Preliminary tests of post-repair properties of the vehicle body energy-consuming structures

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Preliminary tests of post-repair properties of the vehicle body energy-consuming structures

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Abstract. The subject matter of the publication concerns numerical analysis and empirical research on the strength parameters of thin-walled energy-consuming structures subjected to crushing, which include the front longitudinal of the vehicle. The influence of welding processes applied during post-accident repair on selected mechanical properties of repaired elements was investigated. The process of creating a half wave will be touched, as a result of local buckling of the profile which is characteristic for the fourth class cross-sections, responsible for the progressive course of deformation. The results of the numerical analysis were compared with the results of empirical studies for selected states of stresses. The strength tests of connections as well as the entire models are presented. The result of the above tests is an attempt to answer the question: whether the partial change of the front longitudinal, in the conditions specified by the vehicle manufacturer in post-accident repair technology of energy-consuming elements, restores the usable properties of strength properties to the original state.

1. Introduction
The bodies of modern passenger cars are constructed and manufactured mainly as self-supporting structures. Therefore, their damage during a collision is often related to the violation (deformation) of significant structural elements of the car. Hence the question arises whether the removal of such damage with special care while choosing the repair technology and its implementation, will restore the strength values to their original state. Partial replacement technology assumes cutting out a part of the damaged part of the vehicle structure, permanently connected to the rest of the body, and in this place welding a new element, using a specific technological process regime.

Welding is accompanied by changes in the structure of the material in the zone of heat influence, inclusions, discontinuities or shape changes, due to deformations caused by welding shrinkage [1]. In the case of car front longitudinal, which constitutes a zone of controlled deformation, it is particularly important to achieve the assumed delay during the collision. In the case of thin-walled energy-consuming structures, any change in parameters may limit the absorption of impact energy in the initial collision phase, which may result in a higher instantaneous delay during further deformation of the front part of the vehicle and/or its deeper deformation.

In this article a numerical analysis of displacements and stresses of a top-hat profile system was carried out, taking into consideration the deformation of energy-consuming structures, during frontal collision at an angle of 0° and 30° with respect to the longitudinal axis of the system, unrepaired longitudinal model and for the welded model, taking into account changes in strength properties in the
HAZ (heat-affected) zone and the weld. Angle values were selected based on the results of frontal crash tests NCAP for 30° collisions, variant B - for 0° collisions, FMVSS No. 208, National Highway Traffic Safety Administration [2]. Conducted empirical studies take into account selected material tests, and a variant of deformation of thin-walled energy-consuming structures as a result of compression at an angle of 0°.

2. Material research

2.1. Selection of testing material

AHSS high-strength steel of a DP type (two-phase steel), of which the car's longitudinalis were produced in most of the manufactured vehicles, was used for the tests. This steel is characterized by a ferritic-martensitic structure, good formability due to soft ferrite, and high strength due to the martensite islands [3].

![Figure 1. Microstructure of AHSS steel DP type with visible martensitic islands in a ferritic matrix](image)

2.2. Sample preparation

The samples were prepared by welding the material with the MIG method, butt-welding with the parameters:

| Method | Shielding gas mixture | Welding voltage | Welding current intensity | Wire feeding speed | Determination of welding wire |
|--------|-----------------------|-----------------|--------------------------|--------------------|------------------------------|
| MIG    | Ar + 18[%] CO₂        | 18 [V]          | 35 [A]                   | 2,4 [m/min]        | G3Sil                        |

2.3. Examination of tensile strength and hardness of welded joint.

Measuring series consisted of 8 samples. During the study the force was recorded as a function of time. In the case of incomplete weld penetration of the welded edges or other execution irregularities the results of removing some of the samples were rejected after the initial inspection. The remaining results were further analyzed. The obtained results of the experiment for the welded samples are presented in Table 3.

| Item | Sample No. 2 | Sample No. 3 | Sample No. 6 | Sample No. 7 |
|------|--------------|--------------|--------------|--------------|
| Rm[MPa] | 708         | 683          | 669          | 640          |
Table 4. Test results of tensile strength of butt-welded joint of AHSS steel type DP800, rejected samples

| Item          | Sample No. 1 | Sample No. 4 | Sample No. 5 | Sample No. 8 |
|---------------|--------------|--------------|--------------|--------------|
| $R_m$ [MPa]   | 577          | 405          | 472          | 460          |

A hardness test of native steel material DP800, $R_m = 872$ [MPa] and hardness test in the welded area were carried out, perpendicularly to the welding line. The test was performed with a static hardness tester, Rockwell HRA according to PN-EN ISO 6508-1: 2002.

Fig.2. Hardness graph of the joint, welded by a static Rockwell HRA of the test steel DP800

Table 5. The results of the Rockwell HRA static hardness test of the steel DP800 welded joint

| Measurement width relative to the transverse axis of the sample [mm]| -15 | 10 | -6 | -4 | -2.5 | -1 | 1 | 2.5 | 3 | 4 | 6 | 10 | 15 |
|---------------------------------------------------------------|-----|----|----|----|------|----|---|-----|---|---|---|----|----|
| HRA hardness                                                  | 62  | 62 | 59 | 54 | 52   | 59 | 60| 49   | 50 | 55 | 59 | 62  | 62 |

2.4. Results

Only four samples were considered to be correct out of the eight ones that were cut from the finished complex omega profile prepared for further testing. The limit of the tensile strength of these welded joints $R_m$ was at an average level of 675 [MPa]. Thus, the average drop in the value of $R_m$ for the welded joint in relation to the base material is 22.5 [%]. The material tested was characterized by the lack of a distinct plasticity point. Analyzing the character of cracks in the tension samples, it can be noticed that in each sample which was taken as a correct one, the crack occurred at the HAZ area.

3. Parameters of energy consumption of a crushed thin-walled profile

The process of absorbing energy by thin-walled profiles is in most cases initiated by elastic or elastic-plastic buckling of one or several walls of the system, followed by the propagation of plasticized areas located in the so-called plastic articulated joints. These joints are a kind of nodes of the plastic mechanism of destruction, therefore the measure of efficiency for an energy absorber is the amount of dissipated energy in the deformation process of this mechanism [10].

According to the literature, with properly selected geometrical parameters of the system, its destruction occurs as a result of exceeding the plasticity point of the material in the weakest cross-section, that is, the local loss of stability occurs at the imperfection site, resulting in the first plastic wave [7].

The most important parameter characterizing the energy consumption of profiles is the medium power $P_{śr}$. It is defined as the quotient of the amount absorbed by the $E_i$ i energy profile of the total shortening of the $\delta_k$ profile. The energy consumption of the profile increases with the increase in its value. The discussed parameter allows to compare "resistance" to crushing profiles of different geometries [11,12,13,14]:

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45.0
50.0
55.0
60.0
65.0

-15 -13 -11 -9 -7 -5 -3 -1 1 3 5 7 9 11 13 15

Hardness HRA
Distance from weld axis, [mm]
The value of the $E_c$ energy absorbed by the crushed profile of a different geometry presents the area under the load-displacement curve $P=P(\delta)$ which can be calculated by integrating the area under the curve in the range of stable crushing, i.e. from 0 to the final shortening $\delta K$. This is the area of a progressive fold formation [11,12,13,14]:

$$E_c = \int_{0}^{\delta K} F(\delta) d\delta = F_S \delta K [J]$$

(2)

The maximum power $P_{\text{max}}$ is the highest force occurring during the crushing process. It usually appears at the beginning of the course and determines the value of the force necessary to create the first fold. The maximum power $P_{\text{max}}$ is usually smaller in the case of quasi-static experiments. This is due to the strengthening of steel as the deformation speed increases [11,12,13,14]:

$$P_{\text{max}} = \max \{F(\delta), \delta \epsilon(0, \delta K), [N]\}$$

(3)

4. Modeling and numerical analysis of the energy-consuming structure of a top-hat profile

A mixed solid mesh generator was used for the calculations, the omega profile model was divided into finite elements. Constraints in the bottom part of the profile preventing from movement relative to the Txyz axis were placed on the model developed in this way. In the upper part of the transverse profile a displacement in the vertical direction Tz was applied. It was assumed that the model is made of isotropic steel with the following properties: Young's modulus $E = 2.1 \times 10^5$ [MPa], Poisson number $\nu = 0.3$, density $\rho = 7890$ [kg/m$^3$], tensile strength $Rm = 1050$ [MPa], plasticity limit $R_{0.2} = 747$ [MPa]. The results of the FEM (finite element method) analysis in the form of reduced stress distribution according to the Huber-Mises hypothesis.

4.1. Numerical analysis No. 1

If the load capacity of the system depends on its weakest link, the recognition of the crushing mechanism, it indicates the area of the edge and the top plane of the hat profile as the place where the boundary load capacity $P_\text{gr}$ of the system will be reached first as a result of the formation of half-wave and transition to a new form of bending. Therefore, the model was simplified, omitting welded joints calculations, due to much greater strength of this profile part on compression, as well as geometrical complexity which significantly hinders the calculation, giving a continuous connection over the entire contact surface of the constituent profile parts instead.
Figure 3. Characteristics of force - displacement for Tz, from numerical analysis of the energy-consuming structure of the top-hat profile as a result of bending forces reaction (compression and cross-section tension) at an angle of 30° to the longitudinal axis of the system, in variant A - bending towards the upper part of the hat of the omega profile, variant B - bending towards the stupa and flat bar of the omega profile

4.1.1. Results

The numerical analysis confirms the significantly greater strength of the lower part of the omega profile cross-section, ie: the stupa of the hat profile together with the flat bar, at the complex state of stress during bending, ie with simultaneous compression and tension of the constituent elements.

4.2. Numerical analysis No. 2 for a complex state of stress

After determining the areas in which the P_gr limit load of the system with the transition to a new form of bending will be reached first, the profile has been modeled taking into account the changes in strength properties resulting from the welding process that take place in the HAZ and the weld. However, the modeling of inclusions, discontinuities or shape defects caused by welding contractions deformations was omitted.

The analysis was based on data collected during material tests of the strength of welded joints, presented above. Geometric parameters of the width of the heat affected zone (HAZ), welds, were determined based on the average of the samples made.

Table 6. The results of numerical analysis of energy intensity parameters for variant A - bending towards the upper part of the omega profile hat, variant B - bending towards stupas and the flat bar of the omega profile

| Variant   | P_gr [kN] | E_c [J] | P_max [kN] |
|-----------|-----------|---------|------------|
| Variant A | 15,9      | 1143    | 51,574     |
| Variant B | 34,59     | 2483    | 32,617     |
A mixed solid mesh generator was used for the calculation, the omega profile model was divided into 95178 finite elements spread on 132153 nodes. On the model developed in this way, constraints in the bottom part of the profile parallel to the cross-section on the height of 145 [mm] were placed, which prevented from displacement relative to the Txyz axis. In the upper part of the transverse profile a vertical displacement in the direction of Tz and Tyx=0 was applied.

**Figure 4.** Characteristics of force - displacement for Tz, from numerical analysis of the energy-consuming structure of a top-hat profile as a result of bending forces response (compression and tension) at an angle of 30° to the longitudinal axis of the system, in variant F - for the model without any changes introduced, G - for the model including changes in strength properties of HAZ bands and the weld.

**Figure 5.** Characteristics of compression work - displacement for Tz, from numerical analysis of the energy-consuming structure of a top-hat profile as a result of bending forces (compression and tension) at an angle of 30° to the longitudinal axis of the system, in variant F - for the model without changes introduced, G - for the model including changes in strength properties of HAZ bands and the weld.

### 4.2.1. Results

Numerical analysis confirms much greater durability of the model, which does not include changes in strength properties in the HAZ bands and the weld which take place in the welding process.

**Table 7.** Results of numerical analysis of energy-consuming parameters carried out at an angle of 30° to the longitudinal axis of the system, in variant F - for the model without introduced changes, G - for the model including changes in strength properties in the HAZ bands and the weld.

| Variant   | $P_a$ [kN] | $E_c$ [J] | $P_{\text{max}}$ [kN] |
|-----------|------------|-----------|-----------------------|
| Variant F | 29.77      | 670       | 41.126                |
| Variant G | 23.73      | 534       | 35.732                |
4.3. Numerical analysis No. 3 for a simple state of compressive stresses

Analogical to the above-discussed examples, a numerical analysis of the compression model in relation to the longitudinal axis of the system was carried out.

A mixed solid mesh generator was used for the calculations, the omega profile model was divided into 132891 finite elements spread on 208102 nodes. On such a developed model, in the bottom part of the transverse profile constraints preventing from displacement relative to the Txyz axis were placed. In the upper part of the transverse profile, a displacement in the vertical direction Tz was applied.

**Figure 6.** Characteristics of force - displacement for Tz, from numerical analysis of the energy-consuming structure of a top-hat profile as a result of compression forces response at an angle of 0° to the longitudinal axis of the system, in variant H - for the model without any changes introduced, I - for the model including changes in strength properties of HAZ bands and the weld.

**Figure 7.** Characteristics of compression work - displacement for Tz, from numerical analysis of the energy-consuming structure of a top-hat profile as a result of compression forces at an angle of 0° to the longitudinal axis of the system, in variant H - for the model without changes introduced, I - for the model including changes in strength properties of HAZ bands and the weld.

4.3.1. Results

Numerical analysis confirms much greater durability of the model, which does not include changes in strength properties, in the HAZ bands and the weld, which take place in the welding process.
Table 8. Results of numerical analysis of energy-consuming parameters carried out at an angle of 0° to the longitudinal axis of the system, in variant H - for the model without introduced changes, I - for the model including changes in strength properties in the HAZ bands and the weld

| Variant   | $P_u$ [kN] | $E_c$ [J] | $P_{max}$ [kN] |
|-----------|------------|-----------|----------------|
| Variant H | 88,76      | 925       | 113,18         |
| Variant I | 64,38      | 665       | 97,94          |

4.4. Analysis of the obtained results and further assumptions

The above numerical analysis of the developed models clearly indicates that the changes in strength properties in the narrow bands of the model structure, reflecting the HAZ areas and the weld, significantly weaken the original energy-consumption parameters of the model structure. The result of the simulation confirms that with properly selected geometrical parameters of the system, its destruction occurs as a result of exceeding the plasticity point of the material in the weakest cross-section [7]. The modeled shape of the detail reflects the welded joint whose weld has been grinded to the thickness of the base material, as in the case of post-collision repairs to preserve the aesthetic values.

The analysis of the local buckling process and the associated formation of half-waves on the surface of the system suggests that it would be reasonable to use the reinforcement of the wall at the connection point. This will result in spontaneously shifting the half-waves formed on its surface, far from the place of changes in the material structure, and creating a buckling in another place. Such reinforcement can be implemented, for example using a washer. However, this solution may be difficult in some cases because the longitudinal, with its technological assembly of the parts, is a closed profile, which will prevent the control from the inside. It is also possible to use the natural phenomenon which is the thickness of the weld. However, this solution worsens the aesthetic qualities of the repaired system, on the other hand it may allow to preserve the original strength properties.

5. Preparation of a top-hat energy-consuming structure model

For the axial compression test, energy-consuming structures made of DP1000 sheet with the parameters described above were prepared. These models were made of sheet metal along the rolling direction [KW 0], the forms had a height corresponding to the ending dimension of the column of 300 [mm], width - 220 [mm] and 100 [mm] resulting from the figure of the part development. They were subsequently formed on the press brake. The resulting components were subjected to a spot welding process.

5.1. The course of strength tests of energy-consuming structures for a simple state of compressive stresses

The measurement series consisted of 6 samples, two non-welded and four welded. During the test, the force as a function of time at a deformation rate of 50 mm/min was recorded.
Figure 8. Characteristics of force - displacement, from empirical studies of the energy-consuming structure of a top-hat profile as a result of the compression forces reaction at an angle of $0^\circ$ to the longitudinal axis of the system, for a non-welded model and for a welded model.

Figure 9. Characteristics of the compression work - displacement, from empirical studies of the energy-consuming structure of the top-hat profile as a result of the compression forces reaction at an angle of $0^\circ$ to the longitudinal axis of the system, for the non-welded model and for the welded model.

Table 8. Summary of energy-consumption parameters of the analyzed systems with statistical analysis

|                  | $P_{av}$ [kN] | $E_{c}$ [J] | $P_{max}$ [kN] |
|------------------|---------------|-------------|-----------------|
| Non-welded model | 44,15         | 882,92      | 105,96          |
| Non-welded model II | 41,48     | 829,61      | 106,28          |
| Welded model     | 41,63         | 832,67      | 102,30          |
| Welded model II  | 43,36         | 867,20      | 109,52          |
| Welded model III | 39,48         | 798,54      | 104,30          |
| Welded model IV  | 41,35         | 827,18      | 109,18          |
| **Average**      | **41,91**     | **839,69**  | **106,26**      |
| Standard deviation | 1,65       | 30,42       | 2,78            |
| 2x Standard deviation | 3,30      | 60,84       | 5,57            |
6. Conclusion

On the basis of the carried out compression tests it can be noticed that for the deformation speed of 50 mm/min, statistically significant differences in the increase of power $P_{\text{sr}}$, $P_{\text{max}}$ or strain energy $E_c$, causing the destruction of unwelded and welded axially compressed longitudinals are not observed. A single measurement result should be in the range $P_{\text{sr}} = 41.91 \pm 3.3$ [kN], $P_{\text{max}} = 106.26 \pm 5.57$ [kN], $E_c = 839 \pm 60.84$ [J], at 95 [%].

The results of the numerical analysis and the results of empirical research indicate a significant effect of the weld grinding process on the load capacity of the tested system, and more specifically the influence of the cross-section on its carrying capacity. Therefore, the assumption, as Timoshenko proved, that the destruction occurs as a result of exceeding the plasticity point of the material in the weakest cross-section [7], which means that the local loss of stability occurs at the imperfection site, resulting in the first plastic wave, should be complemented by this studied case. Here, apart from differences in strength in the transverse bands of the system, there are also differences in the size of its cross-section. For pure compression of the tested system its shape change will take place when the stresses occurring in the compressed cross-section exceed the value of plastic strain in the actual effective width. This happens because the limit load, above which the shape change of the compressed plate occurs, does not depend on its width, but is proportional to the square of its thickness, provided that the plate edges remain straight [7].

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