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Visual diagnostics of physical quantities based on the functional-voxel modeling method

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Abstract

The paper proposes a method of functional voxel modeling (FVM) of stresses arising under the influence of a force or heat load in an isotropic body. We consider the principles of modeling the unit stress in a volume vector a geometric object, set by analogy with the normal vector with two parameters: the function of the value and the function of the angle of direction.The principles of constructing a functional-voxel model are demonstrated that allows a computer to graphically represent a three-dimensional vector as a set of M-images displaying local geometric characteristics of the obtained functional area.The possibilities of constructing stress fields from distributed loads by means of sequential addition of a single stress distributed in space are considered . The principles of constructing a single thermal stress and constructing distributed fields based on it are considered separately. Existing approaches are used to model the shape of thermal expansion of the body. The obtained visual images of stresses and strains are compared with the simulated results in the existing computational modules based on FEM. The advantages of visualizing the results obtained from the standpoint of accuracy and clarity of representation are demonstrated. The prospects of such an approach to modeling visual physical quantities in relation to the visual diagnostics of the part geometry are considered.

Keywords: Functional-voxel method, M-image, R-functions, three-dimensional vector, the local geometric characteristics.

Introduction

Despite the increased interest in the task of visualization of simulated physical quantities, to date, no hardware or software tools has been proposed that can provide an adequate result.Even obtaining the value of the stress at a specific point of an isotropic body entails calculations with relative to the values which can be measured by instruments [1,2] or are calculated by complex differential equations (FEM). For example, the resulting deformation of the body helps to simulate the intense field acting in this case. The fact that stress is a structural quantity that influences the design process is shown by developing new directions for designing optimal geometry of structures relative to premodeled stresses. Thus, there is a need to obtain local stress (stress from a point load) as a structural unit for a minimum site. The selection of such a stress element allows you to proceed to the design of stress fields of any configuration. Existing CAD design modules such as SolidWorks, PTC Creo, ANSYS, etc. [3] do not allow effective work with local stress and are focused on modeling grid regions. At the same time, any attempts to model the point load lead to a complex problem of singularity of the simulated mesh, which negatively affects the stability of the FEM calculation (Fig.1). The fact that stress is a structural quantity that influences the design process is evidenced by developing new directions in designing the optimal geometry of structures relative to previously modeled stresses. Thus, it becomes necessary to obtain local stress (stress from a point load) as a structural unit for a minimum site. The selection of such a stress element allows us to proceed to the design of stress fields of any configuration. Existing CAD design modules such as SolidWorks, PTC Creo, ANSYS, etc. [3] do not allow effective work with local stress and focus on modeling grid regions. Moreover, any attempts to simulate a point load lead to the difficult problem of the singularity of the simulated mesh, which negatively affects the stability of the FEM calculation (Fig. 1). Uniform thickening of the grid leads to an increase in the estimated time, and even to a lack of RAM in the computer.

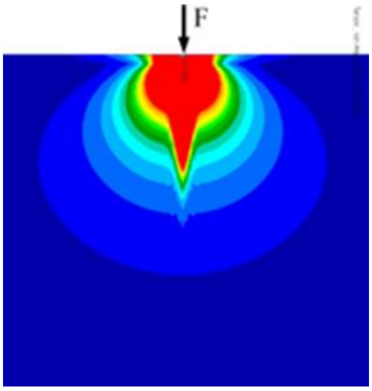


Figure 1: Example of the result of calculating the stress after applying the grid singularity at the point of force application

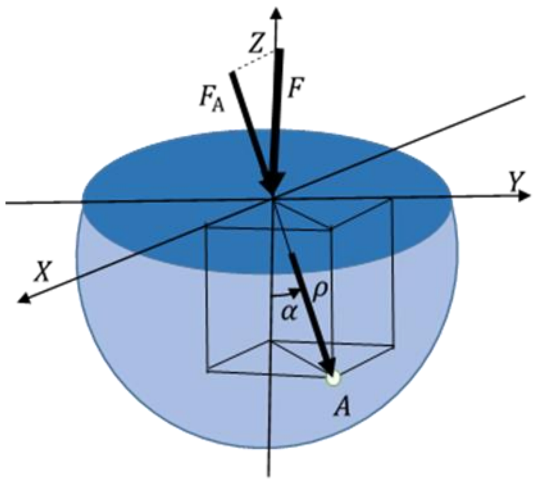


Figure 2: Distribution of the force flux in a area near of point of application of force

The approach to the construction a local stress model considered in the article is one of the directions of a whole series of studies conducted by prof. Tolok A.V.It is devoted to the application of the functional voxel modeling method (VFM) [4] in solving engineering problems of the life cycle.Prior to this, such problems as finding the path with obstacles [5], problems of geometric modeling [6], problems of calculating the integral values of objects of complex geometry [7], solving mathematical programming problems [8], etc. were considered.The basis of the PCM method is the principle of organizing symbolic and graphical information on a computer that combines the analytical form for describing the space of a function $f(x_n) = 0$ with a multidimensional model of a voxel representation of its local geometric characteristics. That is, any continuous function of the form $f(x_m) = 0$ in a given space m can be represented as a computer model containing a linear polynomial $n_1x_1 + n_2x_2 + \dots + n_{m+1} = 0$ (local function) at each point in this space, describing it tangent. In this case the normal components $(n_1, n_2, \dots, n_{m+1})$ are aligned with the gradation of the color palette, and each such component forms its own m-dimensional voxel.As a result, the space of the original function of m-dimension can be represented on the computer by the number of voxel images equal to $m + 1$. Such an approach allows one to obtain differential and integral characteristics for research at points of a functional multidimensional domain in a computer representation [9].

The proposed approach to computer modeling of local stresses is based on the theory of strength of materials [10], which relates to the study of tensor elements. With the transition to grid methods of calculation (FE, MGE, etc.), the theoretical aspects of this subject are undeservedly reduced to student study and are rarely used in computer practice.This is due to the fact that the approaches of strength of materials describe the principle of modeling stress at a single point of application of force and writes the law for the selected slope of a given cross section. Having settled on this, the theory of sopromat does not allow simulating the transition from the vector of the applied force to the volumetric stress vector, as a geometric object that occurs in a solid isotropic medium and allows modeling of local stress.

1. Volume vector

We introduce the geometric concept of a volume vector as a unit of the volume distribution of a force vector in a solid isotropic medium.
Definition. A *volume vector* should be understood as a geometric object, defined by analogy with a conventional vector (as a directed segment from the starting point, having an angle of direction α and a distant of ρ), however, the direction function $\alpha(\alpha)$ and the function of the value p(p) are defined for the starting point.

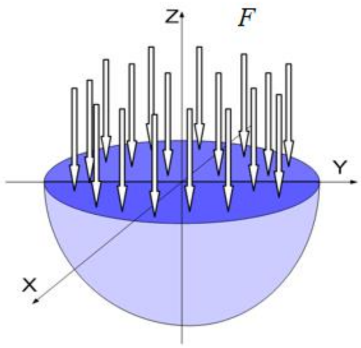


Figure 3: Directional Flow force F

For example, we simulate the volume vector of local stress arising in a solid isotropic body as a result of the action of a vertically applied force vector. In this case, the force application point is considered the starting point of the volume vector. Let's start by building the function $\rho(\rho)$. To do this, it is necessary to determine certain conventions, without which it is impossible to ensure the transition from a continuous law, characterized by infinite approximations, to its discrete model. We localize the point of force application by certain unit neighborhood, i.e. sphere with a unit surface are $S^1 = 4\pi R^2$, где $R = 1/(2\sqrt{\pi})$. We generalizes the law by adding the variable parameter ρ as an increment of the distribution radius of the force vector $S = 4\pi(R+\rho)^2$. Opening the brackets and transform the right part, we get $S = 1 + 2\sqrt{\pi}\rho + 4\pi\rho^2 = 1 + \rho/R + 4\pi R^2$. Considering that the increase in the area under the applied force acts inversely with the applied force F, the desired law ρ can be written as $\rho(\rho) = 1/(1 + \rho/R + 4\pi\rho^2)$. Further, it should be noted that in the case of the application of the force F to the surface of a solid body, the considered neighborhood of the point turns into a hemisphere, which means that the law changes to $\rho(\rho) = 2/(1 + \rho/R + 4\pi\rho^2)$ respectively.
Now let's turn to the construction of the law $\alpha(\alpha)$. Figure 2 demonstrates the principle of projecting the force F on a perpendicular to the main site of normal stress. The perpendicular to such a site is determined by the direction of the straight line passing between the point of the body under consideration A and the application's point of force F (the starting point of the volume vector). The projection of the force $F_A = F cos\alpha$. Next, we should return to physical conventions and understand that the applied force must have some of a planar neighborhood's radius of the application, in our case, the radius of the neighborhood is taken as R.
Figure 3 shows the cross section of the application of force F in the form of a directed flow to a flat area bounded by radius R. Taking the body as an infinite beam of bounded planes intersected at point $\boldsymbol{A}$ you can imagine an infinite number of rotatable minimal neighborhoods with the unidirectional flow of force F applied to them (Fig. .4a). Figure 4b demon-

strates a separate case of such a turn of the neighborhood relative to the flow F, where there is a decrease in the number of flow elements (in the form of arrows) falling on the site of the neighborhood area when turning by the angle αIn Fig. 4b, the rotation is shown by the arrow. Given the obtained property, the projection F_A takes the following form: $F_A = F\cos\alpha\cos\alpha = F cos^2\alpha$.

Figure 4: Changing in load flow when a single neighborhood is rotated

Combining the functional laws *of* $\rho(\rho)$ and $\alpha(\alpha)$by multiplication, we obtain the general functional law for constructing the volume stress vector $\sigma = V(\rho(\rho), \alpha(\alpha))$:

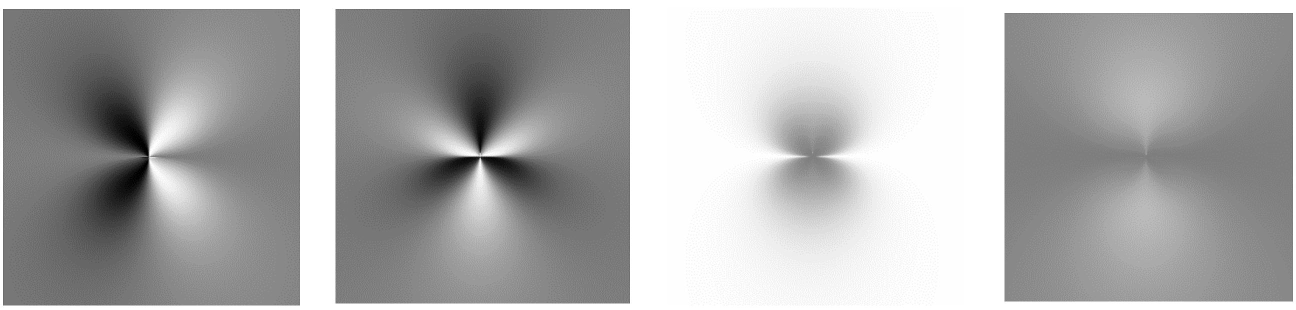
$$\sigma = \frac{F cos^2\alpha}{1 + 2\frac{\rho}{R} + 4\pi\rho^2}, \qquad R = \frac{1}{2\sqrt{\pi}}. \tag{1}$$

If the origin of the coordinate system is set at the application's point of force, then $\rho(x, y, z) = \sqrt{x_A^2 + y_A^2 + z_A^2}$. In this case, it is also easy to calculate the value $\cos\alpha$.

2. Functionaly voxelny model of arrea pressure

In [3], the process of constructing a functional voxel model for the domain of analytic function is described in sufficient detail. It will ensure the transition of the analytical continuous representation of the volume vector function σ to a discrete functional-voxel computer representation. In this case, a computer organization of voxel images is created that provide an area's description of the domain's volume vector function at the presentation's level by its local geometric characteristics. For illustration purposes, Figure 5 illustrates an example of a two-dimensional representation of the central section in the xOz plane of a volume vector in the form of four model images (M-images). The first two M-images store information about the normal components n_1 and n_2 on the Ox and Oz axes, т the third M-image represents the values of the n_3 component for the σ value axis , and the fourth M-image is the n4 component and provides the necessary information to determine the position of the normal on the function area. Moreover, the function $\sigma = V(\rho(\rho), \alpha(\alpha))$ is replaced by a local function of the form

$$\sigma = \frac{n_4}{n_3} - \frac{n_1}{n_3}x - \frac{n_2}{n_3}z, \text{ where } n_l = \frac{2\left(C_l - \frac{P}{2}\right)}{P}, \ l\text{=1...4}, \ \text{P=256 – halftone palette.} \tag{2}$$



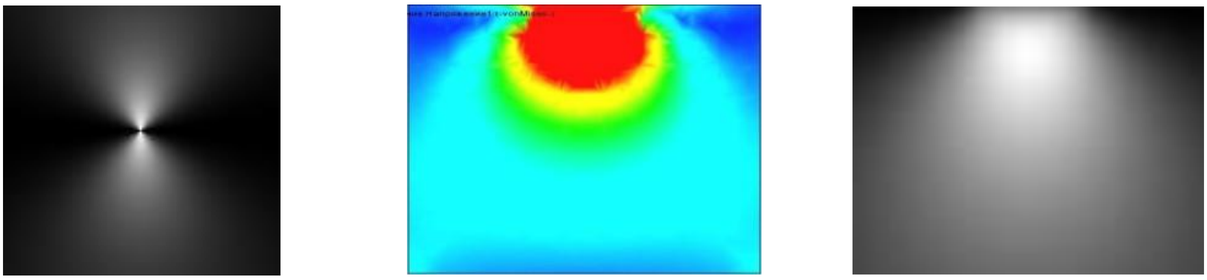
C_1 C_2 C_3 C_4

Figure 5: M-images depicting local geometric characteristics of the unit for a single normal stress

Calculating σ using the formula (2) allows us to calculate the palette for the image of the unit stress values:

$$c^{l}_{i,j} = \frac{256\sigma_{i,j}}{F}. \tag{3}$$

Figure 6a shows an image of normal values for a unit pressure distributed over a tone gradation.



a b c

Figure 6: Visualization of the normal stress during localization of the power load: a) Image of the unit stress by the FVM method, b) Image of the pressure when the load localization by the FEM method, c) distribution of the unit vector over the local area of the force application by the PCM method.

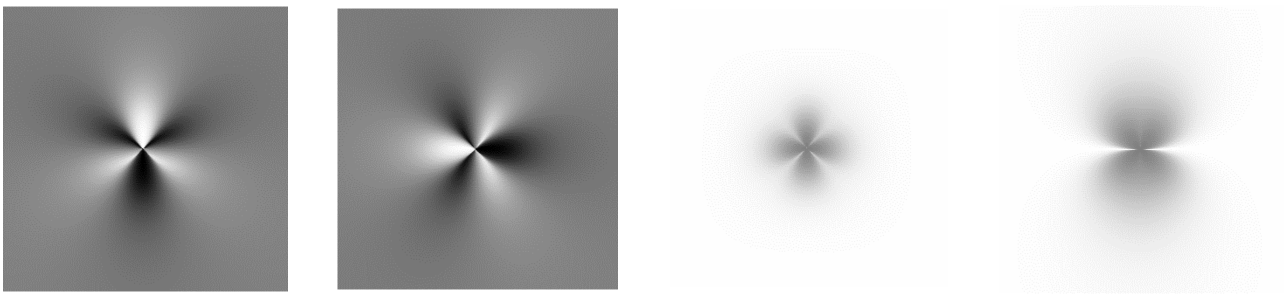
Figure 6b is presented for comparison. It was obtained on the FEM grid when trying to set the minimum area of force application. It is clear that it is not possible to bring such a localization to a single point as it is done in the FVM, however, it will not be difficult to solve the inverse problem of reducing the unit stress at the point (Fig.6a) obtained by the FVM to a distribution over a certain area of the minimum areas'section values of unit stresses, taking into account their spatial location. Figure 6c shows the distribution of unit stresses for the local loading section. It should be noted that the results are similar to Figure 6b, but the image (6c) obtained by the sum of unit stresses is more attractive, since it looks continuously smooth in accordance with the physical law itself and its image is stable to changes in the space discretization step and does not depend on the shape mesh element simulated for FEM.

3. FV-model of tangent unit stress

Since the tangent stress is orthogonal to the normal one, the module of the volume vector model $\tau = V\big(\rho(\rho), \alpha(\alpha)\big)$ takes the form

$$\tau = \frac{F \sin\alpha \cos\alpha}{1 + 2\frac{\rho}{R} + 4\pi\rho^2}, \qquad R = \frac{1}{2\sqrt{\pi}} \tag{4}$$

At the same time, M-images of the created FV-model display the corresponding local geometric characteristics on the considered function area (Fig. 7).



C_1 C_2 C_3 C_4

Figure 7: M-images displaying local geometric characteristics for a unit tangent stress

In Figure 8, by analogy with the sixth figure, the results of modeling images of tangent stresses applied to the minimum area inside the body are shown sequentially. Figure 8a is derived from M-images and a local function

$$\tau = \frac{n_4}{n_3} - \frac{n_1}{n_3}x - \frac{n_2}{n_3}z, \text{where } n_l = \frac{2\left(C_l - \frac{P}{2}\right)}{P}, \ l\text{=1...4}, \ \text{P=256 – halftone palette} \qquad (5)$$

The image in Figure 8b depicts the result of displaying the image of tangent stresses for a local load, modeled by the FEM method. The red region is the region of maximum positive values of the function τ, and the blue region is negative - the minimum. A similar simulation using the FVM allows you to get an image similar in content, but only with a more pronounced smooth shape of the formed stress surface.

a b

Figure 8: Visualization of the tangential stress during localization of the power load: a) Image of a single voltage using the FVM method, b) Image of the stress during localization of the load using the FEM method

4. Temperature unit stress

To build an image of a unit of temperature stress, you can use the rules for constructing a volume vector, the principles of which are described in the first paragraph. In this case, the direction's absence of the applied temperature should be taken into account, which means that the function $\alpha(\alpha) = 0$, and the value of the temperature applied to the surface of the body allows us to use the function of the value $\rho(\rho)$ to model the stress distribution in the body. An analytically volume vector for a unit of temperature stress can be written:

$$\sigma_\theta = \frac{2\theta}{1 + 2\frac{\rho}{R} + 4\pi\rho^2}, \qquad R = \frac{1}{2\sqrt{\pi}},$$

where θ is the temperature applied at a point on the boundary of the body.
Functionalvoxel model is determined by similarity with the voltage arising from the force effects and leads to a similar local function

$$\sigma_\theta = \frac{n_4}{n_3} - \frac{n_1}{n_3}x - \frac{n_2}{n_3}z,$$

where

$$n_l = \frac{2\left(C_l - \frac{P}{2}\right)}{P}$$

, l=1...4, P=256 – halftone palette.

Figure 9 presents M-images characterizing the local geometric characteristics in the considered area.

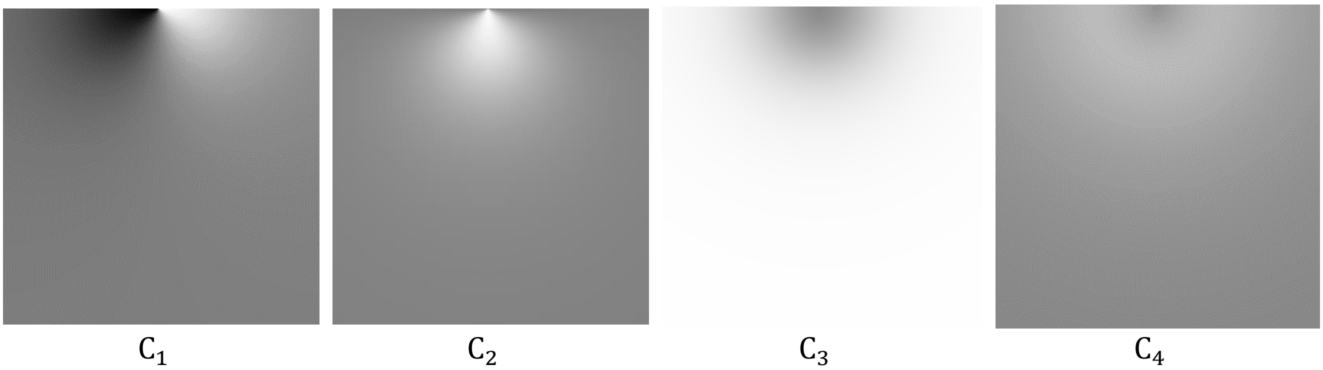


Figure 9: M-images showing local geometric characteristics for a single temperature stress

Figure 10a shows the result of modeling images of temperature stress applied at a surface point on the surface of an isotropic body by the proposed approach. For visual comparison the obtained model calculation results by analogy with the previous cases, the results of the calculating the same problem using the FEM method are presented (Fig. 10b). The distribution of temperature load is carried out by ordinary summation of point loads uniformly distributed along the selected direction. Figures 10b, d show the result of heat load distribution along the Ox axis for both approaches, respectively. The results show the shape of the resulting temperature distribution is identical in both cases.

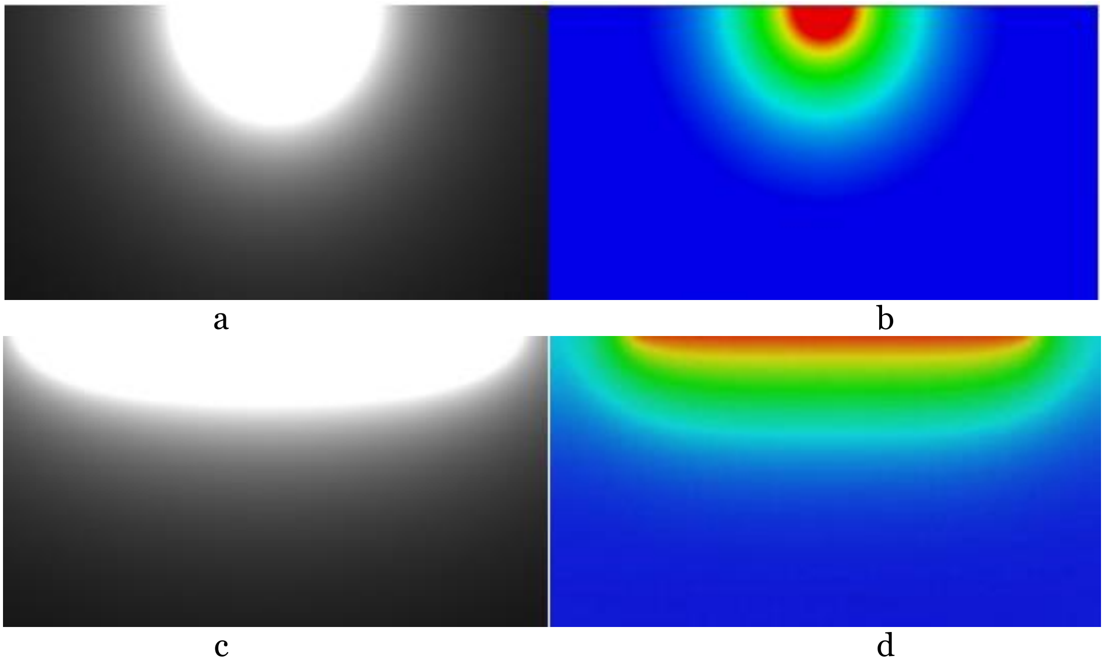
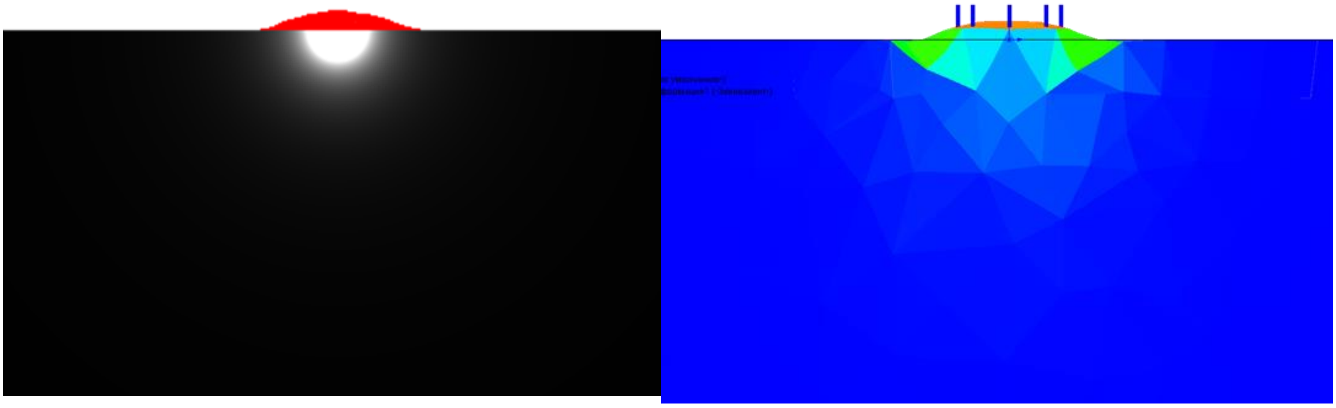


Figure 10: Examples of visualization of thermal stress simulation results: a) Calculation of thermal stress for the temperature applied at a point by the FEM method, b) FEM method for the same task, c) Calculation of thermal stress for the distributed temperature by the FEM method, d) the FEM method for that same task.

5. Modeling of local thermal expansion

The thermal expansion of the material is an important parameter for any mechanical process. Its accounting is necessary in various technologies related to the accuracy of material processing, etc. Consider the problem of modeling the shape of thermal expansion for the possibility of visual diagnostics. Based on the obtained functional-voxel model, which allows one to obtain σ_θ values for each point of the considered area without any difficulties, the shape of the additional relative volume is simulated with the expected expansion of the material depending on temperature values:

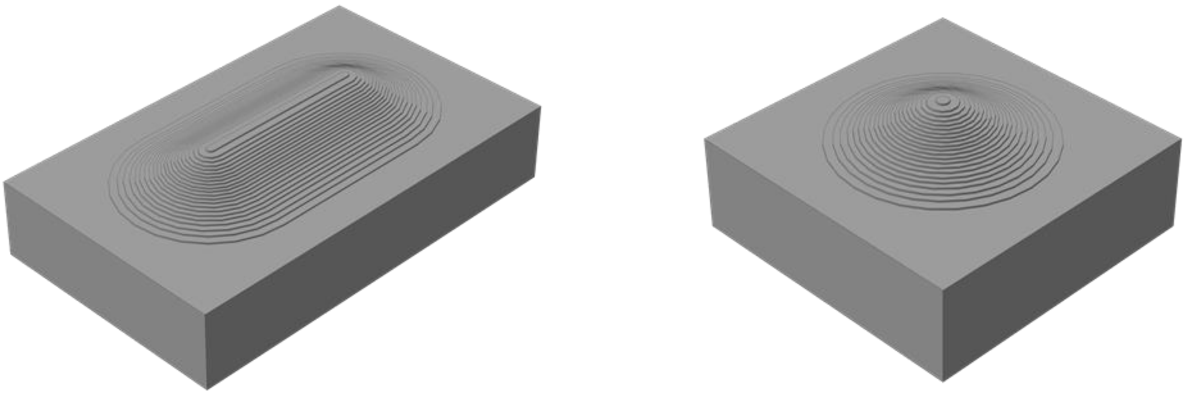
$\Delta V = \alpha_V V \sigma_\theta$,
where α_V – coefficient of thermal expansion.
Figure 11a, b gives an example of the result of modeling the shape of thermal expansion by the proposed method and the FE method on a triangulated grid for visual comparison. In both cases, the result was obtained in a comparable time period of calculation.There is an obvious difference in the visibility of presenting the same result for the case of using the voxel (Fig. 11a) and polygonal (Fig. 11b) models.



a b

Figure 11: Visualization's examples of the thermal expansion results of modeling : a) calculation of the cross section shape of the thermal expansion of the material for the temperature, applied at the point by the FWM method, b) calculation of the cross section shape of the thermal expansion of the material for the temperature, localized small neighborhood by the FEM method.

Figure 12 shows an example of spatial modeling of the form of thermal expansion, constructed by the functional-voxel method as one of the means of visual diagnostics of the thermal process.



a b

Figure 12: Examples of constructing the form of thermal expansion: a) For uniformly distributed thermal loading, b) For point thermal loading.

6. Conclusion

In this paper, we considered the means of local geometry in computer representation for modeling physical quantities. At the present stage, geometric modeling accompanies engineering tasks, limited to the procedure for constructing a finite element mesh and its adjustment. Further, methods related to mathematical physics are based on the construction of complex differential equations enter into the calculation. At the same time, the local (differential) geometry, which is intended for the subsequent stage of modeling physical quantities on the minimal sections of the object, has not yet received its computer representation. The main advantage of the proposed approach is the absence in the differential equations' calculations of the grid decomposition used in the FEM. The discretization of the function space proposed in the FVM basically contains the derivation of differential characteristics that make it possible to model complex physical processes with simple algebraic expressions of laws. Additional advantages of the proposed approach can also be considered the possibility of significantly simplifying the calculation at the investigated point in space, as well as the possibility of parallelizing the computational process with the existing simplest means. The prospect of further research is to develop tools modeling more complex problem statements for engineering calculations based on the developed approach.

References

[1] Device for measuring mechanical stresses in metal products // RF Patent No. 2079825. 1997. Zhukov S. V., Zhukov V. S.

[2] Method for determining mechanical stresses and a device for its implementation // RF Patent No. 2195636. 2001. Zhukov S. V., Zhukov V. S., Kapitsa N. N.

[3] *A.B. Kaplun, E.M. Morozov, M.A. Olfepyeva* ANSYS in the hands of an engineer: Practical guide/ M. Book house «LIBROKOM», 2015. – 272 p.

[4] *Tolok A.V.* Functional-voxel method in computer modeling. – Moscow.:Phismatlit, 2016. 105 p.

[5] *Grigoryev S.N., Tolok N.B., Tolok A.V.* Local Search Gradient Algorithm Based on Functional Voxel Modeling // Programming and Computer Software. 2017. Vol. 43, No. 5. C. 300–306.

[6] *Maksimenko-Sheyko K. V., Sheyko T. I., Tolok A. V.* R-function in the analytical design using a system of "RANOK"] / / Vestnik MSTU "Stankin". Scientific peer-reviewed journal. M.: MSTU "Stankin". №4(12). 2010. P. 139-151

[7] Tolok, A.V., Silantyev D. A., Lotarevich E. A., Pushkarev S. A. Voxel-mathematical modelling at the solution of problems of determining the area of surfaces // Information technologies in designing and manufacturing No. 3, 2013, 29-33.

[8] *Tolok A.V., Tolok N.B.* Mathematical Programming Problems Solving by Functional Voxel Method // Automation and Remote Control. 2018. Volume 79, № 9. pp 1703–1712.

[9] *Tolok N.B., Tolok, A.V.,* Functional voxel method, computing / Scientific visualization. M.: MEPhI. 2017. Vol. 2, vol. 9. P. 1-12 http://sv-journal.org/2017-2/01.php?lang=ru

[10] *Starovoitov E. I.* Strength of materials. — M.: Phismatlit, 2008. — P. 384. — 1000 copies. — ISBN 978-5-9221-0883-6