. Cracks of the repaired longitudinals in these zones were observed after dynamical tests. Making an additional butt weld induces a decrease in the values of parameters such as load capacity and stiffness of longitudinals.

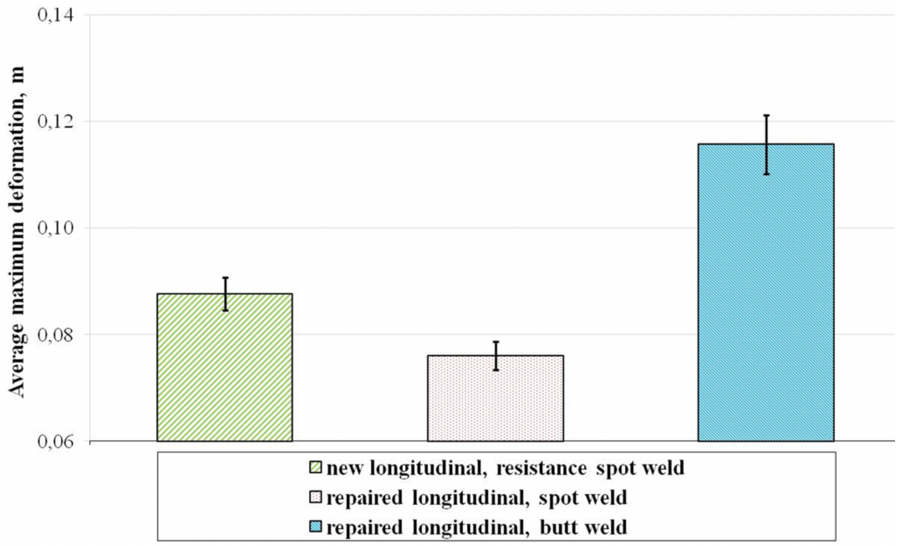

Fig. 11. Values of the average maximum deformation of tested longitudinal

4. SUMMARY

The safety of drivers and passengers of vehicles is still one of the most important topics. Its substantive scope includes the issue of passive safety of the vehicle. This is a particularly interesting issue when it comes to the self-supporting steel body of the vehicle and its repairs. The aim of this paper was to present and compare the results of dynamic studies on model energy-consuming for different real objects (different kinds of model longitudinals). For the investigation, a test stand was designed and constructed (experimental test stand) with the ability of deceleration and deformation measurement. On the basis of this investigation, it is possible to conclude that passive safety of vehicles is a very important subject and the car body is one of the passive safety aspects. Moreover, a longitudinal is the component that absorbs a lot of impact energy and it is possible to carry out crash tests on individual components of the car body (instead of the whole car).

The time course of the impact deceleration has a characteristic shape (high values at the beginning of the process and subsequent variations of the parameter value). For longitudinals with spot welds made by the MAG welding method (instead of spot resistance welds), the values of maximum deceleration during impact were bigger than those for unrepaired (new) longitudinals (with spot resistance welds), but for longitudinals with spot resistance welds and with butt welds made by the MAG welding method, the values of maximum deceleration during impact were smaller than those for unrepaired (new) longitudinals (with spot resistance welds). In case of longitudinals with spot welds made by the MAG welding method (instead of spot resistance welds), the values of maximum deformation during impact were smaller than those for unrepaired (new) longitudinals (with spot resistance welds), but for longitudinals with spot resistance welds and with butt welds made by the MAG welding method, the values of maximum deformation during impact were bigger than for those unrepaired (new) longitudinals (with spot resistance welds). For longitudinals with spot welds made by the MAG welding method (instead of spot resistance welds), the load capacity and rigidity were bigger than those for unrepaired (new) longitudinals (with spot resistance welds) and for longitudinals with spot resistance welds and with butt welds made by the MAG welding method, the load capacity and rigidity were smaller than those for unrepaired (new) longitudinals (with spot resistance welds).

On the basis of this investigation, it is possible to conclude the following:

- passive safety of a vehicle is a very important subject also when it comes to post-accident repairs because it influences the passive safety level during continued use of the vehicle,
- longitudinal is the component that absorbs a lot of impact energy during a car crash and its technical condition is very important from the viewpoint of the safety of the driver and passengers,
- it is possible to carry out crash tests on individual components of the car body (instead of the whole car),
- from the point of view of the maximum value of the deceleration during collision, it is better to repair the longitudinal by replacing the part of the damaged longitudinal (with butt weld) than to repair the longitudinal by replacing the damaged part of the longitudinal (with spot welds) and
- from the point of view of the maximum deformation of repaired longitudinal during next collision, it is better to repair the longitudinal by replacing the damaged part of the longitudinal (with spot welds) than to repair the longitudinal by replacing the part of damaged longitudinal (with butt weld), but the differences are so small that both post-accident repair methods can be used.

References

1. Tobota, A. & Karliński, J. & Kopczyński, A. Axial crushing of monotubal and bitubal circular foam-filled sections. *Journal of Achievements in Materials and Manufacturing Engineering*. 2007. Vol. 22. No. 2. P. 71-74.
2. Song, H.W. & Wan, Z.M. & Xie, Z.M. & Du, X.W. Axial impact behavior and energy absorption efficiency of composite wrapped metal tubes. *International Journal of Impact Engineering*. 2000. Vol. 24. No. 4. P. 385-401.
3. Romaniszyn, K.M. Wpływ struktury przodu nadwozia na energochłonność. *Zeszyty Naukowe Politechniki Świętokrzyskiej, Mechanika*. 2006. Z. 84. Kielce. P. 287-292. [In Polish: Influence of the front body structure on energy consumption].
4. Shipway, P. & Wood, J. The hardness and sliding wear behaviour of a bainitic steel. *Wear*. 1997. Vols. 203-204. P. 196-205.
5. Leitner, M. & Pichler, P. & Steinwender, F. & Guster, Ch. Wear and fatigue resistance of mild steel components reinforced by arc welded hard layers. *Surface and Coatings Technology*. 2017. Vol. 330. P. 140-148.
6. Stanik, Z. & Peruń, G. & Matyja, T. Effective methods for the diagnosis of vehicles rolling bearings wear and damages. *Archives of Metallurgy and Materials*. 2015. Vol. 60. No. 3. P. 1718-1724.
7. Zhang, H. & Wu, Y. & Li, Q. & Hong, X. Mechanical properties and rolling-sliding wear performance of dual phase austempered ductile iron as potential metro wheel material. *Wear*. 2018. Vols. 406-407. P 156-165.
8. Krneta, M. & Samardžić, I & Ivandić, Ž & Marić, D. Joining materials by metalock repair method. *Metalurgija*. 2018. Vol. 57. No. 1-2. P. 142-144.
9. Bąkowski, H. Wear mechanism of spheroidal cast iron piston ring-aluminum matrix composite cylinder liner contact. *Archives of Metallurgy and Materials*. 2018. Vol. 63. No. 1. P. 481-490.
10. Zhang, N. & Zhang, J. & Lu, J. & Zhang, M. & Zeng, D. & Song, Q. Wear and friction behavior of austempered ductile iron as railway wheel material. *Materials & Design*. 2016. Vol. 89. P. 815-822.
11. Kozuba, J. & Mendala, J. Corrosion Resistance of Steel Sheets with Zn Protective Coatings. *IEEE - Proceeding of the New Trends in Aviation Development (NTAD)* – 14th International Scientific Conference. 26-29.09.2019. Chlumec nad Cidlinou. Czech Republic.
12. Dahil, L. Effect on the vibration of the suspension system. *Metalurgija*. 2017. Vol. 56. Nos. 3-4. P. 375-378.
13. Kozuba, J. & Wieszała, R. & Piątkowski, J. Mechanical properties of the AlSi10MnMg alloy with a different content of manganese and magnesium intended for light die-casting. *IEEE – Proceeding of the New Trends in Aviation Development (NTAD)* – 14th International Scientific Conference. 26-29.09.2019. Chlumec nad Cidlinou. Czech Republic.

14. Baranowski, P. & Burdzik, R. & Piwnik, J. Measure and analysis of crash vehicle deformation. *Research and Didactic Equipment*. 2011. Vol. 16. No. 1. P. 11-16.
15. Matyja, T. & Łazarz, B. Modelling the coupled flexural and torsional vibrations in rotating machines in transient states. *Journal of Vibroengineering*. 2014. Vol. 16. No. 4. P. 1911-1924.
16. Celin, R. & Burja, J. Effect of cooling rates on the weld heat affected zone coarse grain microstructure. *Metallurgical and Materials Engineering*. 2018. Vol. 24. No. 1. P. 37-44.
17. Arai, Y. & Yamazaki, K. & Mizuno, K. & Kubota, H. Full-width tests to evaluate structural interaction. *20th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*. Lyon. France. 18-21.06.2007. Paper No. 07-0195.
18. Szczucka-Lastoa, B. & Gajdzik, B. & Węgrzyn, T. & Wszołek, Ł. Steel weld metal deposit measured properties after immediate micro-jet cooling. *METALS*. 2017. Vol. 7. No. 9. P. 1-9.
19. Rajendran, R. & Prem Sai, K. & Chandrasekar, B. & Gokhale, A. & Basu, S. Impact energy absorption of aluminium foam fitted AISI 304L stainless steel tube. *Materials and Design*. 2009. Vol. 30. No. 5. P. 1777-1784.
20. Tarigopula, V. & Langseth, M. & Hopperstad, O.S. & Clausen, A.H. Axial crushing of thin-walled high-strength steel sections, *International Journal of Impact Engineering*. 2006. Vol. 32. No. 5. P. 847-882.
21. Czech, P. Diagnose car engine exhaust system damage using bispectral analysis and radial basic function. *Proceedings of the International Conference on Computer, Networks and Communication Engineering. ICCNCE 2013*. 23-24.05.2013. Beijing. Peoples Republic of China. P. 312-315.
22. Skrucany, T. & Sarkan, B. & Figlus, T. & Synak, F. & Vrabel, J. Measuring of noise emitted by moving vehicles. *Dynamics ff Civil Engineering and Transport Structures and Wind Engineering (DYN-WIND'2017)*. 2017. Vol. 107. P. 1-8.
23. Gill A. Ocena skuteczności działania elementów bezpieczeństwa biernego samochodów osobowych na podstawie wyników badań zderzeniowych. *Zeszyty Naukowe Politechniki Poznańskiej, Maszyny Robocze i Transport*. 2001. No. 53. Poznań. P. 117-123. [In Polish: Assessment of the effectiveness of the passive safety components of passenger cars based on the results of crash tests].
24. Hadryś, D. & Miros, M. Coefficient of restitution of model repaired car body parts. *Journal of Achievements in Materials and Manufacturing Engineering*. 2008. Vol. 28. No. 1. P. 51-54.
25. Juntikka, R. & Hallstrom, S. Weight-balanced drop test method for characterization of dynamic propertiesof cellular materials. *International Journal of Impact Engineering*. 2004. Vol. 30. No. 5. P. 541-554.
26. Mizuno, K. & Tateishi, K. & Arai, Y. & Nishomoto, T. Research on vehicle compatibility in Japan. *18th International Technical Conference on the Enhanced Safety of Vehicles*. NHTSA. 2003. Nagoya. Japan.
27. Hadryś, D. Mechanical properties of plug welds after micro-jet cooling. *Archives of Metallurgy and Materials*. 2016. Vol. 61. No. 4. P. 1771-1775.
28. Węgrzyn, T. & Piwnik, J. & Borek, A. & Kurc-Lisiecka, A. Impact toughness of WMD after MAG welding with micro-jet cooling. *Materiali in Tehnologije*. 2016. Vol. 50. No. 6. P. 1001-1004.
29. Peroni, L. & Avalle, M. & Belingardi, G. Comparison of the energy absorption capability of crash boxes assembled by spot-weld and continuous joining techniques. *International Journal of Impact Engineering*. 2008. Vol. 36. No. 3. P. 498-511.
30. He, L. & Lin, X. An improved mathematical model for vehicle crash against highway guardrails. *Archives of Transport*. 2018. Vol. 48. No. 4. P. 41-49.
31. Hadryś, D. & Węgrzyn, T. & Piwnik, J. & Wszołek, Ł. & Węgrzyn, D. Compressive strength of steel frames after welding with micro-jet cooling. *Archives of Metallurgy and Materials*. 2016. Vol. 61. No. 1. P. 123-126.
32. Technical data and training materials from - Manufacturer's documentation for technology of post-accident repair of car body. 2008. Nissan. Japan Motors.

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