

Numerical Analysis of the Impact of Geometric Parameters of the Outcuts in the Wing Torsion Box Wall on the Mechanical Properties of the Structure

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ABSTRACT

The study presents the results of comprehensive numerical analyses of an unusual solution in the field of geometry of holes in the wall of the wing torsion box subjected to torsion. Due to the nature of loads acting on the wing structure in flight conditions, it is possible to modify the current standard solutions.

The proposed solution based on the concept of application the elliptical holes, representing relieving or inspection cutouts. However, in relation to traditional solutions using circular forms of holes, this involves a fundamental change in the nature of stress distribution and the resulting need to use new types of local reinforcements of the structure. The subject of the study constituted thin-walled load-bearing structure representing fragment of the torsion box of the wing. Considerations were supported on the series of numerical experiments, accomplished by means of the FEM nonlinear procedures. The analyses were supposed to indicate the dependencies between the geometric parameters of the cutouts and the nature of advanced deformations and the distribution of internal forces.

Keywords: outcut, advanced deformation, finite elements method, nonlinear analysis.

INTRODUCTION

Due to increasingly higher requirements in the field of exploitation economics, contemporary aeronautical structures are constantly evolving in terms of the details of the used technical solutions. This entails the need to look for new ways of shaping the elements of the load-bearing structures, aimed at reducing their mass, while meeting the safety requirements.

The wing is one of the key elements of an airframe, with a significant mass fraction in the aircraft structure, and in particular it is its most loaded component, in most typical structures constituting a combination of a wing spar and a torsion box, the geometry of which is generally due to aerodynamic limitations. In a large part of cases of structural solutions, the perimeter of the torsion box is located in the part of the wing

adjacent to the leading edge, and its closing wall is also a component of the wing spar (Fig. 1).

In the case of the front part of the torsion box, which has the curvature, there is no possibility to form advanced deformations, due to the need to maintain the rigidity of the system and the desirable aerodynamic properties of the wing [8, 11]. However, the closing wall is an element that has a natural tendency to lose stability, due to the way it works. In flight conditions, the structure is subjected to bending and torsion, which in both cases results in the formation of a draw field within the wall segment limited by adjacent ribs (Fig. 2).

The torsional moment acting on the torsion box is the result of the impact of aerodynamic circulation, and the bending moment is formed as a result of the impact of pressure forces acting on the airfoil, resulting in the occurrence of a lift force.

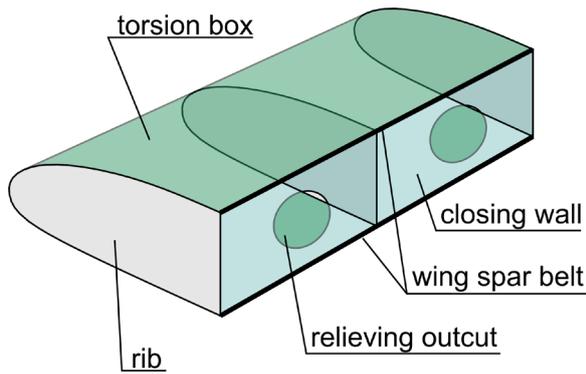


Figure 1. Diagram of typical wing support structure

In the case of airplanes of a larger size and mass, for example passenger or transport ones, the loading of the torsion box wall is the result of the sum of the torsion and bending effects. From the design assumptions of this type of aircraft, the wing loads of a negative nature have a significantly lower value than those occurring in the basic flight states. It shows that in the case of loads with the highest values, the nature of the draw fields appearing in the wall segments of the torsion box corresponds to the one presented in Figure 2. This assumption is based on the concept of searching for alternative geometric forms of lightening or inspection holes presented in this study.

PURPOSE AND SCOPE OF THE STUDY

The subject of the discussion was a thin-walled structure modelling a fragment of the thin-walled torsion box of the wing (Fig. 3).

The structure consisted of four ribs, modelling the shape of a fragment of the symmetrical aerodynamic profile of the wing and the cover of

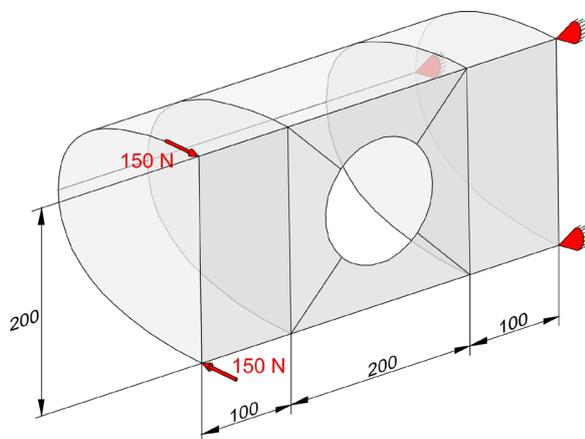


Figure 3. Diagram of tested structure and method of fixing and loading.

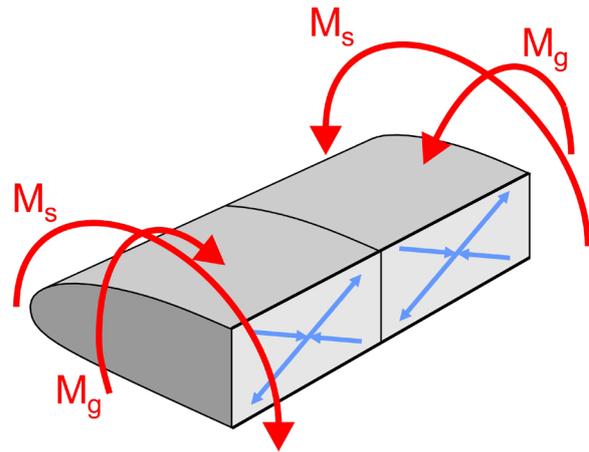


Figure 2. Impact of torsion box loads on wall operation

the front part of the torsion box and the closing wall, in the middle segment of which there was an cutout, modelling an inspection or lightening hole. The structure was subjected to torsion by the use of a pair of forces applied to the peripheral rib.

The fixing method referred to a typical solution used in aviation technology, consisting of three nodes corresponding to the bonds between the spar belts and the reinforcement of the leading edge and the hull elements.

An assumption was made about the model nature of the material, which enables the future confirmation of the obtained results using a laboratory experiment. Therefore, it was based on the mechanical characteristics of polycarbonate, marked by elastic properties in a significant range of stress values. The physical constants of the material were: $E=2150 \text{ MPa}$, $\nu=0.38$.

Although the research focused on the middle segment of the structure, additional peripheral segments of a shorter length were used. It was supposed to eliminate the influence of the effects of load application concentrated on the deformation state and stress distribution in the central segment. The reference object was a structure with a circular cutout. The remaining cases corresponded to elliptical cutouts with a larger semi-axis oriented along the main diagonal of the segment, in the direction corresponding to the axis of the draw field (Fig. 4).

The main purpose of the analyzes was to determine the impact of the dependencies between the characteristic dimensions of the cutout on the nature of advanced deformations and the corresponding stress distribution [8, 9]. During the analyzes, the rule of maintaining a constant surface

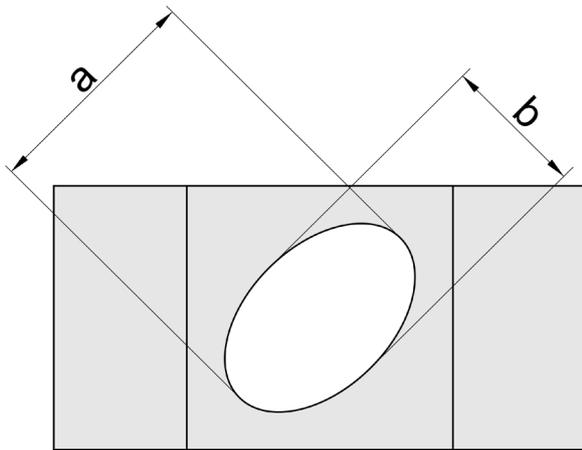


Figure 4. General form of elliptical cutout.

of the cutout was adopted. In the next step, a new design solution of the system was proposed, enabling a homogeneous stress distribution in the area of the torsion box wall [11].

NUMERICAL ANALYSES

In many cases of nonlinear numerical analyzes of thin-walled structure elements, the factor necessary to obtain the correct forms of advanced deformations is the presence of initial imperfections[1][4]. A frequently used method of obtaining them is conducting a preliminary, linearized stability analysis, the result of which are post-buckling deformations determined by solving the problem with eigenvalues, generally corresponding with their nature to real forms [6, 7]. After proper treatment, they can constitute a data set containing modified information about the geometry of the object, constituting the basis for the proper nonlinear analysis, which comes down to determining the course of the equilibrium path of the system, in the general case constituting a hypersurface in the n-dimensional state space, where n is the number of degrees of freedom of the system. In each subsequent step of the analysis, corresponding to the consecutive increase in load, the relationship between the current state of the structure and the load is described by the matrix equation of residual forces [2, 3, 5]:

$$r(u, \lambda) = 0 \tag{1}$$

where: μ is a state vector containing current displacement components of structure nodes,

λ is a control parameter corresponding to the current load level, and r is residual vector containing unbalanced force components related to the current state of deformation of the system [15, 16].

All nonlinear procedures have an incremental phase. For each successive increment, at the transition from state n to the state $n+1$, the following increments occur:

$$\begin{aligned} \Delta u_n &= u_{n+1} - u_n, \\ \Delta \lambda_n &= \lambda_{n+1} - \lambda_n \end{aligned} \tag{2}$$

In order to avoid the discrepancy between the actual equilibrium path and the path determined on the basis of incremental steps, known as the drift error, an additional equation is formulated during successive increments, called the increment control equation or the constraint equation[6][10]:

$$c(\Delta u_n, \Delta \lambda_n) = 0 \tag{3}$$

constituting a condition defined by the user, resulting from the adopted correction strategy.

In the case of issues similar to the discussed one, related to the occurrence of the draw field with simultaneous torsional deformation of the entire system, it is not necessary to create an initial imperfection [12, 14]. Therefore, the basis for determining advanced deformations is the selection of a proper incremental method and a complementary correction strategy [13].

In the case under consideration, the Newton-Raphson prediction method was used in its basic form, with load correction. Numerical analyzes were conducted using the commercial MSC PATRAN/MSC MARC software, based on the finite element method. Geometric models of the analyzed structures (Fig. 5) were realized with the use of the editor included in the above software, as well as on the basis of the DSS CATIA software.

Based on a series of linear analyzes, the minimum grid density was determined to ensure the convergence of the numerical solution. As a result, in the nonlinear analyzes, a grid containing approximately 20,000 nodes and 19,000 surface

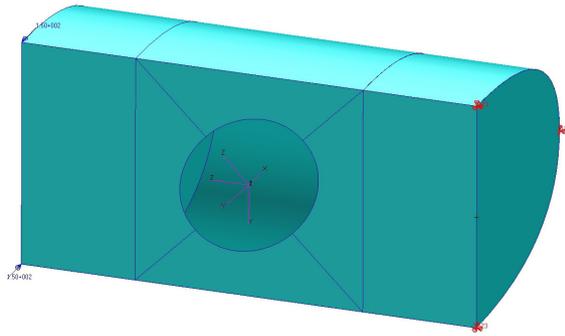


Figure 5. Exemplary geometrical model of the structure

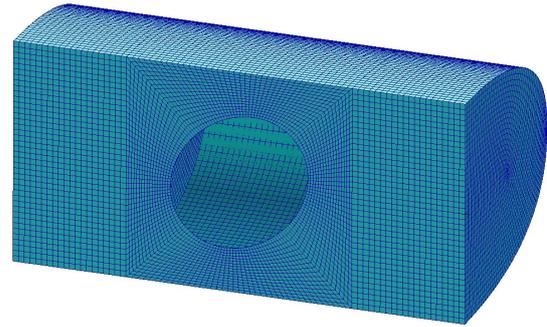


Figure 6. Exemplary form of finite element grid

elements with bilinear shape functions were used (Fig. 6).

A structure with a circular cutout was adopted as the reference system. As a result of the numerical analysis, a form of advanced deformations typical for this type of structure was obtained (Fig. 7a). From the point of view of a comparative analysis with other solutions, the distribution of stresses adjacent to the cutout seems to be the most important (Fig. 7b).

It should be noticed that the stress distribution in the examined area reveals several concentration zones, both in the corners of the segment wall and in the direct adjacency to the cutout edge. Attention is also drawn to the fact that the values of the reduced stress in the tensile and compressed area of the wall cover are of the same order. In practice, this form of stress distribution makes it necessary to use additional elements reinforcing the edge of the hole, in the form of a frame or, in the case of lower load levels, a special shape of the edge. In the subsequent stages, numerical analyses of a number of models with slightly changing proportions between the dimensions a and b of the cutout were conducted (Fig. 8–10).

In all analyzed cases, the form of stability loss is of the same nature, which results from the characteristic type of load. However, it should be noted that with the change in the proportion of geometric parameters of the cutout, the size of the wall area within which its buckling occurs is reduced. As a result of numerical analyses of a number of system cases, the relationship between the a/b relation and the maximum displacement of a fragment of the wall area subjected to advanced deformation in the adjacency of the cutout edge was determined (Fig. 11).

The consequence of adopting an elliptical form of the cutout is also an increase in the value of reduced stress in the region of the largest critical deformation (Fig. 11). However, while assessing the utilitarian aspect of the presented considerations, attention should be paid to a significant change in the nature of stress distribution as the mutual relationship of the ellipse semi-axis length increases. As it increases, there is a clear reduction in the level of stress on the major part of the wall segment. This also applies to the edge of the cutout itself.

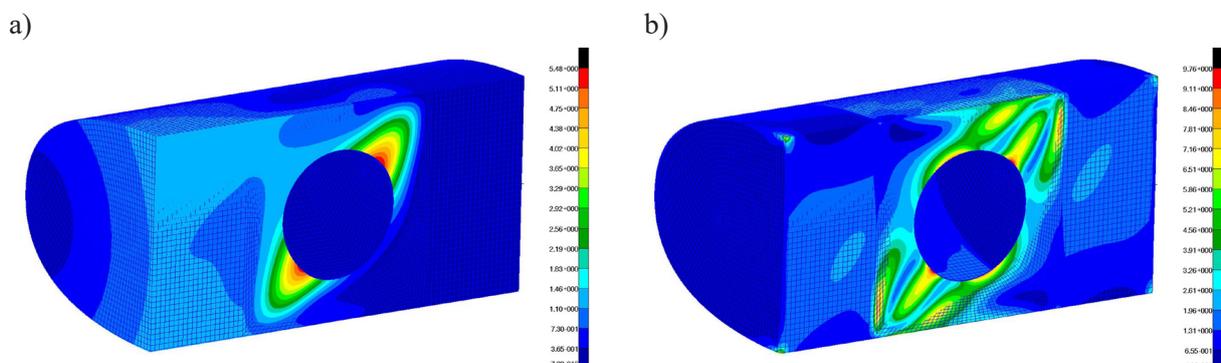


Figure 7. Results of the numerical analysis of the model with a circular outcut: a) displacement distribution [mm], b) reduced stress distribution according to the Huber-Mises-Hencky hypothesis [MPa]

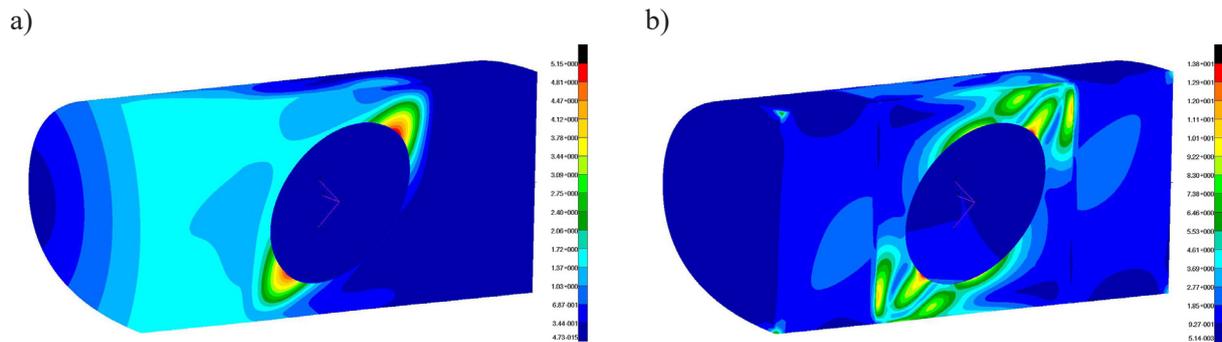


Figure 8. Results of the numerical analysis of the model with an elliptical cutout (a=80 mm, b=60 mm): a) displacement distribution [mm], b) reduced stress distribution according to the Huber-Mises-Hencky hypothesis [MPa]

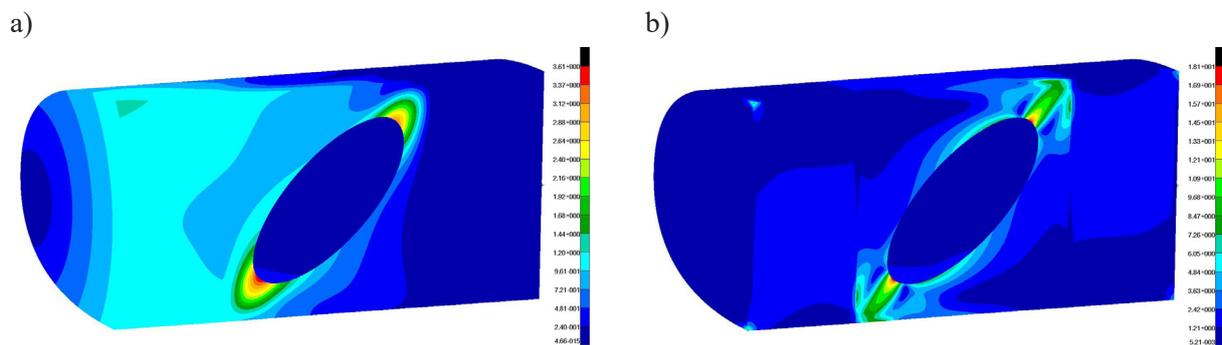


Figure 9. Results of the numerical analysis of the model with an elliptical cutout (a=90 mm, b=40 mm): a) displacement distribution [mm], b) reduced stress distribution according to the Huber-Mises-Hencky hypothesis [MPa]

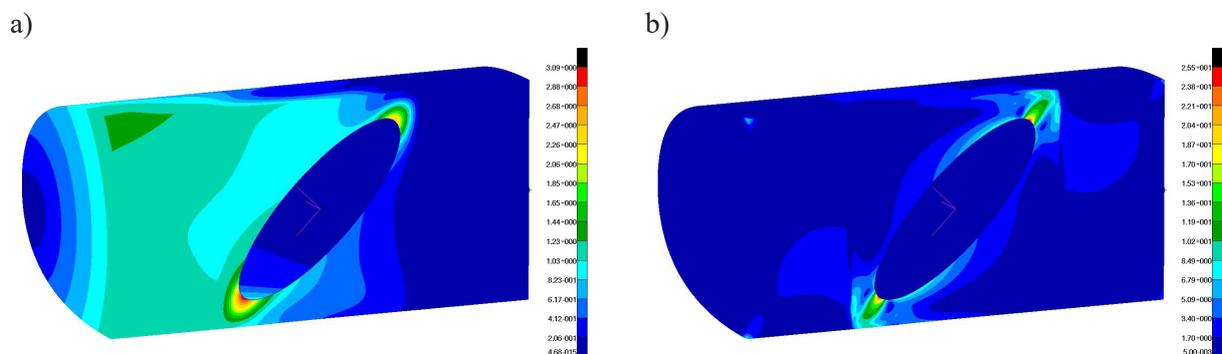


Figure 10. Results of the numerical analysis of the model with an elliptical cutout (a=102.85 mm, b=35 mm): a) displacement distribution [mm], b) reduced stress distribution according to the Huber-Mises-Hencky hypothesis [MPa]

The area of stress concentration, located adjacent to the edge, on the diagonal of the pulling field, becomes significantly smaller than in the case of a circular hole. The final effect, in the form of significant stress redistribution, seems to be beneficial due to the lower probability of the occurrence of potential fatigue defects. In addition, it creates a potential for reducing the mass necessary for the application of reinforcements. In the case of most such structures, the lightening

or service holes in the areas of the wing with a relatively high load, e.g. near its root, are reinforced with frames attached to the edge, which in the case of stress distribution corresponding to a circular hole, seems to be indispensable.

In the proposed solution, it seems possible to use a local reinforcement, which would result in a reduction in the wing mass. In the next step of the considerations, a numerical experiment was conducted, the aim of which was to analyze an

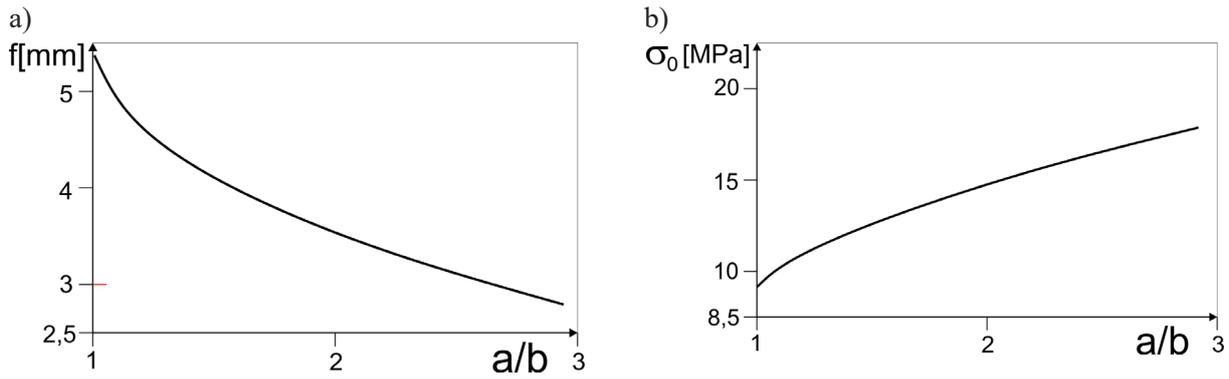


Figure 11. The dependencies between the relationship of geometric parameters of the output a/b and: a) the maximum displacement in the direction perpendicular to the plane of the wall f , b) the maximum value of reduced stress σ_0 according to the H-M-H hypothesis.

alternative solution consisting in the application of the above concept of local reinforcements (Fig. 12).

The proposed solution is in fact a small modification of the output system, consisting in a twofold increase in the thickness of small areas of the wall, marked green in the drawing. In the numerical model, the density of the finite element grid similar to the previously used ones was applied, and the form of the grid itself was modified, due to the different geometric distribution of the model surface. Nonlinear numerical analysis of the modified model showed that the torsion box wall did not undergo advanced deformations at all, whereas the distribution of reduced stress does not reveal dangerous concentration zones (Fig. 13).

The above picture was created based on the color spectrum corresponding to the range of stress values corresponding to the output model (Fig. 10b). A comparison of the results obtained for both versions of the model enables to recognize the potential usefulness of the proposed solution.

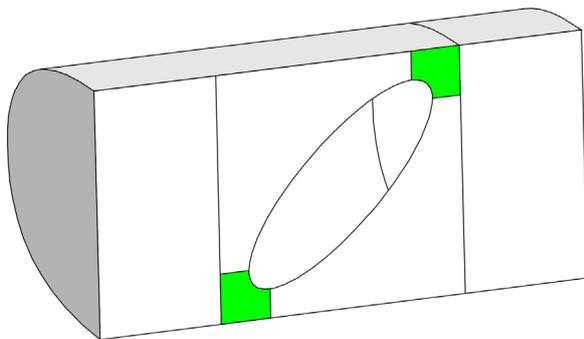


Figure 12. Modified version of the construction solution, containing local reinforcement (green color)

CONCLUSIONS

To sum up, the presented results of nonlinear numerical analyses enable to formulate a number of conclusions and construction recommendations. The cutouts in the walls of the spars, acting as inspection or lightening holes, in the case of most aircraft, may take a form different from the circular one, which forces the use of additional stiffening elements, in the form of frames. Converting the geometric form of the cutout from circular to elliptical causes a significant redistribution of the stress distribution in the torsion box wall, reducing the area of concentration. The elliptical form of the cutout, with the proper relationship of the semi-axis length, enables the use of a structural solution based on the local reinforcement of a small area of the torsion box wall. The proposed solution affects a significant increase in the value of the critical load of the torsion box wall, with a potentially lower mass of the reinforcing elements than in the case of

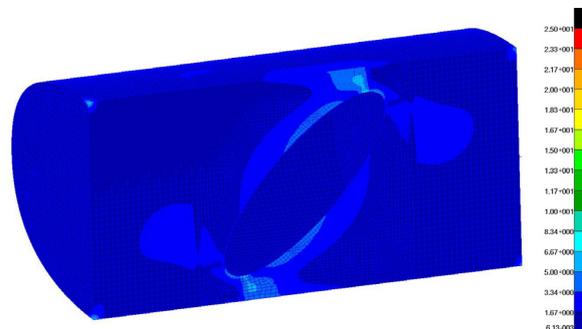


Figure 13. The results of the numerical analysis of the model with an elliptical cutout ($a=102.85\text{mm}$, $b=35\text{mm}$) with local reinforcements: the distribution of reduced stress according to the Huber-Mises-Hencky hypothesis [MPa]

a traditional solution based on a circular cutout. The presented considerations were based on a numerical experiment, which in the case of potential use of the proposed solution should be supported by a model experiment. Proving the practical usefulness of the presented considerations requires further analyses, taking into account the presence of reinforcements of holes in the form of frames and integral reinforcements, in the form of a geometric modification of the cutout edge, reflecting the effect of plastic pressing. It is also necessary to specify the a/b relationship for which the most favorable mass balance can be obtained if the proposed solution is applied. This also makes it necessary to precisely compare the mass of the analyzed structures. The presented considerations have the character of a preliminary analysis of the issue of modifying the geometric form of the cutouts in the torsion box wall. It is expected that the research will continue, using a model experiment and measurements of deformation of the tested structures using optical scanners.

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