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Effects of spot welding on the functionality of thin-wall elements of car‘s deformation zone

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1. Introduction

Our roads are filled with second-hand vehicles. Needless to say, that those cars frequently happen to be used after some accident. Almost every accident of a car leads to irreversible damage in the passive safety systems of the vehicle. Fortunately some of those systems can be replaced or repaired, for example, safety airbags with their control modules and seat belts with tension sensor assemblies can be replaced after the car crash. However the major problem is with the car body and its deformational zones.

Car crash under higher speeds usually leads to substantial changes in the body geometry and damages of deformational zones [1-3]. As it often happens, geometry of the car body and deformational zones are repaired after the accident making it possible the further use of the car. Repair of deformational zones includes straightening, sometimes welding, and some parts get simply replaced [4, 5]. In any case such restructuring changes mechanical properties of materials as they are exposed to plastic deformation and are thermally processed. This changes characteristics of some junctions too, as instead of factory spot-welding parts are inter-welded manually.

The aim of this research is to estimate the influence of the spot-welded connections quality on the main crash characteristics as absorbed energy, deformation form or axial shortening. The experimental quasi-static and impact tests of the axial crushing of columns were performed to validate finite element (FE) models which were used for the simulations to evaluate the influence of spot-welding.

2. Experimental research and results

The U-shape specimen was selected for the purpose of our research. Thin-walled columns with the length of 20 cm had the similar cross-section as automotive longerons (Fig. 1).

The experimental quasi-static and impact tests were performed with the thin-walled columns (Fig. 2). The layout of spot-welding was symmetrical.

Fig. 1 Specimens used for the quasi-static and dynamical experiment

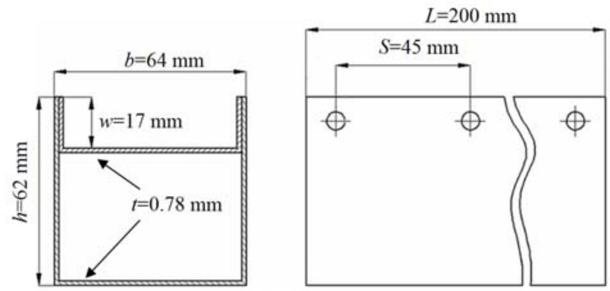


Fig. 2 The dimensions of spot-welded specimen

The quasi-static axial compression tests were run on the universal hydraulic 5 t tension-compression testing machine, which applied the axial load through flat end platens without any additional fixing. Crosshead speed was approximately 0.3 mm/s.

The mean crush load can be calculated by Wierzbicki and Abramowicz [6] analytical equation

$$F_m = 13.06\sigma_0 t^2 \sqrt[3]{\frac{b}{t}} \tag{1}$$

where σ_0 is the mean plastic stress, t is the thickness, b is the width of the longerone.

In the test the specimen is buckled at crushing distance of 100 mm. The load-compression curves were obtained.

The dynamic testing equipment (Fig. 3) involved impact by the solid of 60 kg in weight with the initial speed at the impact of 6 m/s. The required speed was obtained by selecting a height from which the mass was dropped down. To prevent the impacting mass from deviations and to ensure the symmetric impact, a specific guide-rod *4* with the diameter of 10 mm was installed. With the purpose of a very precise placement of a specimen, the specific centring components *2* were used. Acceleration sensors *6* were installed on the impacting mass. Accelerometers of Type „Wilcoxon 784 A“ were used for testing. Characteristics of accelerometer:

Sensitivity, 25°C	100 mV/g
Acceleration Range	50 g
Frequency Response	4-7000 Hz
Power required voltage	18-30 V
Sensing Element Design	PZT ceramic
Weight	45 grams

The analogue signal of sensors readings was converted by Device „Picoscop – 3424“ to the digital signal that was recorded on a computer using the program „Picoscope 6" designed by the manufacturer of this device. Several initial experiments lead to the observation that in the initial stage of the impact, high-frequency vibrations occurred that were undesirable in our case as they significantly distorted findings of our testing. To reduce the vibrations a mechanical damper was used between the specimen and the impacting mass.

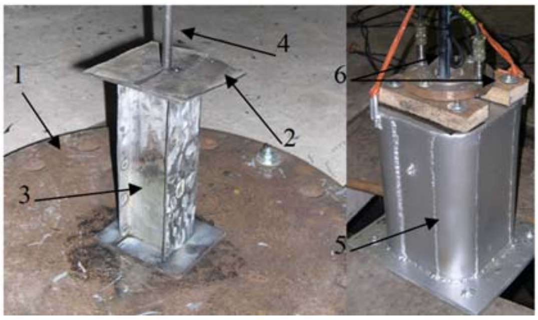


Fig. 3 Equipment of dynamical experiment: *1* – basement; *2* – centring components of specimen; *3* – specimen; *4* – guide-rod; *5* – mass; *6* – accelerometers

a b c

Fig. 4 Specimens used for the experiment: a – after the quasi-static test; b – after the dynamical crushing; c – FEA model after the dynamical crushing

To compare the simulation results with the experiment of axially crashed thin-walled elements, it is important that the same material properties as used in the experiment are also used in the material model of the simulation [7, 8]. 6 plates (20x300 mm) are selected as samples for the test. To approximate the tension diagram the material model *MAT_PLASTIC_KINEMATIC in LS-Dyna [9, 10] with linear isotropic strain hardening approximation was used:

$$\begin{cases} \sigma = E\varepsilon; & \text{when} \quad \sigma \le \sigma_Y \\ \sigma = E\varepsilon_Y + E_t(\varepsilon - \varepsilon_Y); & \text{when} \quad \sigma \ge \sigma_Y \end{cases} \qquad (2)$$

where E is Young's modulus; σ_Y is yield strength; ε_Y is yield strain; E_t is tangential modulus

Tangential modulus was calculated

$$E_t = \frac{\sigma_U - \sigma_Y}{\varepsilon_U - \varepsilon_Y} \qquad (3)$$

where σ_U is true ultimate tensile stress; ε_U is true uniform strain

The main mechanical properties of the material used for FE simulations are presented in the Table 1.

The quasi-static experiment, dynamic crushing experiment and FEA simulating results of the longerone deformation histories are shown in Fig. 5 and Fig. 6.

Table 1

Mechanical properties of the material

Nr.	σ_y, MPa	σ_u, MPa	ε_u	E_t, MPa
1	287.2	430.1	0.262	547.4
2	286.4	424.7	0.270	514.6
3	306.6	430.1	0.255	487.9
4	306.9	424.7	0.266	445.0
5	296.4	421.9	0.259	488.3
6	296.6	416.7	0.261	462.7
av.	**296.7**	**424.7**	**0.262**	**491.0**
CV	**3.01**	**1.20**	**2.01**	**7.44**

CV is coefficient of variation

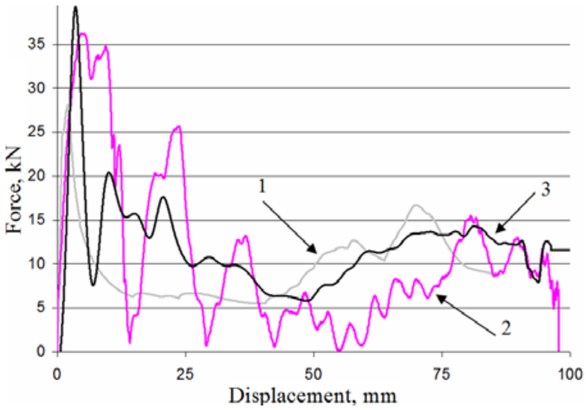


Fig. 5 Force displacement curve: *1* – quasi-static experiment; *2* – dynamic experiment; *3* – FE simulations

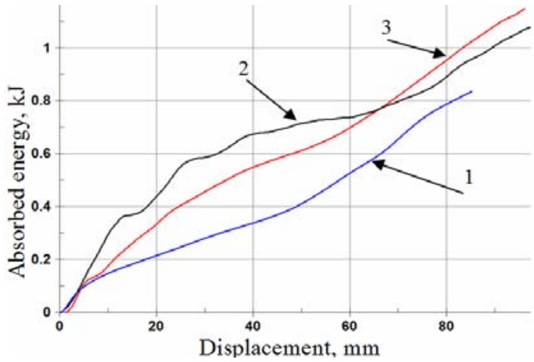
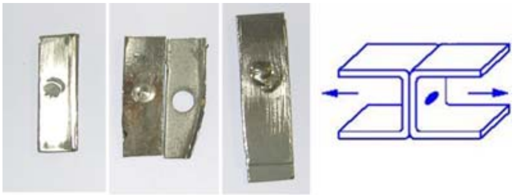


Fig. 6 Absorbed energy: *1* – quasi-static experiment; *2* – dynamical crushing experiment; *3* – FE simulations

3. The influence of spot-welded connections to the parameters of axially crushed columns

In automobiles, deformation zones are usually made of several tinplate sheets that initially undergo pressing to obtain their specific form. These thin-plate sheets are interconnected by spot-welding. When repairing sometimes it is necessary to separate individual panels of the deformation zone in order to recover their primary form (Fig. 7, a, b and c). The most common way for separating the spot-welded sheet metal parts is drilling out using the special drilling device. The diameter of the drilling device is selected according to the diameter of the spot-weld. Predominant diameter of the drill is 8 mm. After recovering the primary form of the panels they are interwelded again. The panels are welded manually at the former spot-welded areas.



a b c d

Fig. 7 Spot-welding: a – original spot-welding; b – dismounted spot-welding; c – manually spot-welded; d – scheme of experiment

In case of manual welding the strength of spot-welds is dependent on the following factors: preparation of the connective components (elimination of paints, primers and corrosion), intensity of the welding current and of course the level of qualification of the welder [11]. Selection of inadequate manual welding mode can result in a welding of a very low quality. At least one missed spot-welding doubles the spacing between adjacent connections in our research profile.

Critical axial and shear forces are the main mechanical characteristics of the spot-welded connections. The experimental testing of manufactory and manually spot-welded connections (Fig. 7, d) were performed to determine the axial and shear forces that destroy the connection. Table 2 presents the results of the test.

Table 2

Mechanical properties of spot-welding connections

Nr.	Original spot-welding		Manual spot-welding	
	Shear F_{max}, kN	Axial F_{max}, kN	Shear F_{max}, kN	Axial F_{max}, kN
1	9.8	7.6	9.6	3.8
2	10.2	9.2	9.4	4.2
3	9.6	8.0	9.5	4.3
4	9.8	7.8	9.6	4.6
5	10	8.4	8.6	4.0
6	9.6	8.2	9.1	4.4
av	**9.8**	**8.2**	**9.3**	**4.2**
CV	**2.41**	**6.89**	**4.19**	**6.82**

CV is coefficient of variation

Experimental testing of the strength of spot-welded connections showed that the critical axial force at the manually welded spot-welds is reduced to 4.2 kN. Critical shear force remains almost constant.

The spacing of mechanical connections between components, to develop a composite section, is typically based on several strength considerations. The spacing between the spot welded joints according to AISI recommendations should be chosen to prevent Euler buckling of the more slender component at the desired stress level.

Slenderness of the full section is calculated considering that the effective length factor of axially compressed column is equal to 0.5 [12].

$$\lambda = \frac{L_{ef}}{r} = 0.5L\sqrt{\frac{A}{I}} \quad (4)$$

where r is radius of gyration; L_{ef} is effective length of the column, I is principal moments of inertia, A is area of cross section.

Slenderness characteristics of separate elements are shown in Table 3.

Table 3

Slenderness characteristics of separate elements

Nr	Area A, mm^2	Principal moments of inertia		Radius of gyration		Slenderness of elements	
		I_x, mm^4	I_y, mm^4	r_x, mm	r_y, mm	λ_x	λ_y
1	144	62382	114209	20.81	28.16	4.80	3.55
2	74	2011	41093	5.21	23.56	19.18	4.24
Sum	218	100403	155302	21.46	26.69	4.66	3.75

AISI requires a connection spacing that limits the slenderness ratio of the channel between connectors to the critical slenderness ratio of the composite section. For connected component the effective length factor is considered at 0.6 [12].

The spacing between spot-welded connections is calculated:

$$s \le \lambda_{sum} \frac{r_{min}}{0.6} \le 41 \text{ mm} \quad (5)$$

where λ_{sum} is slenderness of full column, $r_{min} = 5.21\,\text{mm}$ is minimum radius of gyration of separate component.

Dynamic experiments lead to the observation that axial shortening was significantly larger in those specimens that had some ruptured spot-welds although load (mass and initial speed) was the same in all the cases. The specimen with two ruptures of spot-welding was deformed by 11 cm, whereas the specimen with no spot-welding ruptures was deformed only by 9.5 cm (Fig. 8).

a b

Fig. 8 Specimens after the dynamical crushing: a – with good spot-welding; b – with collapsed spot-welding in two places

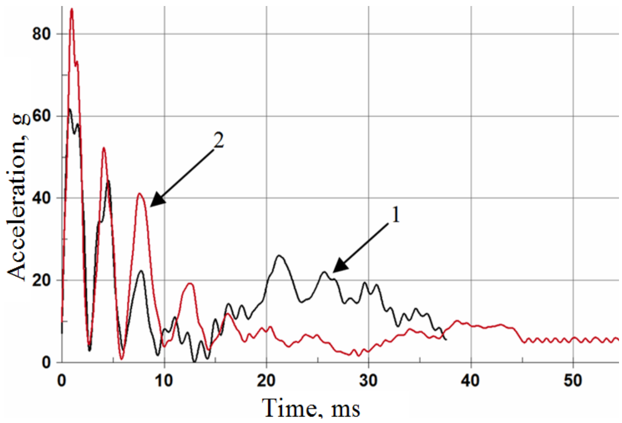


Fig. 9 Deceleration of the mass curve: *1* – with good spot-welding; *2* – with collapsed spot-welding

Experimental results of axially crushed thin-walled elements with factory and manually spot-welded connections are shown in Fig. 9 and 10.

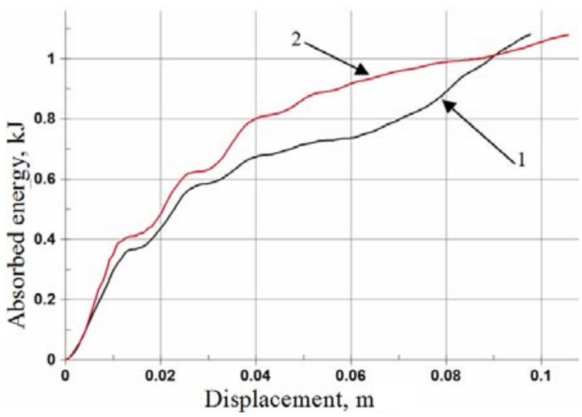


Fig. 10 Absorbed energy: *1* – with good spot-welding; *2* – with collapsed spot-welding

Based on the findings of above-described experimental tests and results of calculations, we have examined, using FE model, the influence of partial or total failure of a spot-welding on the deformation of the specimen and amount of the energy absorbed. Fig. 11 presents the layout and numbering of spot-welding.

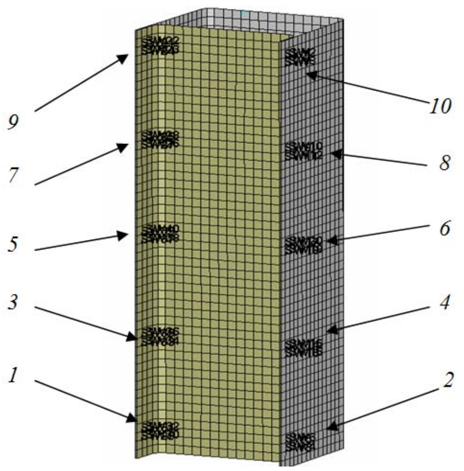


Fig. 11 Location and numeration of the spot-welding

Now, let's investigate the influence of impaired spot-welds on the deformation of the specimen. Variations of manual and original spot-welding by FEA simulation are shown in Table 4.

Fig. 12 shows the influence of spot welded connections on the deformed shapes, their strength characteristics and distance between the spot welding.

It is obvious that greater distance between spot-welded connections may have significant influence on the axially crushing behavior and therefore can significantly decrease the amount of energy absorbed. Using characteristics of axial strength of the manually spot welded connections the deformed form looks similarly except for the fact that the absorbed energy decreased slightly.

The typical force deflections curves of axially crushed thin-walled columns obtained from FE simulations are presented in Fig. 13.

Table 4

Variations of manual and original spot-welding by FEA simulation

Nr.	Spot-welding		Axial shortening		Absorbed energy*		F_m*
	Original	Manual	m	%	kJ	%	kN
1	1-10	-	0.092	100	1.16	100	12.6
2	1,2,5-10	3,4	0.116	126	0.99	85	10.8
3	1,3,5-10	2,4	0.105	114	1.02	88	11.1
4	1-4,7-10	5,6	0.103	112	1.07	92	11.6
5	1-4, 9, 10	5-8	0.103	112	1.07	92	11.6
6	1,2,7-10	3-6	0.118	128	0.99	85	10.8
7	1-6	7-10	0.119	129	0.99	85	10.8
8	1,2	3-10	0.119	129	0.99	85	10.8
9	-	1-10	0.122	133	0.97	84	10.5
10	1,2,4-10	3**	0.106	115	0.97	84	10.5
11	1,2,5-10	3,4**	0.129	140	0.87	75	9.5
12	1-4,7-10	5,6**	0.147	160	0.83	72	9.0
13	1,2,4,6-10	3,5**	0.147	160	0.83	72	9.0
14	1,2,7-10	3-6**	0.158	172	0.76	66	8.3
15	1-4,9-10	5-8**	0.149	162	0.82	71	8.9
16	1-6,9,10	7-8**	0.124	135	1.00	86	10.9

* - with 0.092 m axial shortening.

** - not connected spot-weld locations ($F_{axial} = 0$ N).

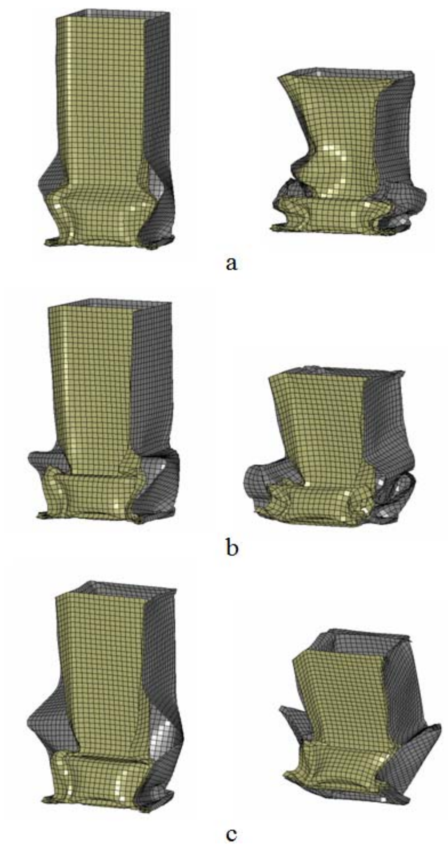


Fig. 12 The deformed shapes of thin-walled columns crushed 40 and 80mm: a) connections welded by manufactory; b) at *5*, *6* positions connections welded manually; c) no connections at *5*, *6* positions

Connections welded by manufactory or manually in the FE model have been evaluated changing the data of normal and shear failure forces. Taking in to consideration

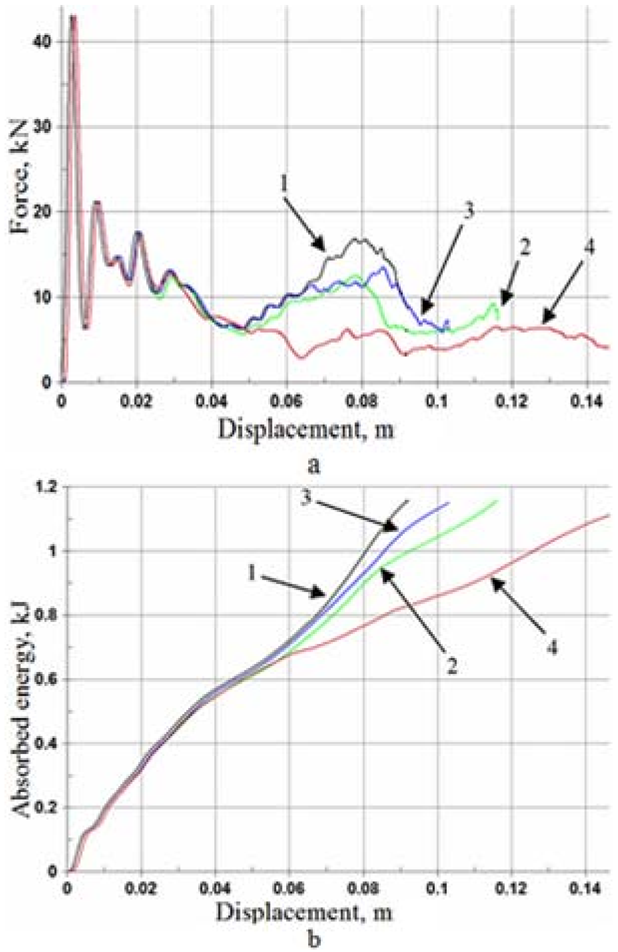


Fig. 13 Results of FE simulations of axially crushed thin-walled columns a) Force deflection curve, b) absorbed energy; *1* - all connections welded by manufactory; *2* - at *3*, *4* positions connections welded manually; *3* - at *5*, *6* positions connections welded manually; *4* - no connections at *5*, *6* positions

that in some cases of repairing process we could obtain faulty welded connections in FE model it is simulated by removing spot welds. Comparing the curves of axially crushed columns connected by factory welding, manual welding at 5, 6 positions and nonwelded 5, 6 positions we can see, that at the beginning the force-deflections curves are similar in all the cases. Later, at the moment of second wave formation the differences are visible. The columns with nonwelded 5, 6 positions do not have second wave therefore the energy absorption is significantly smaller than in other cases. The columns with characteristics of manually welded connections initiate the formation of second wave but need smaller axial force for it therefore the energy absorption is slightly smaller.

4. Conclusions

1. Comparing the experimental results of statically and dynamically axial crushed thin-walled columns we see that the dynamically deformed thin-walled columns absorb from 10 to 50% more energy than those statically deformed.

2. The results of FE simulations show good match with the results of dynamical (drop weight) experiments, therefore the influence of spot-welded connections characteristics on the behavior of axially crushed thin-walled columns were analyzed using FE simulations.

3. By FE simulations it was determined that:

- depending on the specific position, characteristics of spot-welding can have more or less influence on the amount of energy absorbed at one unit of length;
- in case of the axial shortening of 0.092 m, failure of the spot-welds in those positions where a wave forms at the initial moment causes the energy absorbed by the specimen to reduce by 15%;
- comparing the behavior of axially crushed columns connected by factory welding between the columns with nonwelded connections in the middle of them we can see, that at the beginning the force-deflections curves are similar but at the moment of second wave formation the differences are visible. The columns with nonwelded middle do not have second wave therefore the energy absorption is significantly smaller than in other cases.

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SUVIRINIMO KOKYBĖS ĮTAKOS AUTOMOBILIO DEFORMACINIŲ ZONŲ ELEMENTŲ FUNKCIONALUMUI TYRIMAS

R e z i u m ė

Atlikto tyrimo tikslas buvo nustatyti pakitusių taškinio suvirinimo jungčių charakteristikų įtaką ašinio smūgio metu tipinių automobilio deformacinių zonų elementų absorbuotos energijos kiekiui, deformavimo pobūdžiui ir deformacijų dydžiui. BE modeliui, kuriuo naudojantis buvo modeliuojama taškinio suvirinimo įtaka bandinio deformavimui, patikrinti atlikti kvazistatiniai ir dinaminiai eksperimentai. Statiniais ir dinaminiais ekeperimentais nustatyta, kad bandinys apkrautas dinaminėmis apkrovomis, absorbuoja nuo 10 % iki 50 % daugiau energijos. Patvirtinta gera BE modeliavimo metu gautų rezultatų koreliacija su dinaminių bandymų rezultatais. Modeliavimas parodė, kad susilpnėjęs taškinis suvirinimas turi nemažos įtakos bandinio elgsenai deformavimo metu ir sumažina absorbuotos energijos kiekį.

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EFFECTS OF SPOT WELDING ON THE FUNCTIONALITY OF THIN-WALL ELEMENTS OF CAR‘S DEFORMATION ZONE

S u m m a r y

The effect of changed characteristics of the spot-welded connections on the absorbed energy, deformation form and axial shortening of typical thin-walled elements of car’s deformation zones was estimated. The experimental quasi-static and impact tests of the axial crushing of columns were performed to validate FE models which were used for the simulations to evaluate the influence of spot-welding on the mechanical behavior. The experimental results of statically and dynamically axial crushed thin-walled columns showed that the dynamically deformed thin-walled columns absorb from 10 to 50% more energy than those statically deformed. The good correlation between the results of dynamical experiments and FE simulations was obtained. The FE simulations show that reducing strength of spot-welded connections changes the behavior and decreases the amount of absorbed energy.

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ КАЧЕСТВА СВАРКИ ЭЛЕМЕНТОВ ДЕФОРМАЦИОННЫХ ЗОН АВТОМОБИЛЯ НА ИХ ФУНКЦИОНАЛЬНОСТЬ

Р е з ю м е

Целью настоящей работы являлось исследование влияния качества контактной сварки типичных элементов деформационных зон автомобилей на величину поглощенной энергии, форму потери устойчивости и величину деформации при осевом ударе. Модель КЭ, использованная при моделировании влияния качества сварки на деформацию образца, экспериментально проверена квазистатически и динамически. Результаты статических и динамических тестов показали, что при динамической нагрузке образец поглощает от 10 % до 50 % больше энергии. Моделирование методом КЭ подтвердило существенное влияние качества сварки на поведение образца при нагрузке и уменьшение поглощённой энергии при осевом деформировании.

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