AN EXPERIMENTAL STUDY FOR APPLYING GENERATIVE DESIGN TO FABRICATE A LIGHT METALLIC STRUCTURAL ELEMENT

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The present experimental study consists on fabrication detailing for realizing a light metallic structural element in a spatial particular shape, from perspective of utility, novelty and efficiency of generative design tools implementation. This study demonstrates the potential of a large creativity promoted by the modern formatting methodology of algorithmic design – curved crease folding – and advantages of generative design implementation, such as real-time calculation, easy to modify the established initial details, rapid selection of the optimal design variant.

Keywords: generative design, curved crease folding, design process, Grasshopper

1. Introduction

Nowadays, as it's known, generative design concepts can offer various computer programs in order to support industrial designers dealing with the computation to generate complex volumes [1-8]. Using generative design methods, the 3D objects are defined through mathematical algorithms from various software programs. These 3D software packages, like Grasshopper's object-oriented, extendable programming environment, offers the possibility to

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create, in a free manner, a wide-range of possible design solutions starting from a defined spatial shape, instead of using an unique and fixed digital model. In that way, both industrial designers and generative designers can cooperate more closely, the first ones concentrating on the construction and proportioning of the project shape, and the second ones applying proper software in order to facilitate the flexibility of the modelling process by finding, testing and choosing various constructive variants, to finally establish the convenient one.

Starting from this general concept, in algorithmic design, the designing of complex solid volumes through generative geometric design can be processed using different formatting methodology in function of specific designing vision. Among these formatting methodologies (like shape grammars, Lindermayer systems, swarm intelligence) two are most actual in algorithmic architecture: "*boundary solid grammars*" [9] and "*curved crease folding*" [10] (based on developable surfaces concept). Present experimental study refers to the second one, which use spatial curved lines drawn on developable surfaces. The developable surfaces are of three types [11]: tangential, conical and cylindrical (excluding a fourth type, the planar surface).

2. The selection and the establishment of the experimental model shape

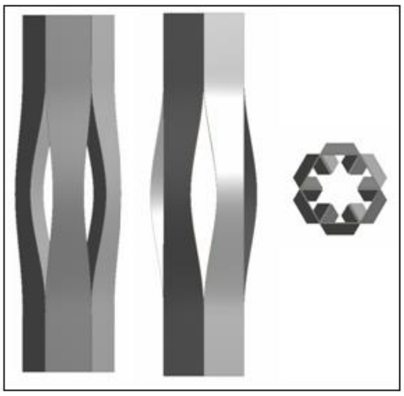
The objective of present paper consists of design and execution of a free-form light metallic structural element with both structural and decorative role, having also an esthetical impact.

The idea of present experimental model came from the column with cusps of *David Huffman* - famous geometric paper folding – Fig. 1 [12]. Starting from here, the prototype which has inspired the shape of the structural element is illustrated in Fig. 2. The shape of the structural element has been decided to resemble, in a modified interpretation, a column from antiquity, but with the possibility of various destinations: structural or decorative one.

It has been intended to obtain the column form from several metallic bands (6 bands for this particular case), twofold on curved lines, which represents, as mentioned above, a modern and widely used formatting methodology in actual algorithmic design – "*curved crease folding*".

The material selection, in a proper manner for this experimental model, has in view several aspects: the structural performance of the entire element, the reliability, the outlining of a technological method for an efficient processing, and the financial issues overview. The result of this analysis leads to the possibility of using different metallic materials, with various thicknesses and various chemical compositions, but in direct line with mechanical load requirements.

Fig. 1. "Column with cusps" by David Huffman. Reconstructed model by Duks Koschitz [12]



a)

b)

Fig. 2-a, b. The prototype of the structural element.

3. Methods, tools and the phases of implementation

The main phases of the project implementation until final execution were as follow:

A. **<u>Study on layouts</u>**, which have been assembled from sheets of cardboard and twofold on established trajectories, in purpose to obtain various volumetric solutions. The final selected solution is represented in Fig. 2.

B. **<u>The algorithmic digital simulation</u>** of the selected prototype shape in order to be able to change the parameters, if necessary. From structural and esthetical point of view, this simulation allows study the 3D volume of the experimental model.

It has been used the modelling software 3D Rhinoceros, augmented by Grasshopper plug-in of algorithmic design and extended with Kangaroo and Karamba packs for simulation and physical analysis. The followed steps were: (a) The generation of the developable surface; (b) the simulation of the folding process – using Kangaroo; (c) the structural analysis, using finite element analysis – Karamba.

The proposed curved column as experimental model is a structure with an evident geometric non-linearity, for which the axial strain is distributed on normal direction to the structure axis. The geometric non-linearity is manifested through transition from linear compression to deflection and even to buckling of the structure. The geometric model, used for the simulation, is represented by a quarter of real developable surface, due to the two plans of symmetry through which can be divided the column and the applied strains also – Fig. 3.

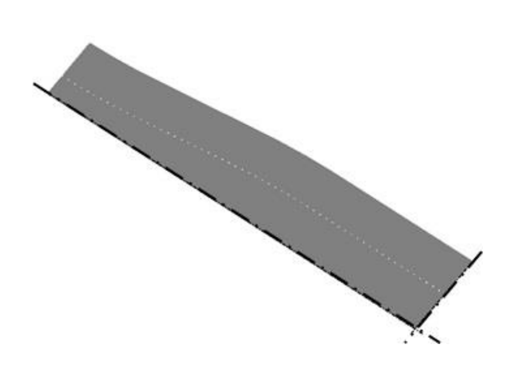


Fig. 3. Geometric model with marked lines of symmetry

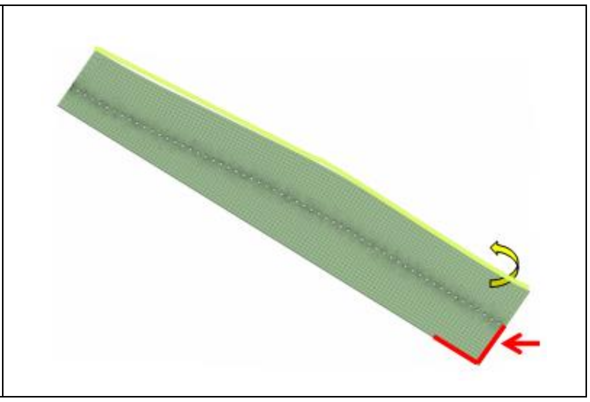


Fig. 4. The discretized model with adequate dimensioning of the finite elements (Loadings and constraints are considered)

Fig. 4 represents the geometric model which has been discretized with adequate dimensioning of the finite elements, considering that in the zone of stress concentrators is necessary a higher density of finite elements. By this, is better managed the apparition of the flow tensions. The yellow arrow indicates the applying of a rotation around the long axis of the piece (the yellow side). The rotation is of 135° and is uniform applied on entire piece side. The red arrow indicates where has been imposed a constraint for displacement on normal direction to plan.

In order to anticipate the material behaviour during plastic deformation, an analysis of folding process on folding line it has been effectuated; the folding line has been drawn by perforating some holes on the metallic band.

C. <u>The simulation of the band plastic deformation</u>

The material properties correspond to structural steel and are offered by ANSYS [13]. Thus, considering the safety criteria of material flowing, the material model has an isotropic bilinear plasticity. The criteria of maximum energy of deformation (applicable to ductile materials), known as "*von Mises-Hencky theory*" [13-15] or theory of shear stress in octahedral plan, assert that the deformation of a solid cannot be realized only by hydrostatic stress component, being initiated by the presence and the intensity of the shear stresses.

For a particular stress condition (σ_1, σ_2, σ_3), the value of the shear stress τ_{max} is as follow:

$$\tau_{max} = \frac{1}{2}\max(|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|) = S_{sy} = \frac{1}{2}S_y \tag{1}$$

where S_{sy} represent the value of initiation of the flow for the shear-stress, and S_y represent the value of the yield strength. The flow begins when the equivalent stress strain reaches a critical value, named stress of limit – S_{limit}.

$$\sigma_e \geq S_{limit} \tag{2}$$

Von Mises criteria can be applied by identifying, in the simulated structure, the locations of the tensions higher than flow tensions, respectively the locations for which is not respected the following equation:

$$\frac{\sigma_e}{S_{limit}} < 1 \tag{3}$$

In the case of plastic deformation, this fraction must be > 1, and the positions for which the value > 1 are those for which the material suffer plastic deformations. This assertion is identical with the following condition:

$$\frac{\sigma_e}{S_y} > 1 \tag{4}$$

where S_y is the yield strength of the material.

However, it must have in view that material can be destroyed by bottlenecking and breaking. Thus, the condition by which the maximum equivalent stress must be lower than breaking strength it must be respected:

$$\frac{\sigma_e}{S_u} < 1 \tag{5}$$

The means by which can be shown through ANSYS that plastic deformation occurs are:

- The Safety Factor: $$F_s = \frac{S_{limit}}{\sigma_e} \tag{6}$$

- The Safety Margin: $$M_s = F_s - 1 = \frac{S_{limit}}{\sigma_e} - 1 \tag{7}$$

- The Stress Ratio: $$\sigma_e^* = \frac{1}{F_s} = \frac{\sigma_e}{S_{limit}} \tag{8}$$

In order to obtain plastic deformations in a controlled manner, the location of some stress concentrators is indicated. These stress concentrators can be holes (like below done simulations), gutters or zones with material properties differentiation (through heat or chemical treatments, irradiation etc.). The presence of these zones make possible that the developed tensions super-pass the yield strength and, thus, deciding the way by which can be attend the final solid shape. As long as the material suffers deformations situated below limit of elasticity, the analysis of the structure can be realized using the linear stress-strain equation [13-15]:

$$[\sigma_{ij}] = [D]\ \{\varepsilon^{el}\} \quad (9)$$

where $[\sigma_{ij}]$ is the strength vector with the format $[\ \sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{yz}, \sigma_{xz}]^T$; D is the matrix of rigidity; $\{\varepsilon^{el}\} = \{\varepsilon\} - \{\varepsilon^{th}\}$ – is the elastic deformation, where $\{\varepsilon\}$ is total deformation and $\{\varepsilon^{th}\}$ is *th* deformation due to *thermal* effects.

The geometric model of the studied experimental structural element, in a column shape, is obtained by folding a planar band along a folding line. As a consequence, is evident the transition from a linear behaviour to a non-linear plasticity. In that case:

$\{\varepsilon^{el}\} = \{\varepsilon\} - \{\varepsilon^{th}\}-\{\varepsilon^{pl}\}$, where $\{\varepsilon^{pl}\}$ refers to plastic deformations.

The material will behave different in the zone with plastic deformation. In this region, the elastic properties of the material are amended by hardening, so, overall, will be formed zones with different modulus of elasticity and flowing criteria. The material properties distribution cannot be known before the band folding, so, the model with finite elements must closely follow the technological process for structure obtaining. Thus, is necessary the simulation of the plastic deformation, firstly, followed after that by the simulation of the column under load. The obtained results indicate a high stress concentration on the line which joins the perforations for folding. This high stress concentration suggests the modification of the perforations shape, or the replacement of the perforations with a gutter, in order to prevent the high stress accumulation.

Fig. 5 indicates the normal displacement on band plan. It can be observed that the band centre (the cross point of symmetry axes) has moved on desired direction with 25 mm, together with the displacement of the outboard parts on inverse direction. This effect appears due to the implementation method of the constraints and also to the fact that folding occurs on curved line. The yellow shading colour from Fig. 5 indicates that, on perpendicular direction to the band plan, the displacement is zero, fact which provokes displacements on the direction of band long axis.

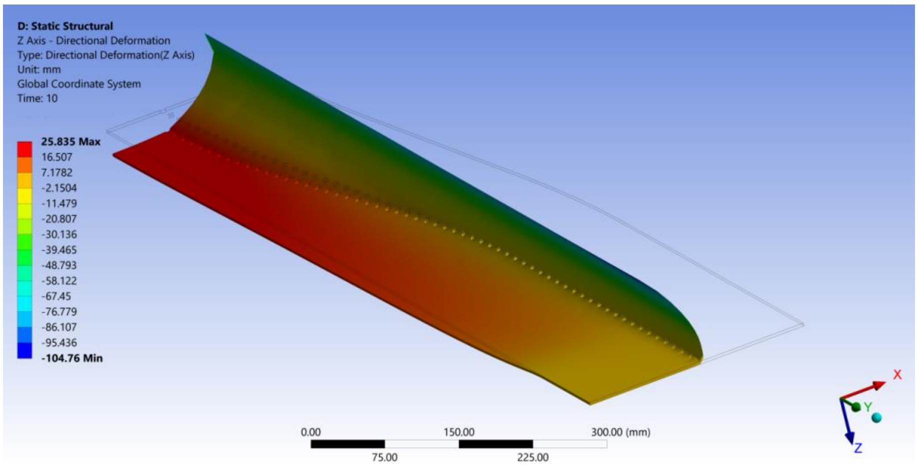


Fig. 5. The displacements on normal direction to the band plan (Z)

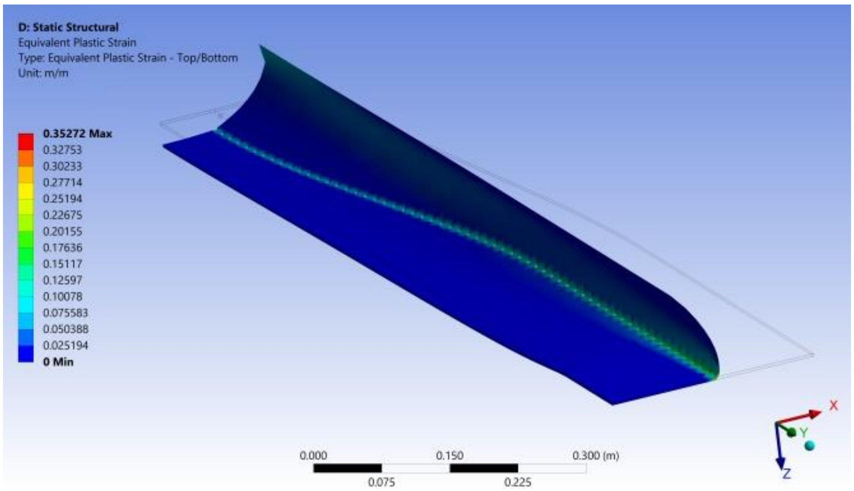


Fig. 6. The relative plastic deformation

Fig. 6 shows the displacements on long axis direction. It can be observed that a contraction of about 1 mm appears on band length. The point of maximum contraction is on the line on which have been processed perforations, which favours the folding. Moreover, it can be observed that the contraction effect is present on entire length of folding line, but not in central zone which, due to the symmetry, a null displacement on this direction is imposing. This contraction is caused by the direction of folding line. On the one hand, this direction dictates the accentuated exit from the plan of the band centre, but, on the other hand, the centre of the outboard part it moves more and pulls out the extremities.

Fig. 7 indicates the distribution of plastic deformation, which is concentrated in the perforations region, like was expected. This fact represents the way by which the local geometry of the band was affected. In this region, the material suffers a plastic deformation and, as a consequence, the mechanical properties modify, fact which is very important for the column resistance analysis as structural element.

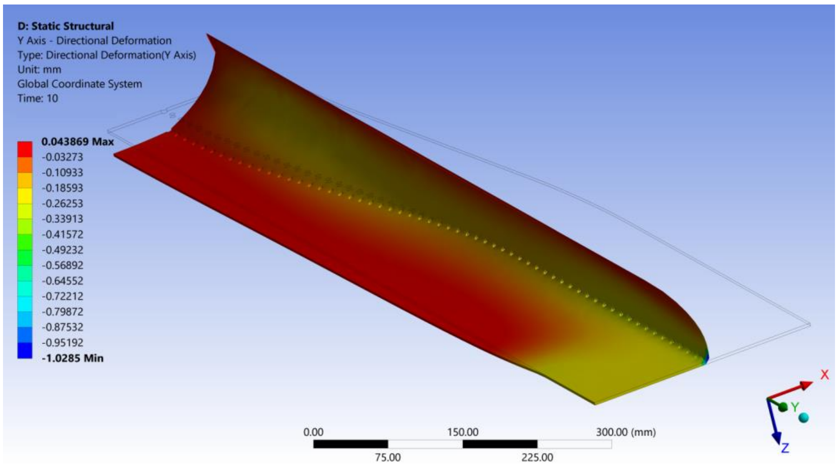


Fig. 7. The displacements on long axis direction (Y)

D. Phenomena details in folding region of the studied developed surface

- **Case 1 – the triangular gutter**

Like for any analysis, the mesh has been dimensioned, in order to minimize the calculus errors. Thus, the peak area, which is a stress concentrator, has beneficiate of more attention in present study, because the mesh quality is increased by number and dimensions of the finite elements. On the angle sides are presented contact elements. The used elements are of shell type, and the applied technology of planar tensions, because a section is concerned. In the peak area, due to the tensions which forms, the material suffers a displacement. The zone with the lower resistance is the oblique wall of the gutter.

Fig. 10 indicates where plastic deformations appear and the place where the material can break. At the bottom, the deformations are of extension, and provoke the displacement of the material and possible breaking. The direction of crack propagation is to the triangle peak, the crack being of type I, formed at material extension.

Fig. 11 shows the displacement of the median line, for which the stress is null. It is visible, also, the stress concentration in the triangle peak and in the zone of his projection on opposite side.

- **Case 2 – the trapezoidal gutter**

Like in triangular case, it has been used the most qualitative mesh for this case also. The zones with maximal deformations have moved to inferior trapeze corners. In this case, each corner will become a stress concentrator, the deformation distribution being much uniform. Unlike the anterior case, the plastic deformations are much small and much less present on opposite side of the gutter. However, the risk of crack apparition through extension remains at high level.

The von Mises stress shows the localization of the stress concentrators at the small base of the trapeze, which leads to two possible crack propagation ways (Fig. 15).

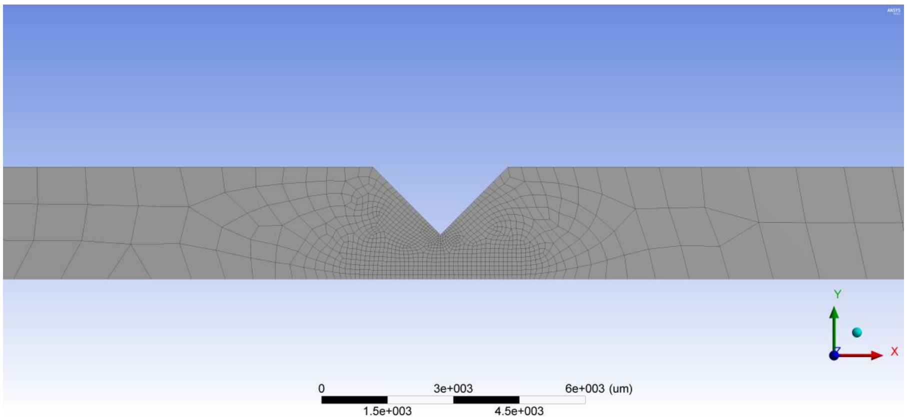


Fig. 8. Band meshing for a triangular gutter of deformation promoting.

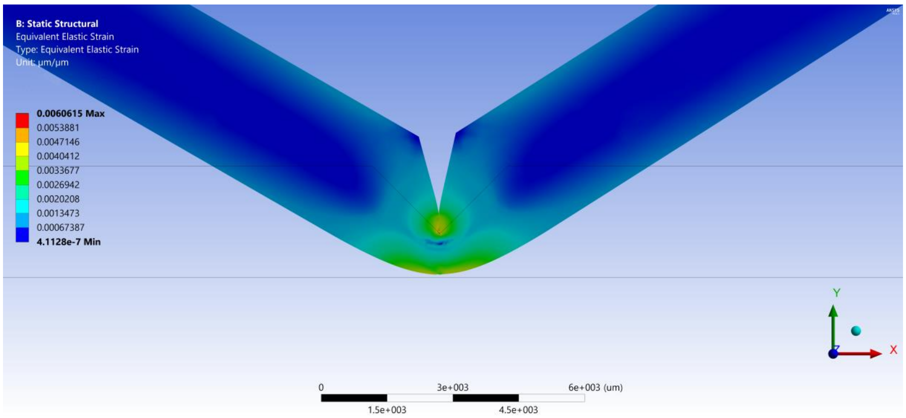


Fig. 9. The relative plastic deformation for the case of a band folding with an angle of 30°

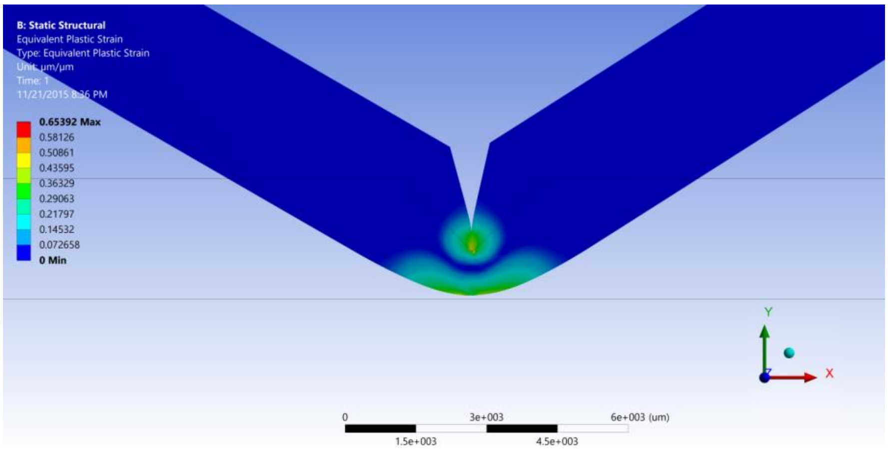


Fig. 10. In section plastic deformation distribution.

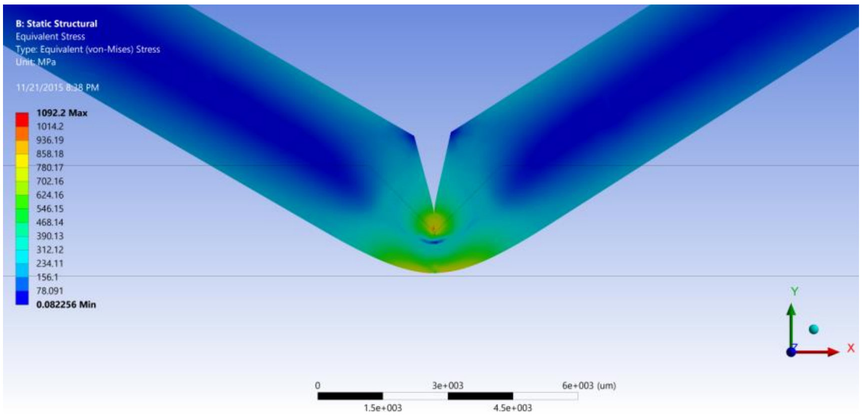


Fig. 11. The distribution of the von Mises stress in the section plan

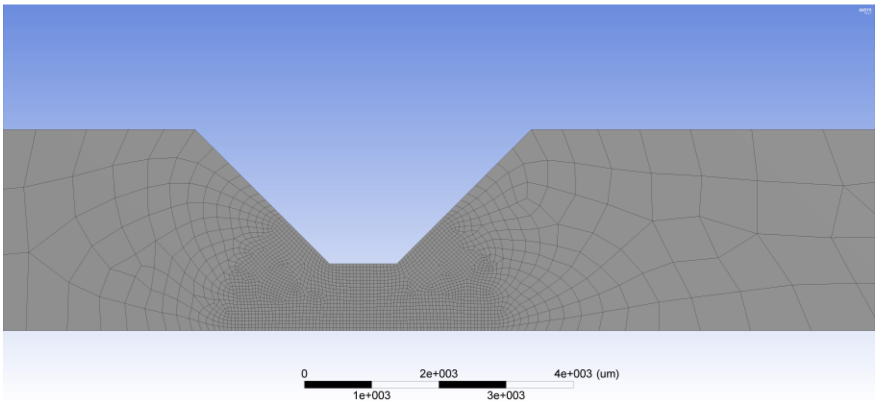


Fig. 12. Band meshing for a trapezoidal gutter of deformation promoting

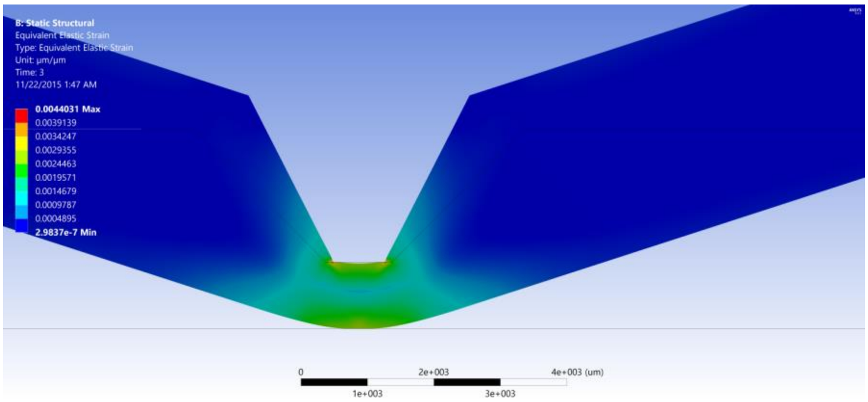


Fig. 13. The relative plastic deformation for the case of a band folding with an angle of 20°.

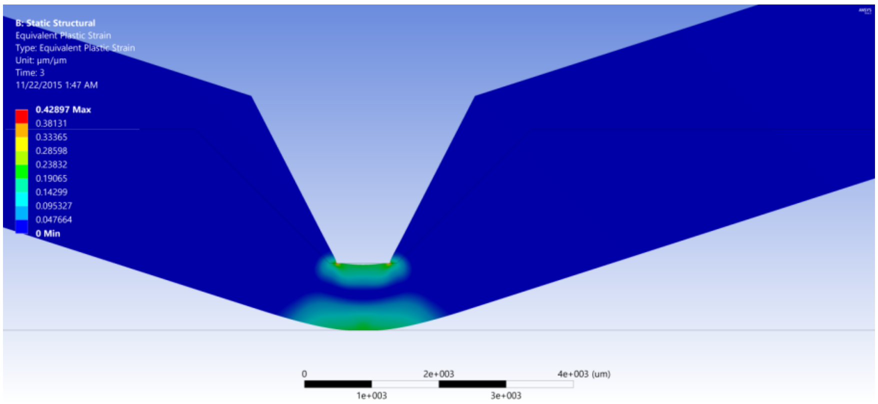


Fig. 14. In section plastic deformation distribution

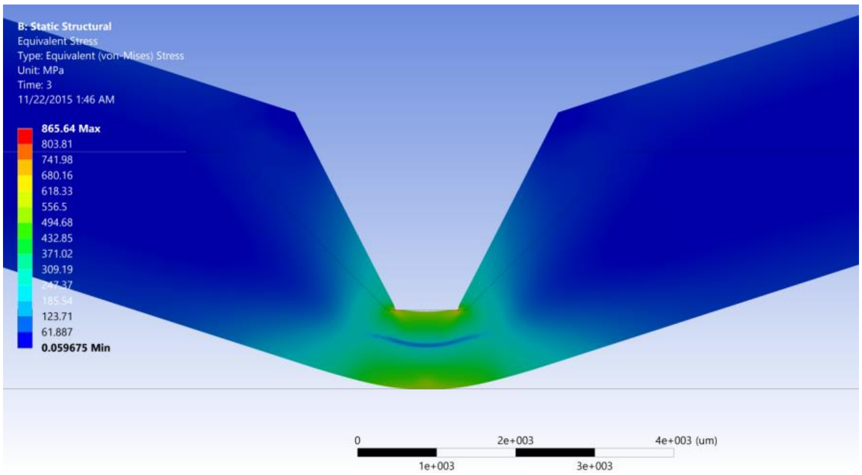


Fig. 15. The distribution of the von Mises stress in the section plan

E. The simulation of the real process of model execution

The real execution of the experimental model implies decisions referring to the metallic material selection, to the material thickness establishment and to the relaxation modality of the material in folding zone. The folding lines can be drawn through ebb gutters (which is a preferred variant for materials with large thickness, such as aluminium) or through successive circular or elongated perforations. The variant with elongated perforations is the most efficient and the cheapest from all tested. Moreover, this variant has an esthetical advantage, if column is enlightened from the interior side. Fig. 16 indicates some examples of above discussed variants by drawing the folding lines through ebb gutters, circular or elongated perforations.

a) **b)** **c)**

Fig. 16. Different grooves examples, used for folding lines in various models: (a) - Rusty Sheet Steel Chair – design by Max Lamb [16]; (b) – metal ring – design by Tove Knuts [17]; (c) - Chair – design by Felix Klingmüller [18].

4. The execution of the experimental model

The experimental model has been decided to be executed on the scale of 1:3, using a band from TDA steel for stamping, in format of 2000 x 1000 x 1 mm. All necessary coordinates of the column architectural model in developed area have been transferred to the operational program of the CNC stamping machine. Initially, has been selected the variant with ebb gutters, for which has been tried several depths; but the applied subsequent stamping has not reach acceptable results. Therefore, it has been chosen the variant with successive circular or elongated perforations, located on folding lines.

In Fig. 17, the models with circular perforations realized with different diameters and steps are indicated. Figs. 18 - 20 indicate the models realized with elongated perforations. The stamping process has been realized on CNC stamping machine, using a calibrated punch and die. The perforations processing has been followed by the folding stage along perforation lines. It has been applied two methods: stamping with articulated knifes, manually or electrical operated, and stamping with prisms, CNC hydraulic operated. After stamping process, the column constituents have been calibrated and welded.

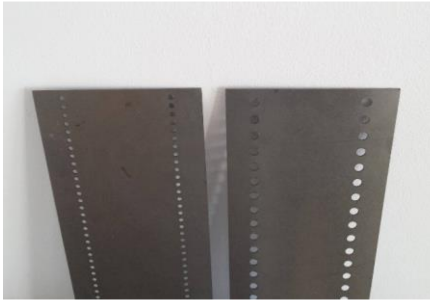


Fig. 17. Different stamping models with circular perforations

Fig. 18. The metallic experimental model (stamping with elongated perforations)

Fig. 19. Metallic prototype (stamping with elongated perforations)

Fig. 20. The metallic experimental model (stamping with elongated perforations)

The applied welding technology uses a controlled atmosphere, the welding cord being executed for inside zones, on reinforcements sides, in order to not affecting the visible areas and to assure the rigidity of the entire structure. After welding and finishing the exterior sides, it has been realized the anti-corrosive protection through sizing and liquid dyeing of entire experimental model. Generally, in function of architectural demands and selected material, this anti-corrosive protection can use other various technologies.

5. Conclusions

This experimental study aimed to highlight the advantages and disadvantages of the generative design process applied on metallic structural element with initial selected shape, using the *curved creased folding* method. Even if the designing process of an initial selected shape with a developable surface is proved to be a constrained design process, the main advantage is that it can be anticipated the distribution of the stress concentrators in the intended structure and, consequently, the structure mechanical behaviour. Knowing that, the folding process can be efficiently guided. Another advantage is that by applying a curved folding method to a developable surface of a structural element, it can be rich an aesthetical character also, by cumulating a decorative with the structural behaviour. Thus, the generative design tools can help the industrial designers to improve their creativity to obtain new efficient structural elements with interesting decorative role also.

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