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INFLUENCE OF STRESS CONCENTRATORS UPON THE DEFORMABILITY OF A STRAIGHT BAR

BY

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Abstract. The paper discusses the influence of various concentrators upon the stresses and deformability of straight bars subjected to tensile strain. For four different types of concentrators, both analytical calculations and finite elements analyses were performed, for determining the deformation capacity of the bars containing them. The area of materials release was the same for all four concentrators, respectively 100 mm^2. Under such conditions, the differences result only from the shape of the concentrators employed. For a bar with a circular concentrator, experimental determinations, finite elements analyses and analytical calculations were performed under the same stress conditions, similar results being obtained.

Key words: analytical calculations, deformability, finite elements, stress concentrators.

1. Introduction

Study on the physical aspects of axial tension evidences that normal stresses σ_x, are uniformly distributed on the cross section of the bar. This situation is valid only for bars with constant section along the axis but, even in such a case, the uniform distributions of stresses is explained exclusively by

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cross sections occurring at sufficient distance from the application point of the external load, which also includes the supports (Lurie, 1999). The stress values in the area of load application, deduced either experimentally or by the methods of the elasticity theory are much higher than the so-called uniformly distributed nominal stress.

If the section has sudden variations, voids, notches, joining, all these influence unfavorably the local distribution of stresses which, in some points, may attain much higher values than those resulting from an uniform distribution on the section. The value of the coefficient of stress concentration, K_t, depends on the configuration and size of stress concentrations, as well as on the material from which the piece is made. The values of coefficient K_t are provided in engineering handbooks (Rozhanskaya & Levinova, 1996). According to the theory of elasticity, $b > 10\ d$, $\sigma_{\max} = K_t \cdot \sigma_n = 3\sigma_n$, which means a concentration coefficient in front of the void $K_t = 3$ (Fig. 1*a*). The limit of the elastic domain, $N_{\lim}$, is attained when the flow limit σ_c is reached in the most stressed fiber, (Fig. 1*b*). From this value on, the longitudinal fibers tangent to the void will be longer, without an additional load under a constant value σ_c, which means that they get plasticized.

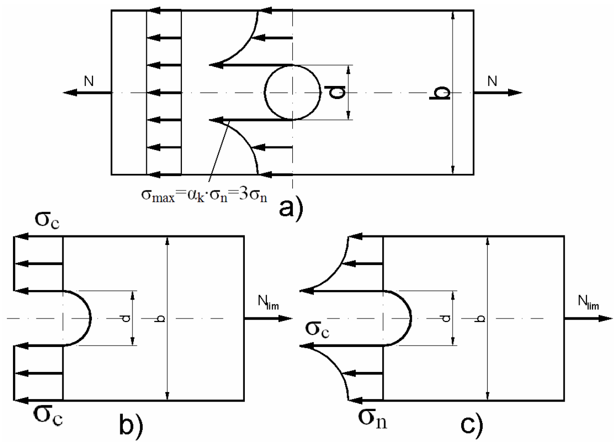


Fig. 1 − Bar with stress concentrators.

In an intermediary situation (Fig. 1*c*), two zones may be distinguished, namely: a central, plasticized zone, over which σ_c is uniformly distributed, and the peripherical, elastic zones with a non-uniform distribution of stresses. If the force continues to increase, at the limit value all fibers reach the flow limit, (Fig. 1*b*), uniformly distributed on the section of the bar. The axial effort corresponding to this case is: $N_{\lim}= \sigma_c \cdot A_{net}$. Consequently, the flowing level from the Prandtl curve caused a plastic redistribution on the net section of the bar, so that, at the limit state of stress, strain is uniformly distributed.

2. Analytical Calculation of Displacements in Bars Subjected to Tensile Stress

In the case of straight bars, leaned in different points and axially subjected to forces or moments, the final positions of the cross sections may be determined by considering a section from one of the respective supports as a guide mark. As known, for the respective support, displacement in such point is null. The same holds true for the programs of finite elements analysis, where the conditions of displacement over the contour represent limit conditions, on the basis of which the equation system may be checked. Usually, for leaned bars axially-stressed with either forces or moments, one of the ends is considered as fixed, a conventional diagram of the displacement being plotted for establishing the relative displacements among the various sections of the bar. In this way there may be calculated, without errors, the strain and stresses occurring in different points of the bar, as a result of the external stresses.

Calculation of the displacements of the cross sections of straight bars should consider certain hypotheses, such as (Sheppard & Tongue, 2005):

– the material from which these bars are made is viewed as homogeneous, with isotropic behavior under stress;

– the externally applied stress causes deformations only in the elastic domain;

– the hypothesis of Bernoulli, according to which a section plane, perpendicular to the axis of the bar prior to stress application will remain plane and perpendicular to the axis of the bar after stress application, as well, is considered as valid.

Let us consider a straight bar, with a constant section, with a fixed end, loaded at the other end with a force or moment guided according to the geometric axis of the bar, Fig. 2.

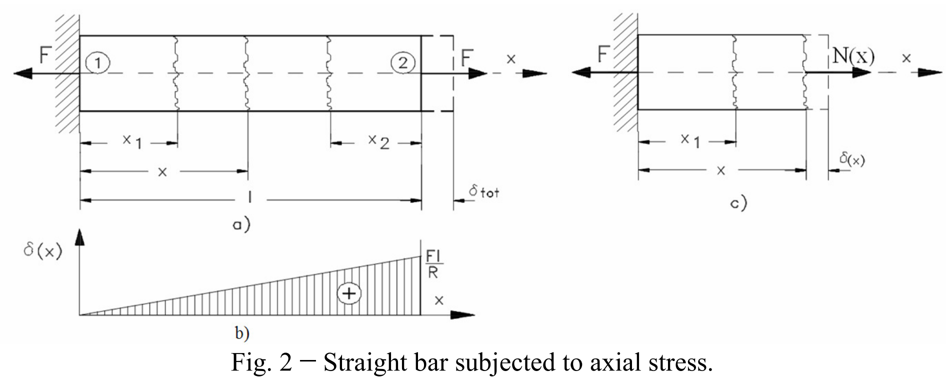


Fig. 2 – Straight bar subjected to axial stress.

Under the action of the external load N, the bar gets deformed and, consequently, the various cross sections are shifted, comparatively with the initial position; in this way, if the axial load is a force, the cross sections of the bar will be shifted, and the bar will be elongated, on the whole, with amount δ_{tot} - Fig. 2*a*.

The bar illustrated in Fig. 2*a* is formed of only one region, according to the same variation law of sectional efforts *N*(*x*) - Fig. 2*c*. Under such circumstances, it is known that the total displacement of the bar subjected to tensile stress will be given by relation (Timoshenko, 1976):

$$\delta_{tot} = \int_0^l \frac{N(x)}{R(x)} dx \tag{1}$$

where *N*(*x*) = *F* represents the effort in some section x € [0, l] while *R*(*x*) represents rigidity being given by relation: *R*(*x*) = *E*·*A*(*x*), where: *E* represents the Young modulus; *A*(*x*) − the area of bar's cross section, noted with *x*.

Displacement of some cross section, occurring at distance *x* from the fixed end of the bar (Fig. 2*c*) will be given by relation:

$$\delta(x) = \int_0^x \frac{N(x_1)}{R(x_1)} dx_1 \tag{2}$$

or it will be calculated reported to the free end:

$$\delta(x) = \delta_{tot} \int_0^{(l-x)} \frac{N(x_2)}{R(x_2)} dx_2 \tag{3}$$

with x, x_1 and x_2 considered the same as in Fig. 2*a*.

Under such conditions, the diagram of the displacements of cross sections for the straight bar plotted in Fig. 2*a*, subjected to tensile stress, takes the aspect of the one illustrated in Fig. 2*b*. Different regions of the bar occur when, along it, changes are produced either in the variation law of bar's section, in the law of effort variation, or in both of them (Deutsch, 1979). Consequently, displacement of some section of the bar will be given by relation:

$$\delta(x_i) = \delta_i + \int_0^{x_i} \frac{N(x_{1i})}{R(x_{1i})} dx_{1i} \tag{4}$$

where x_i and x_{1i} are measured starting with section *i*, δ_i representing displacement of the same section.

3. Analytical Calculation of the Displacements of Bars with Concentrators

An analytical calculation of displacements was performed for 4 straight bars on which stress had been applied, each of them making use of a stress concentrator. The stress concentrators applied on such bars are of circular, quadratic, triangular and canal-type Fig. 3.

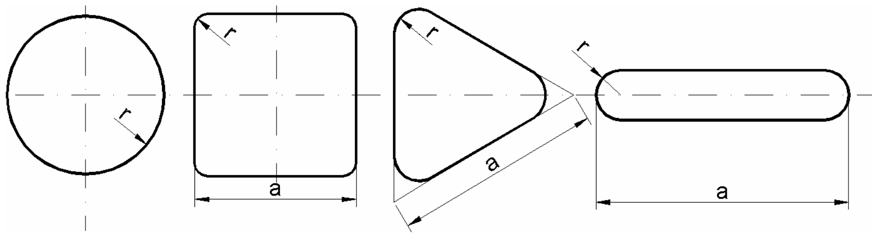


Fig. 3 − Stress concentrators.

The sizes of the bar are 100x40x3 mm^3 ($L \cdot b \cdot t$), *while the cut up area of each concentrator is* A = 100 mm^2. Consequently, the sizes resulting for each concentrator in part are obtained with relations:

− circular: $\sqrt{\dfrac{A}{\pi}} = 5.64\ \text{mm}$

− quadratic: $\sqrt{\dfrac{A}{\pi + 12}} = 2.57\ \text{mm}$; $a = 4\,r$;

− triangular: $\sqrt{\dfrac{A}{6\sqrt{3} + \pi}} = 2.718\ \text{mm}$; $a = 6\,r$;

− canal-type: $\sqrt{\dfrac{A}{4\pi + 12}} = 3.74\ \text{mm}$; $a = 4\,r$.

In the following, a calculation example is provided for the bar with triangular concentrator - Fig. 4. The bar is of plate-type, with thickness t = 3 mm. The geometrical dimensions of such a configuration are: l_{12} = 42.938 mm; l_{23} = 4.077 mm; l_{34} = 8.688 mm; l_{45} = 1.359 mm; l_{56} = 42.938 mm; $A_{conc.}$= 100 mm^2; r = 2.718 mm; a = 16.309 mm. Young modulus takes a value $E = 2 \cdot 10^5$ N/mm.

The bar plotted in Fig. 4, fixed in its left end, had been loaded with a 7000 N force in its free right end.

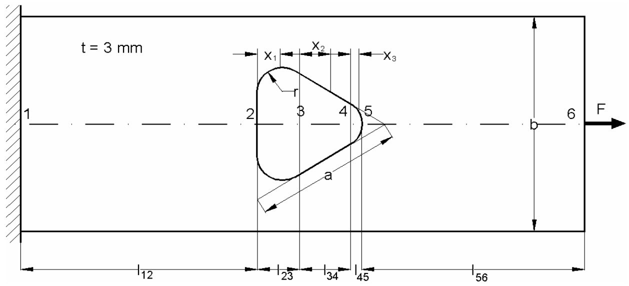


Fig. 4 − Bar with triangular concentrator.

Regions 1-2 and 5-6 have a constant cross section, so that their elongation values are given by relations (5), in which substitution with the above data will also provide the elongation values, in mm:

$$\Delta l_{12} = \frac{Fl_{12}}{AE} = 0.012524\,\text{mm}\,;\ \Delta l_{56} = \frac{Fl_{56}}{AE} = 0.012524\,\text{mm} \tag{5}$$

Elongations of regions 2-3, 3-4 and 4-5, the cross sections of which vary with x_1, x_2 and x_3 (Fig. 4), are given by the general relations (Goanţă, 2001):

$$\Delta l_{23} = \int_0^{l_{23}} \frac{Fdx_1}{A(x_1)E}\,;\ \Delta l_{34} = \int_0^{l_{34}} \frac{Fdx_2}{A(x_2)E}\,;\ \Delta l_{45} = \int_0^{l_{45}} \frac{Fdx_3}{A(x_3)E}$$

Explained of areas $A(x_1)$, $A(x_2)$ and $A(x_3)$ and substitution of the above data lead to:

$$\Delta l_{23} = \int_0^{3r/2} \frac{Fdx_1}{2hE\left[\frac{b}{2} - \frac{a}{2} + \sqrt{3}r - \sqrt{2rx - x^2}\right]} = 0.001668\ \text{mm}$$

$$\Delta l_{34} = \int_0^{\sqrt{3}a/2 - 2r} \frac{Fdx_2}{2hE\left[\frac{b}{2} - \frac{2\sqrt{3}ra}{\sqrt{3}a4r}x - \frac{a - \sqrt{3}r}{2}\right]} = 0.003197\ \text{mm}$$

$$\Delta l_{45} = \int_0^{r/2} \frac{Fdx_3}{2hE\left[\frac{b}{2} - \sqrt{\frac{3r^2}{4} - rx - x^2}\right]} = 0.000432\ \text{mm}$$

Total elongation of the bar will be given by relation:

$$\Delta l_{tot} = \delta_6 = \Delta l_{12} + \Delta l_{23} + \Delta l_{34} + \Delta l_{45} + \Delta l_{56} = 0.030344\,\text{mm}$$

while displacements of points 2, 3, 4 and 5 will be:

$$\delta_2 = \Delta l_{12} = 0.012295\,\text{mm};\ \delta_3 = \Delta l_{12} + \Delta l_{23} = 0.014192\ \text{mm};$$
$$\delta_4 = \Delta l_{12} + \Delta l_{23} + \Delta l_{34} = 0.017389\ \text{mm};$$
$$\delta_5 = \Delta l_{12} + \Delta l_{23} + \Delta l_{34} + \Delta l_{45} = 0.017820\ \text{mm}$$

Calculations for the other concentrators were made in a similar manner, the values, in mm, for the displacements of the corresponding cross sections being listed in Table 1.

Table 1
Analytical Calculation Data

Displacements				
A_{conc} = 100 mm^2			E = 200000 N/mm^2	
F = 7000 N			A_{tot} = 120 mm^2	
L_{tot} = 100 mm			Bar without conc. δ_{tot}=0.0292 mm	
	Circular	Quadratic	Triangular	Canal-type
t	3	3	3	3
b	40	40	40	40
r	5.642	2.570	2.718	3.742
a	11.284	10.280	16.309	14.968
l_{12}	44.358	44.860	42.938	42.516
l_{23}	11.284	2.570	4.077	3.742
l_{34}	44.358	5.140	8.688	7.484
l_{45}		2.570	1.359	3.742
l_{56}		44.860	42.938	42.516
L_t	100	100	100	100
Δl_{12}	0.012938	0.013084	0.012524	0.012401
Δl_{23}	0.004253	0.000968	0.001668	0.001283
Δl_{34}	0.012938	0.002018	0.003197	0.002685
Δl_{45}		0.000968	0.000432	0.001283
Δl_{56}		0.013084	0.012524	0.012401
δ_1	0	0	0	0
δ_2	0.012938	0.013084	0.012524	0.012401
δ_3	0.017190	0.014053	0.014192	0.013684
δ_4	0.030128	0.016070	0.017389	0.016369
δ_5		0.017039	0.017820	0.017652
δ_6		0.030123	0.030344	0.030053

Starting from the above data, Fig. 5 plots the graphs of the cross sections displacements. For an as good visualization as possible, Fig. 6*a* shows exclusively the region from the immediate vicinity of the stress concentrator, between 45 and 55 mm, respectively between 90 and 100 mm - Fig. 6*b*, the concentrators being always placed in central position on the bar with a total length of 100 mm.

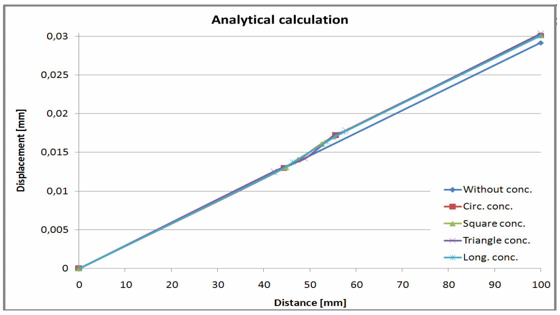
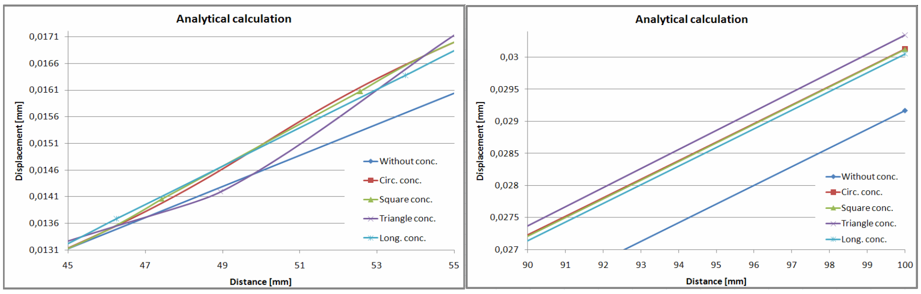


Fig. 5 – Displacements of the cross sections in the vicinity of the concentrator – analytical, l = 0-100 mm.



a *b*

Fig. 6 – Displacements of the cross sections in the vicinity of the concentrator – analytical calculation: l = 45-55 mm (*a*); l = 90-100 mm (*b*).

Analysis of the curves illustrated in Fig. 6 permits the following observations:

– the total displacement of the bar without a stress concentrator is 0.029166, which represents the lowest value recorded;

– in increasing order of displacement of the free end of the bar, there occur the bars with concentrator: of canal- (0.030053 mm), quadratic (0.030123 mm), circular(0.030128 mm) and triangular (0.030344 mm) type;

– at some distance from the stress concentrator one may observe the linearity of displacements, the straight bars being overlapped in the area of enclosure;

− in the area of stress concentrator, deviations from linearity may be observed in all four cases;

− in the area of stress concentrator, the curves get intersected in two or more points;

− for the triangular concentrator, the largest total bar displacement is obtained.

4. Finite Elements Analysis

Finite elements analysis of the bars subjected to tensile stress was performed with the above described concentrators. The bar had been fixed in its left end and stressed at the other end with a 7000 N force. The sizes are the same as for the analytical calculation, respectively (100·40·3) mm^3 (L·b·t). Under such conditions, the stress for the bar without concentrator, or for the bars with concentrator, but at some distance from it, recorded a value:

$$\sigma = \frac{F}{A} = \frac{7000}{120} = 58.33 \text{ MPa}$$

As already mentioned, the cutting up required by the introduction of the 4 concentrators gave a 100 mm^2 area, *for each of them*. The configuration of concentrators is plotted in Fig. 3, while the resulting geometrical sizes are discussed in chapter 3. Fig. 7 presents the maps of stresses σ_{yy} determined according to stress direction, for the 4 cases considered. The observation is made that maximum stresses occur in the weak zones of the sections. Comparatively with a stress of 58.33 MPa, maximum stresses for the cases with concentrators are:

− circular concentrator: $\sigma_{yy\max}$= 182 MPa;

− quadratic concentrator: $\sigma_{yy\max}$= 169 MPa;

− triangular concentrator: $\sigma_{yy\max}$= 255 MPa;

− canal-type concentrator: $\sigma_{yy\max}$= 129 MPa.

Analysis of the stresses maps given in Fig. 7 permits the following conclusions:

− for the circular concentrator, maximum stress is about 3 times higher than the value recorded in the cases without concentrator (182 MPa *versus* 58.33 MPa), as actually shown by theoretical calculations, as well;

− the highest stress, registered for the triangular concentrator, is localized in the immediate vicinity of the connecting rays;

− in all cases, compression stresses are registered on the center of the bar, in the vicinity of the concentrator.

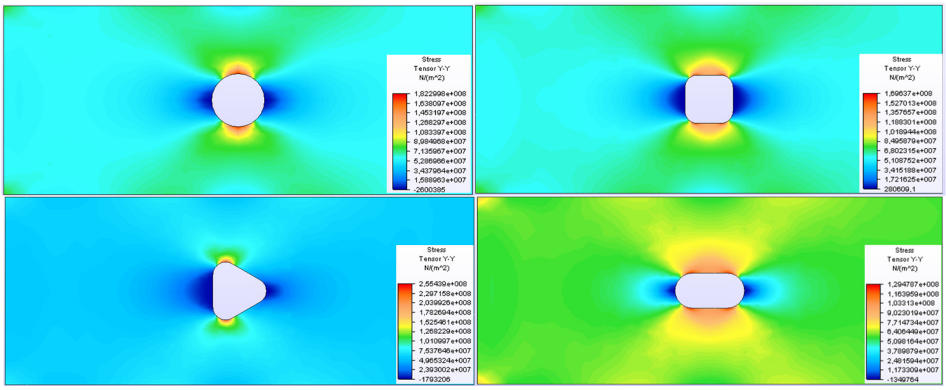


Fig. 7 − Map of stresses, according to stress direction.

For the above-discussed bars with concentrators, the variation graphs of the displacements of the points from the bars' axis, as well as of the points occurring on the lateral part of the bars, have been drawn - Fig. 8. For the sake of comparison, on the same graphs there had been also plotted the curves representing the displacements of the cross sections determined analytically, as well as the straight line representing displacements of the cross sections for the bar without concentrator. Fig. 8 shows that:

− the linearity of displacements at the ends of the bar is maintained, remaining therefore unaffected by the presence of the concentrator;

− comparatively with the bar without concentrator, the total displacement of which had been of 0.029 mm, the other total displacements were, in increasing order: of canal-type 0.0307, quadratic 0.0313, circular 0.0314 mm and triangular 0.0317;

− comparatively with the analytical calculation, the order is maintained, even if the recorded values are slightly different, the ones determined by finite elements analysis being higher;

− stress concentrators cause deviation from linearity of the curves of displacements;

− for the points occurring on the central axis, the shape of the curves of displacements from the fixed end is convex, while that from the load is concave;

− for the points occurring on the lateral part of the bar, the shape of the curve of displacements from the fixed end is concave, while that from the load is convex;

− comparatively with the bar without concentrator, the points from the axis of the bar occurring towards the fixed end are less shifted – the red and blue points from the left part of the concentrator;

− comparatively with the bar without concentrator, the points from the axis of the bar occurring towards the force are more shifted - the red and blue points from the right part of the concentrator;

− comparatively with the bar without concentrator, all points from the lateral part of the bar are more shifted;

− for all four cases with concentrators, the first part of the curve – up to the concentrator – representing the analytical calculation, occurs between the curved representing the displacements of the central and lateral points;

− the same holds true for the curve representing the displacements of the cross sections of bars without concentrator;

− for all four cases with concentrators, the analytically-calculated displacements are lower than those calculated by finite elements analysis, *versus* both the central and the lateral points.

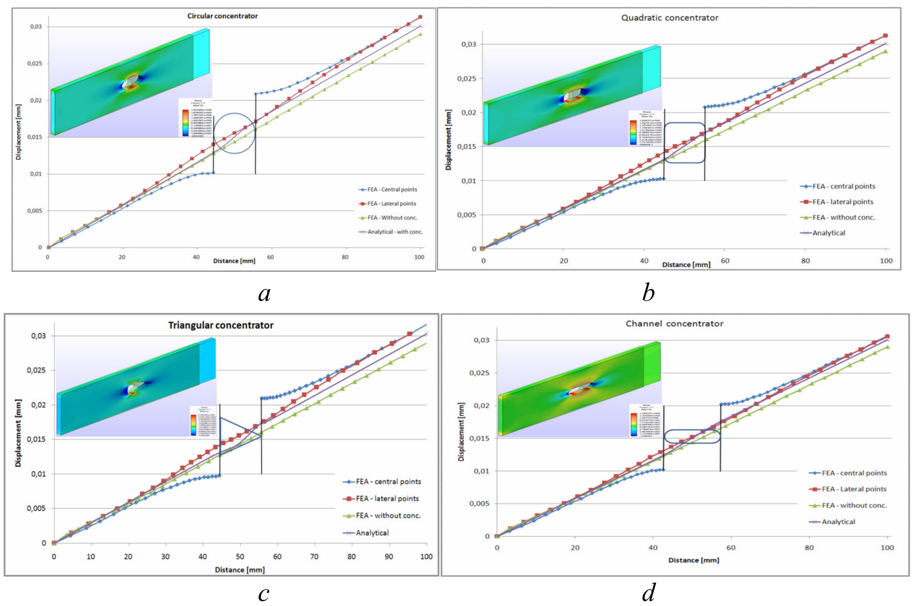
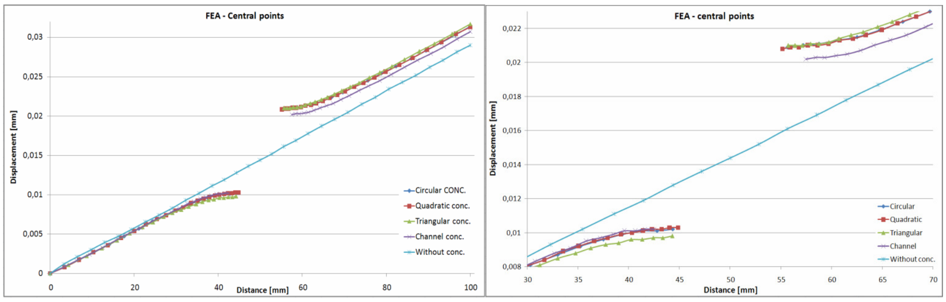


Fig. 8 − Displacements of the central and lateral points – FEA + analytical: *a* − circular concentrator; *b* − quadratic concentrator; *c* − triangular concentrator; *d* − canal-type concentrator.

Fig. 9 plots the curves of displacements for the points occurring on the axis of the central bar for all previously-mentioned four cases of concentrators. For the points from the fixed end, some similarity may be observed among the curves plotted for the circular, quadratic and canal-type concentrators. Nevertheless, for the points from the load, similarities are noticed among the curves drawn for the circular, quadratic and triangular concentrators.



a *b*

Fig. 9 – Displacement of the central points: l = 0-100mm (*a*); l = 30-70 mm (*b*).

The observation is also made that, comparatively with the case without concentrator, the lowest total displacement appears in the canal-type concentrator, which also records the lowest stress in the connection zone. On the other hand, for the points occurring on the left side of the concentrator, the lowest displacement occurs at the bar with triangular concentrator, even if this bar also records the highest total displacement.

5. Tensile Tests on Samples with Concentrator

The experimental determinations made on the test machine considered a bar with circular concentrator. Also, finite elements analysis was developed for the same bar, under the same stress conditions.

Tensile tests were made on a bar with an 80 mm^2 cross section area - Fig. 10, with the universal INSTRON 8801 device, as follows (Mocanu, 1982):

– stresses up to breaking for a flat sample without concentrator;

– stress up to 4000 N (elastic domain) on the sample with concentrator and extensometer;

– stress up to breaking for a flat sample with concentrator.

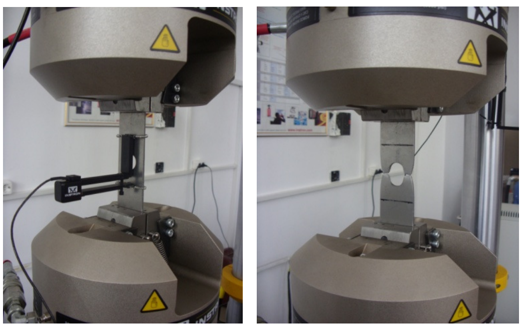
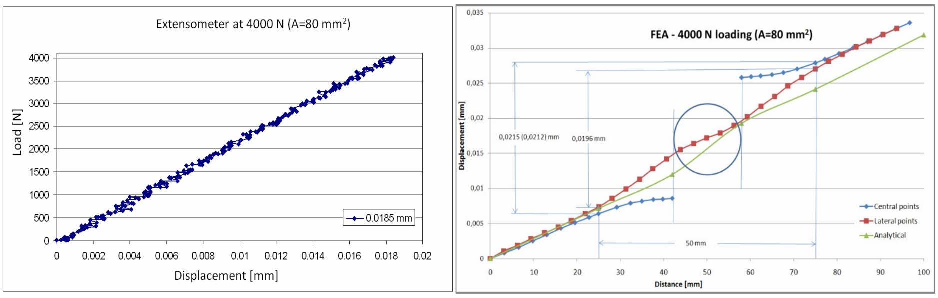


Fig. 10 – Tensile tests on the universal INSTRON 8801 device.

The graph from Fig. 11*a* illustrates the variation of displacements determined with an extensometer, along a 50 mm distance on both sides of a circular concentrator. The total displacement recorded for a 4000 N force was of 0.0185 mm.



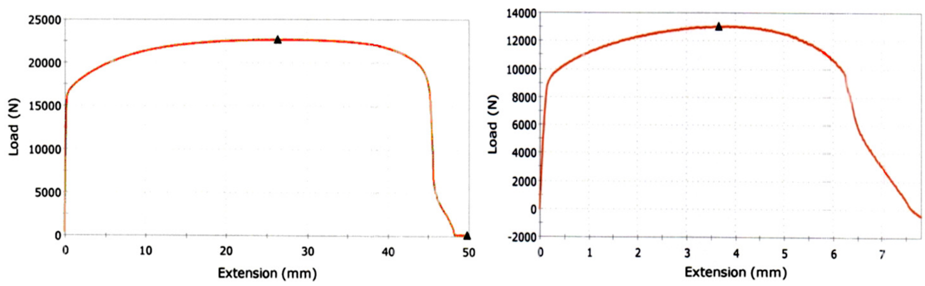
a *b*

Fig. 11 − The force-displacement curve, plotted in the elastic domain with an extensometer (F = 4000 N) (*a*); Displacements along the length of the bar: - finite elements analysis and analytical calculation (*b*).

The red and blue graphs from Fig. 11*b* show, on the basis of finite elements analysis, the variation of displacements in a bar with a hole, fixed at one end and strained to the other with a 4000 N force. The diamond bookmarks represent the displacements of the points from the bar’s axis, while the square bookmarks stand for the displacements of the points from the lateral part of the bar. A slight difference occurs between the displacement measured with an extensometer (0.0185 mm) and the one determined by finite elements analysis (0.0196 mm), over the 50 mm interval, on one side and the other of the hole. The difference may be also caused by the fact that finite elements analysis does not involve the experimentally-determined modulus of longitudinal elasticity and the Poisson coefficient. The values of these elastic characteristics, employed in finite elements analysis were: $E = 2.1\cdot10^5$ N/mm^2, $\nu = 0.29$.

The green curve is plotted on the basis of analytical calculations. If, initially, this curve is in line with the one taken over from finite elements analysis, the observation is made that the hole produces its deviation from linearity because, in analytical calculations, the effect of stress concentration was left aside.

The graphs from Fig. 12 show the characteristic curves taken over from the test machine for samples with and without concentrator.



a *b*

Fig. 12 − Characteristic curve for a bar without concentrator (*a*); Characteristic curve for a bar with concentrator (*b*).

The following observations may be therefore made:

− the maximum force is higher in the bar without concentrator, namely 22500 N *versus* 13000 N;

− in the linear portion, displacements are larger for the bar with concentrator;

− the yield point and ultimate strength are lower in the bar with concentrator;

− breaking elongation is drastically reduced in the bar with circular concentrator: 6.3 mm *versus* 45 mm.

6. Conclusions

Experimental determinations of the deformations of straight bars with various concentrators, subjected to tensile stresses, were performed. Both analytical calculations and finite elements analysis were developed on bars with the same types of concentrators. The area of material's releases was the same for all four concentrators, respectively 100 mm^2. Under such circumstances, the differences are exclusively due to the shape of the concentrators employed.

Analytical calculation of the displacements of the cross sections of the bars with different stress concentrators permits the following conclusions:

− differences may be observed among displacements, as a function of the concentrator type;

− in the vicinity zone of the concentrator, deviations from linearity occur in displacements, both for the points from the axis of the bar and for the lateral ones;

− variations in the displacements of the points vicinity the hole, from the enclosure and load application take different aspects: *convex and concave*;

− lowest displacement occurs in the canal-type concentrator.

Analysis of the stress maps drawn on the basis of finite elements analysis shows that the highest stress is registered in the triangular concentrator, being localized in the immediate vicinity of the connecting rays. In all cases here considered, compression stresses are recorded in the center of the bar neighboring the concentrator.

The graphs plotted on the basis of finite elements analysis evidence the following aspects:

− stress concentrators cause deviation from linearity of the curves of displacements;

− for the points occurring on the central axis, the shape of the curves of displacements from the fixed end is convex, while that from the load is concave;

− comparatively with the bar without concentrator, the points from the axis of the bar positioned from the fixed end is less shifted, while the points from the axis of the bar occurring towards the force are more shifted than in the bar without concentrator, all points from the lateral part of the bar being shifted to a higher extent;

− for all four cases with concentrators, the analytically-calculated displacements are lower than those calculated by finite elements analysis.

Experimental determinations, finite elements analysis and analytical calculations have been performed for a bar with circular concentrator, under identical stress conditions. Slight differences were observed between the displacement measured with an extensometer and the one determined by finite elements analysis over a 50 mm interval, on one side and the other of the hole. The curve plotted on the basis of analytical calculation is similar – in its initial part – with the one taken over from finite elements analysis. It is observed that *the hole produces a deviation* of this curve both from linearity and comparatively with those taken over from finite elements analysis.

Analysis of the characteristic curves drawn - up to breaking - for a bar with and without a concentrator, shows that:

− in the linear portion, displacements are higher for the bar with concentrator;

− the yield point is lower in the bar with concentrator;

− elongation to break is drastically reduced in the bar with circular concentrator.

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INFLUENȚA CONCENTRATORILOR DE TENSIUNE ASUPRA DEFORMABILITĂȚII UNEI BARE DREPTE

(Rezumat)

În cadrul acestei lucrări se prezintă influența diferiților concentratori asupra tensiunilor şi deformabilității barelor drepte supuse la solicitarea de tracțiune. Pentru patru tipuri de concentratori diferiți, s-au făcut atât calcule analitice cât şi analize cu elemente finite, în vederea determinării capacității de deformare a barelor care îi conțin. Aria degajărilor de material a fost aceeaşi pentru toți cei patru concentratori, respectiv 100 mm^2. În aceste condiții, diferențierile provin doar ca urmare a formei concentratorilor utilizați. Pentru o bară cu concentrator circular s-au efectuat atât determinări experimentale, analiză cu elemente finite cât şi un calcul analitic, în aceleaşi condiții de solicitare, obținându-se rezultate apropiate.