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STUDY OF TOWBARS USED IN THE AUTOMOTIVE INDUSTRY USING THE PHOTOELASTOCIMETRY METHOD

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Abstract: *The transport of people and goods involves the use of semi-trailers with one or two axles, trailers of a means of transport, most often a car. The towbars must ensure the fulfillment of severe quality criteria, indicated in the regulations. For this reason, the study of towing systems is an important objective of car manufacturers. In the paper, it is proposed to determine the stresses that appear in the towbars using the experimental method of photoelastocimetry. Based on the results obtained, by comparison with the results obtained by calculation, recommendations regarding the manufacture of towing systems are formulated.*

Key words: towbar ,towball, photoelastocimetry, automotive industry, bending

1. INTRODUCTION

The needs of modern industry and the development of new technologies led to the need to transport objects and people with the same vehicle, a necessity that led to the appearance of the trailer. The trailer does not have the ability to propel itself, it has to be towed by another vehicle. Existing trailers and semi-trailers for motor vehicles are generally extremely varied and perform many tasks (not limited to transporting goods and people). They can be: trailer, platform with tarpaulin, without tarpaulin, electric current generator, tanker, tipper, concrete mixer, refrigerated transport, shop, nacelle, animal transport, etc. (see [1]).

Semi-trailers have no front axle, and during their use they rest on the rear of the tractor vehicle. They are mainly used to transport goods with cars. More complicated systems, such as two-axle trailers, are found in cases where the weight is high, requires balance when stationary and/or this is required for various reasons. Due to the regime during the operation of the car-trailer assembly, the coupling between these two vehicles must be very resistant, both to dynamic and static stresses, but also to the influence of chemical and meteorological factors.

The most common towbars used in cars are L-shaped (Fig. 1). The design of the towing system starts with establishing the maximum load that the vehicle can tow, but its dimensioning must also take into account the rear bumper, which it must bypass, thus the length L is considered to be the distance between the center of the sphere and the middle of the distance between the two holes, and the height H is the distance between the center of the sphere and the axis passing between the two holes (Fig. 1). The diameter of the towball sphere is 50 mm, according to the standard**.** In addition to the mentioned dimensions, it should be specified that these towbars are found with the bending radius R between 25 and 120 mm (Fig. 2), the bending angle α with values between 67° and 150° (Fig. 3), but also with two bends, both on the inside, or one on the inside and the other on the outside (Fig. 4) [2=35].

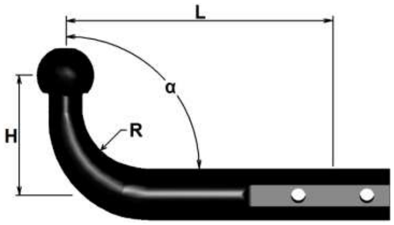

Fig. 1. L-shaped towbar [2=35]

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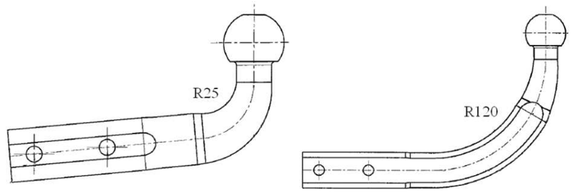

Fig. 2. L-shaped towing hooks with different bending radii

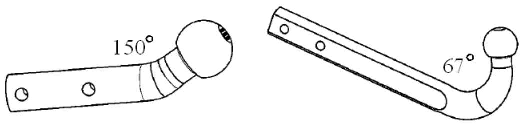

Fig. 3. L-shaped towbars with different bending angles

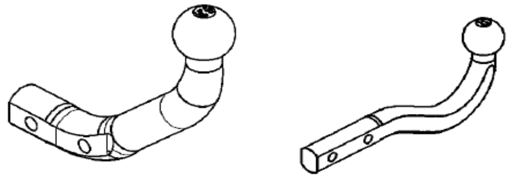

Fig. 4. L-shaped towbars with two bends

The manufacturing technology of simple L-shaped towbars is quite simple, starting from a semi-finished circular bar, cut to the appropriate length, depending on the final dimensions of the product. The next operations are either induction heating and forging to make the ball, followed by turning, or direct turning from a 50 mm diameter, thus making the spherical shape, neck and clearance angle. Towbar bending is done either cold, if the diameter of the material is not generous and the bending radius roll is not small in diameter, or hot, if the diameter of the materials is high and requires a low bending radius. Flattening, marking and drilling are the last operations in the technological itinerary of this type of towbars. Methods to perform a calculus of such devices are presented in [3-5]. The analysis of cthe towball is made by researcher in [6-9]. These researches are determined by the use of alternate materials in the manufacturing of towing system. In the last decades is introduced aluminum [10-11] and composite materials [12-18] instead of steel [19]. In the paper, it is proposed to determine the stresses that appear in the towbars using the experimental method of photoelastocimetry. Based on the results obtained, by comparison with the results obtained by calculation, recommendations regarding the manufacture of towing systems are formulated.

2. MODELS AND METHODS

2.1 Experimental methods of stresses determination

For the activities of experimental determination of stress and strain states, the classic method used is tensometry [20-23], which aims to measure small strains on the surface of a stressed body. In order to arrive at experimental stress values, the deformations given by the stresses will be measured, and in the second phase analogies will be made between deformations and stresses based on known theoretical relationships (using Hook's Law). There are several variants used to measure stresses:

- Electrical tensometry when the technique of measuring non-electrical quantities (generally mechanical) is done electrically. The specific deformations will be determined, and values for stress will be deduced by calculation;
- Photoelastocimetry is an optical method based on the birefringence property of materials. It has the advantage of providing information on the stresses in the entire analyzed system, having favorable results even when there are structures with complex geometry;
- Brittle lacquers - represents a method based on covering the researched model with a thin layer of brittle lacquer and loading it in order to determine the stress state. The resistance to breaking or cracking of the varnish must be lower than the elasticity limit of the studied body, and the thickness of the varnish of a maximum of 0.15 mm;
- VIC (Video Image Correlation) is a relatively recent optical method that is starting to gain ground due to the precise results it can provide.

The paper proposes the use of photoelastocimetry determine the stresses in the towbar.

2.2. Photoelastocimetry

As previously mentioned, photoelastocity is a method of experimentally determining the stresses in a body, based on the birefringence properties of the material subjected to a load. This determination technique can be achieved by two methods: the transparency method and the reflection method [24-27].

The transparency method can be applied to planar and spatial models, the models having to be built from a photoelastic material (optically active, transparent) made to a certain scale, and with the help of an equipment intended for photoelastic research called a polariscope – (Fig.5), the stresses can be determined from the system. This method is the object of study for the present paper.

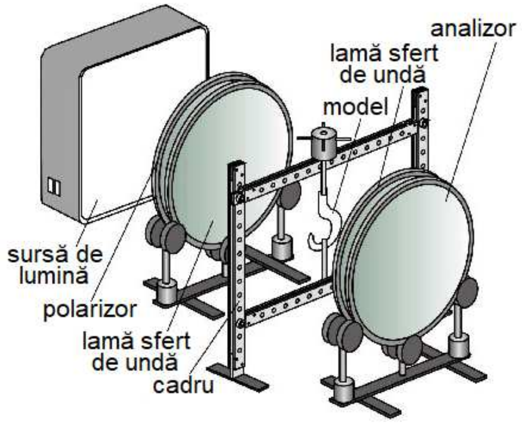

Fig. 5. Polariscop [27]

The reflection method involves determining the stress states using a special polariscope (with reflection), directly on the researched structure, covering the surface of the model with a photoelastic film, loading the system with real stresses. This method allows for both static and dynamic loads.

In order to obtain qualitative results from the study systems, the materials used to make the photoelastic models must meet some minimum conditions, such as: the absence of cracks and gas bubbles, high homogeneity, the highest possible transparency, high modulus of elasticity and rigidity, behavior linear in the elastic range between stresses and strains and between stresses and isochromats, no initial stresses and birefringences, advantageous machinability and no change in properties after machining. Of course, the economic part is also a very important requirement, therefore a quality factor is represented by the purchase price of the material.

Isochromats represent the geometric locations of points where the difference of the principal normal stresses is constant.

$$\sigma_1 - \sigma_2 = constant \qquad (1)$$

Based on the relationship between principal tangential stresses and principal normal stresses, isochromatics can also be defined as the geometric locations of maximum tangential stresses of constant value.

For the plane stress state:

$$\tau_{1,2} = \frac{\sigma_1 - \sigma_2}{2} \qquad (2)$$

wherefrom:

$$\sigma_1 - \sigma_2 = 2 \cdot \tau_{max} \qquad (3)$$

Isochromatic curves whose difference $\sigma_1 - \sigma_2$ is a multiple of a constant value $\sigma_0$will be considered:

$$\sigma_1 - \sigma_2 = k \cdot \sigma_0, \text{ k = 0, 1, 2, 3, 4...} \qquad (4)$$

The order of the isochromat is represented by the number k, and in Fig.6 the isochromat curves are demonstratively represented.

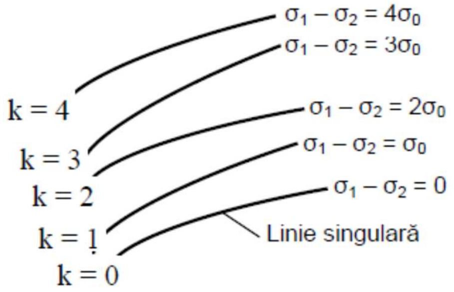

Fig. 6. Isochromat curves

The number k is positive because $\sigma_1 > \sigma_2$ and the difference $\sigma_1 - \sigma_2$ is positive.

When k = 0 and $\sigma_1 - \sigma_2 = 0$ the singular or isochromatic line of order 0 results.

For the plane state of stress, the shape of the isochromat looks like this:

$$\sigma_1 - \sigma_2 = \sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4 \cdot \tau_{xy}^2} = k \cdot \sigma_0 \qquad (5)$$

3.RESULTS

3.1. Stress determination

Due to the complex geometrical shape of the towbar, the calculation to determine the stresses is quite difficult, requiring some tricks to help simplify the calculation method. The manufacturing of the photoelastic model is made of plexiglass, the most advantageous material for the necessary experimental research, both from a technical and economic point of view. Therefore, the contour of the towbar is made from a plexiglass sheet with a thickness of 8 mm, and additionally a disk for photoelastic calibration is made from the same material and with the same thickness of 8 mm, and the diameter of ø63 mm. Being a generously sized model avoided the use of a thinner material plate as there was a risk of inappropriate buckling-like deformation which could have led to erroneous results.

The calculation of the stresses with the help of photoelasticity will be done by two methods, after which the results will be compared.

In the first method, the calibration of the photoelastic material will be carried out using the disk to determine the stress corresponding to an isochromat, after which, with the resulting data, by analogy the stresses in the towbar will be determined.

The second method of determining the stresses is done by considering it to be pure bending in the towbar.

3.2. Calculation of compressive stress in the disc. Material calibration

The dimensions of the disc are known:

D = 63 mm, g = 8 mm.

The disc is subjected to compression on the polariscope fixture as shown in Fig. 7, and with the help of a dynamometer measuring the force *F*, its value is recorded at each appearance of a new isochromat (Table 1).

Table 1.

Centralization of specific values of force according to isochromats appearing on the disc

k	F [N]	σ_0 [MPa]
0	**0**	**0,863**
1	**77,2**	
2	**258,6**	
3	**458,0**	
4	**651,8**	
5	**853,6**	

Fig. 7. The disc seen in the polariscope

Using the experimental values obtained it results σ_0 [1]:

$$\sigma_0 = \frac{8 \cdot F}{k \cdot \pi \cdot D \cdot g} = \frac{8 \cdot 853{,}6}{5 \cdot \pi \cdot 63 \cdot 8} = 0{,}863\ [MPa]$$

With the data collected in Table 1, the calibration curve for the compression load of the disk in Fig.8 is drawn. It is observed that starting from the first isochromat appearing on the disc, the curve of the material is linear, so the material fulfills the condition of linearity between stress and strain.

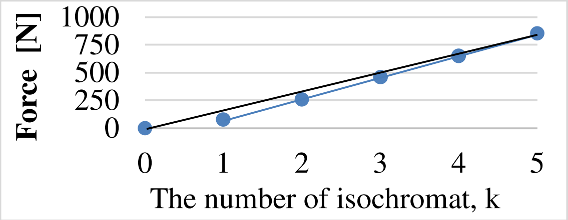

Fig. 8 Calibration curve for disc compression stress

3.3. Calculation of the bending stress of the towbar

The towbar is subjected to a force such that sufficient isochromats appear on the polariscope to perform the stress calculation (Fig.9).

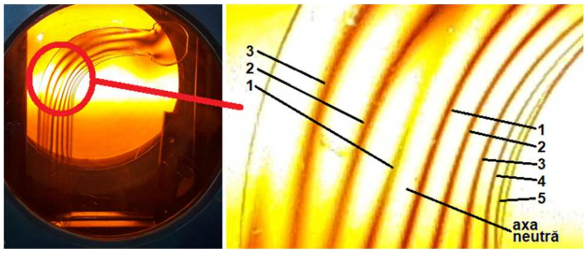

Fig.9. The towbar seen with the polariscope

The force at which the satisfactory number of isochromats appeared is $F = 66.6\ N$, and before determining the stresses, their arrangement is analyzed, thus validating several assumptions made in the analytical calculation chapter, namely:

- approaching the analytical calculation of the towbar with Winkler's method and not with Navier's theorem;
- the neutral axis of the curved area on the towbar does not coincide with the median formed between the inner and outer radius, this being shifted towards the inside of the curvature radius;
- the stresses inside the radius of curvature are more pronounced than the stresses outside the radius of curvature, because the number of isochromats inside is greater than the number of isochromats outside.

Three isochromats appeared on the outside of the radius of curvature, and five isochromats can be visualized on the inside. This confirms that the internal and external stresses are different and the system does not behave like a simple bending stress.

A very interesting phenomenon can also be observed in Fig.9. Following the isochromats from the tail of the towards its towball, in the cylindrical area there are four isochromats on each side of the neutral axis, the neutral axis being located in the center of the cylinder. The interesting aspects appear when the curvature zone begins, the following being noted:

- the neutral axis deviates inwards,
- increases the number of isochromats inside the radius of curvature from 4 to 5, it follows that the stress increases with the approach to the center of the radius of curvature,
- the number of isochromats outside the radius of curvature decreases from 4 to 3, it follows that the stress decreases with the distance from the center of the radius of curvature.

As established, the determination of the towbar stresses will be done in two ways, both using the photoelastocimetry technique.

3.4.Determining the stress in the towbar by analogy with the standard disk

After loading the photoelastic model and identifying the number of isochromats appearing on it, Table 2 is designed, making the correlations between the isochromats appearing on the standard disk and the towing system. According to the disk calibration calculation, the value of an isochromat is σ_0=0.863 MPa.

Table 2 presents results of interest extracted from the analysis based on photoelasticity, the relationship of the stresses in the disc to the towbar, the analogy to the value of the real force in the towbar, and the stress results from the FEM analysis [28,29].

Table 2.

Determination of the stresses in the towbar by analogy with the standard disk

	F [N]	σ_0 [MPa]	k_{int}	σ_{int} [MPa]	k_{ext}	σ_{ext} [MPa]
1. Calculation of the stresses appearing in the towbar according to the disc calibration	F_{model} = 66,6	0,86	1	0,86	1	0,86
			2	1,73	2	1,73
			3	2,59	3	**2,59**
			4	3,45	-	
			5	**4,31**		
2. Calculation of the stresses appearing in the towbar according to the real force, by analogy with the values from point 1	F_{real} = 7.500	97,14	1	97,14	1	97,14
			2	194,27	2	194,27
			3	291,41	3	**291,41**
			4	388,54	**-**	
			5	**485,68**		

The stress values in the towbar obtained by analogy with the standard are:

$$\sigma_{int} = \frac{F_{real} \cdot \sigma_0 \cdot k_{int}}{F_{model}} = \frac{7.500 \cdot 0,86 \cdot 5}{66,6} = 485,68\, MPa$$

$$\sigma_{ext} = \frac{F_{real} \cdot \sigma_0 \cdot k_{ext}}{F_{model}} = \frac{7.500 \cdot 0,86 \cdot 3}{66,6} = 291,41\, MPa$$

3.5.Determination of stresses in the towbar considering bending

After loading the photoelastic model and identifying the number of isochromats appearing on it, Table 5.3 is designed, determining the stress σ_0 based on the previous relationship [1]:

$$\sigma_0 = \frac{\sigma_1}{k} = \frac{\frac{6 \cdot M_i}{g \cdot h^2}}{k} = \frac{6 \cdot F \cdot B_F}{k \cdot g \cdot h^2} = \frac{6 \cdot 66,6 \cdot 120}{5 \cdot 8 \cdot 40^2} = 0,75\, MPa$$

where $B_F = 120$ mm and $h = 40$ mm (h coincides with the diameter of the towbar).

Table 3.

Determination of stresses in the towbar considering bending in the towbar

	F [N]	σ_0 [MPa]	k_{int}	σ_{int} [MPa]	k_{ext}	σ_{ext} [MPa]
1. Calculation of the stresses appearing in the towbar considering the fotoelastic model	F_{model} = 66,6	0,75	5	**3,75**	3	**2,25**
2. Calculation of the stresses appearing in the towbar according to the real force, by analogy with the values from point 1	F_{real} = 7.500	84,38	5	**421,88**	3	**253,13**

The values of the stresses in the towbar resulting from the bending calculation are:

$$\sigma_{int} = \frac{F_{real} \cdot \sigma_0 \cdot k_{int}}{F_{model}} = \frac{7.500 \cdot 0,75 \cdot 5}{66,6} = 421,88\, MPa\ ;$$

$$\sigma_{ext} = \frac{F_{real} \cdot \sigma_0 \cdot k_{ext}}{F_{model}} = \frac{7.500 \cdot 0,75 \cdot 3}{66,6} = 253,13\, MPa\ .$$

This calculation method is purely theoretical and strictly based on Navier's theorem as it appears in research on bending applications of photoelasticity. In reality, it was demonstrated that the shape of this towbar requires solving by Winkler's theorem[1], in this case accepting a hypothetical deviation for the comparison of some results. As is known, the plexiglass model section is rectangular and the actual towbar section is circular, therefore the resulting stresses cannot be simply compared.

From the analysis of the analytical (classical calculation) and numerical (FEM) determination of the stresses in the towbar, an almost perfect similarity is found, considering the mutually validated methods [1].

Therefore, as previously mentioned the fact that the sections of the photoelastic model and the real one are not similar, in order to support the comparison of the results, a hook with a section similar to that of Plexiglas is virtually designed and with the help of FEM the stresses in the areas of interest of the model, after which the results obtained by the two methods based on photoelasticity will be compared with the one based on finite element. The results will be related to those obtained with FEM, as it is considered to be a validated method for the determination of stresses.

Attached in Figure 10 is the FEM analysis of the towbar and the stresses of interest are suggested.

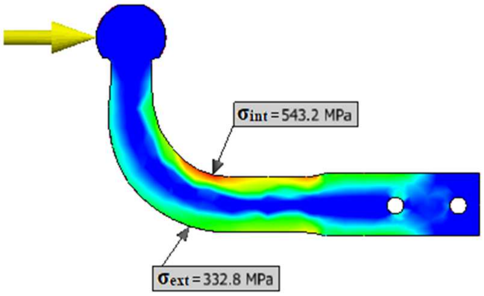

Fig. 10. Towbar with rectangular section for comparison with the towbar subjected to the polariscope

The data obtained regarding the internal/external stress in the towbar bending area are centralized in Table 4.

Table 4.

Centralization of towbar stresses obtained by three calculation methods

Method		σ_{int}	σ_{ext}
1.	FEM	**543,2**	**332,8**
2.	Fotoelastocimetry – standard disc	**485,68**	**291,41**
3.	Fotoelastocimetry – bending	**421,88**	**253,13**

Comparatively analyzing the results obtained by the three methods in Table 4, the graph in Fig. 11 is designed, where the values of the maximum internal and external stresses are centralized.

Looking at Fig. 11, the first conclusion is that the internal (σ_{int}) and external (σ_{ext}) stresses resulting from FEM analysis are higher than those obtained by photoelasticity methods due to the lower values by ≈ 23% than those obtained by FEM, but as presented in the sub-chapter dedicated to this analysis, it is a calculation based on the relationship of Navier, and Winkler's theorem is required for this application, which is why the values differ substantially.

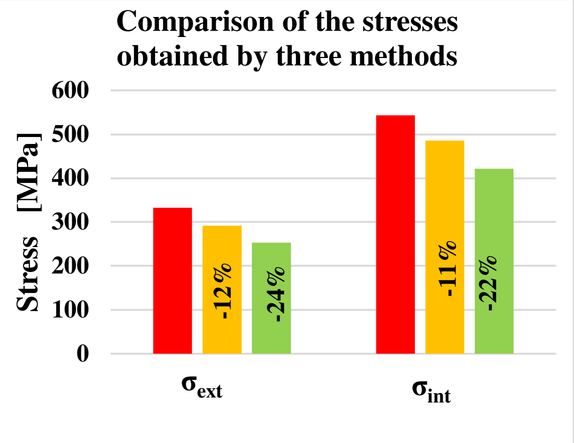

Fig.11. Results obtained using three different methods; red-FEM; orage-standard disc; green-bending

4. DISCUSSION

The positive aspects of this comparison are both the fact that the difference between the FEM and calibration values is ≈ 11% for internal stresses and ≈ 12% for external stresses, meaning a reasonable difference for a non-simple model geometry, and the concordance of the proportionality between the stresses.

The method of determining the stresses through the bending calculation of the photoelastic model seems detached from reality,

Also, another gratifying aspect is the very high similarity of the ratios between σ_{int} and σ_{ext} obtained by the finite element method (≈ 61%) and by photoelasticity methods (≈ 60%).

In general, to obtain the best stress results with the method based on the photoelasticity of materials, it is necessary to have as many isochromats as possible on the model. In this case, the increase of the action force on the model was avoided for reasons of safety to its integrity, in order not to risk cracking and compromising the experimental determinations.

However, with the number of isochromats that appeared during the research of the photoelastic model, the results are more than satisfactory regarding the validation of the entire experiment.

The most important aspect of photoelasticity analysis is to confirm the area of maximum stress in the towbar.

In Table 5, the purely hypothetical values of the stresses appearing in the towbar are centralized, with the idea that it could have been constructed of photoelastic material, but with the geometry identical to that of the real towbar, with a circular section.

Table 5

Stresses obtained under the assumption of a towbar made of photoelastic material, but with the geometry of the real towbar.

Calculus area	Stress [MPa]
Inside radius of curvature , σ_{int}	**164,6**
Outside radius of curvature, σ_{ext}	**104,4**

These values are determined by analogy with the values obtained using FEM, subtracting the percentages obtained in Fig.11 of 11% for the internal stress and 12% for the external stress.

5. CONCLUSIONS

Since in engineering the analytical methods for determining stresses require experimental research, the first practical method is represented by the technique based on photoelasticity regarding the study of stresses in the system.

Photoelasticity is a method of experimentally determining the stresses in a model, based on the birefringence properties of the material subjected to a load. The model is made of a photoelastic material and must respect the shape of the studied system, but not its dimensions, as it can be made on an advantageous scale.

This experiment is carried out with the help of a polariscope. The model is clamped on the frame of the polariscope, after which it is subjected to a load. Observing the charged pattern through the polariscope polarizer, lines on the pattern (isochromats) will be identified, and the number of isochromats will be quantified, each line being assigned a stress value, ultimately resulting in the stress of each area of interest.

In order to determine the specific stress of an isochromatic line, it is necessary to calibrate the material from which the model and standard are made.

The determination of the stresses appearing in the studied photoelastic model is carried out by two calculation methods given by the photoelasticity technique. On the one hand, it is done using a disk for calibrating the photoelastic material, after which the strength calculations of the towbar are carried out by analogy with the standard disk, and on the other hand, pure bending in the towing system is considered.

The results obtained by the two photoelasticity calculation methods are analyzed by comparison with the results obtained by a validated calculation method.

Going through the analytical and numerical methods for determining the stresses resulted in similar values of the stresses in the towbar, and to simplify the process of analyzing the results obtained by the photoelasticity technique, the data are compared with those obtained by FEM.

In reality the section of the towbar is circular and the photoelastic model has a rectangular section. In order to analyze the results obtained by photoelasticity, a model identical to the one made of photoelastic material will be created virtually, it will be subjected to virtual loading so that the results of the two methods can be compared.

The most important aspect of this chapter is given by the experimental confirmation and validation of the critical zone resulting from towbar loading.

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Studiul carligelor de remorcare utilizate in industria autovehiculelor utilizand metoda fotoelastocimetriei

Rezumat. *Transportul de persoane si marfa implica utilizarea semiremorcilor cu una sau doua osii, tractate de un mijloc de transport, cel mai ades un automobil. Carligele de remorcare trebuie sa asigure indeplinirea unor criterii severe de calitate, indicate in normative. Din acest motiv studiul carligelor de remorcare este un obiectiv important al fabricantilor de automobile. In cadrul lucrarii se propune determinarea tensiunilor care apar in carligele de remorcare utilizand metoda experimentala a fotoelastocimetriei. Pe baza rezultatelor obtinute, prin comparatie cu rezulate obtinute prin calcul, se formuleaza recomandari privitoare la fabricarea carligelor de remorcare.*

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