APPLICATION OF MATHEMATICAL MODELLING IN THERMAL STRAIGHTENING OF SHIPBUILDING PANELS

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Described is an example of application of mathematical modelling for investigation of the efficiency of the process of thermal straightening of shipbuilding panels, based on the approach of a combined use of the general thermoplasticity method and approximate shrinkage function method. It is shown that the approach suggested is particularly efficient for prediction of general distortions of large-size spatial structures in the case of a large number of welds contained in them or of local heatings used for straightening. The results of experiments on thermal straightening of shipbuilding panels with buckling distortions have been analysed, and objective factors limiting the efficiency of this technological operation, especially with large thicknesses of the panels, have been revealed.

Keywords: *thin-sheet welded structures, shipbuilding panels, welding distortions, thermal straightening, mathematical modelling, thermoplasticity method, shrinkage function method*

Modelling of the processes of welding or thermal straightening of large-size structures by the finite element and thermoplasticity methods involves problems associated with the required accuracy of solution. Firstly, a large-size structure has to be broken down into a large number of elements, compared with an individual piece, this requiring substantial computing resources and time for computation. Secondly, the problem becomes even more complicated when it is necessary to model a large number of welds or local heatings used for thermal straightening. All this makes finding a solution hardly possible.

General distortions of large-size structures can be determined by using the approximate shrinkage function method, which works within the ranges of the elasticity theory, as the general distortions or displacements of points of a welded structure are an integral characteristic, and just insignificantly depend upon the character of distribution of the shrinkage function (especially at some distance from its application). The study by E.O. Paton [1] can be considered the basic one dedicated to this subject. The study described a comprehensive investigation of residual welding stresses induced in cylindrical vessels by making of circumferential and longitudinal welds, as well as by welding of a bottom, welding-in of branch pipes, etc. Until now this study has not lost its scientific and practical interest. The idea suggested in it for estimation of residual welding stresses by the elasticity theory methods on the basis of a preset value of longitudinal shrinkage deformations, which are determined experimentally from simple tests, found application in a large number of studies [2–8]. The generalised description of the shrinkage function methods is given in study [2].

Figure 1. Sample of shipbuilding panel

A series of experiments was carried out to study the efficiency of thermal straightening of shipbuilding panels with buckling distortions on samples of a limited size (1300 × 1300 mm), prepared with allowance for design peculiarities, a technology and material identical to those of a real shipbuilding panel (Figure 1). A sample of the panel consisted of a skin sheet panel 6 mm thick with longitudinal and transverse frameworks welded in such a way that two buckling zones 600 × 1200 mm in size were formed between the frameworks. The value of buckling had a minus sign (deflection) in the majority of cases and was not in excess of 3–7 mm.

Thermal straightening was performed by heating of both round spots and strips 150 mm long using the indirect-action plasma heat source (effective power $Q_{\rm eff}$ = 1100 W, concentration coefficient K = = 0.004 $1/{\rm mm}^2$), flame heat source ($Q_{\rm eff}$ = 2500 W, K = 0.005 $1/{\rm mm}^2$) and laser source with a defocused beam (Q = 2800 W, uniform distribution of power in a round spot with diameter $D_{\rm h}$ = 24 mm).

Results of the experiments conducted on samples showed a very low efficiency of thermal straightening of buckling distortions. The effect of substantial local bending deformations with a minus sign (deflection) caused by non-uniform heating of the metal sheet through its thickness was observed for almost all heatings. This can explain the fact that the buckling distortions can be decreased only at a positive sign (flexure) of buckling. Therefore, the straightening process was performed not by tension of the skin sheet due to

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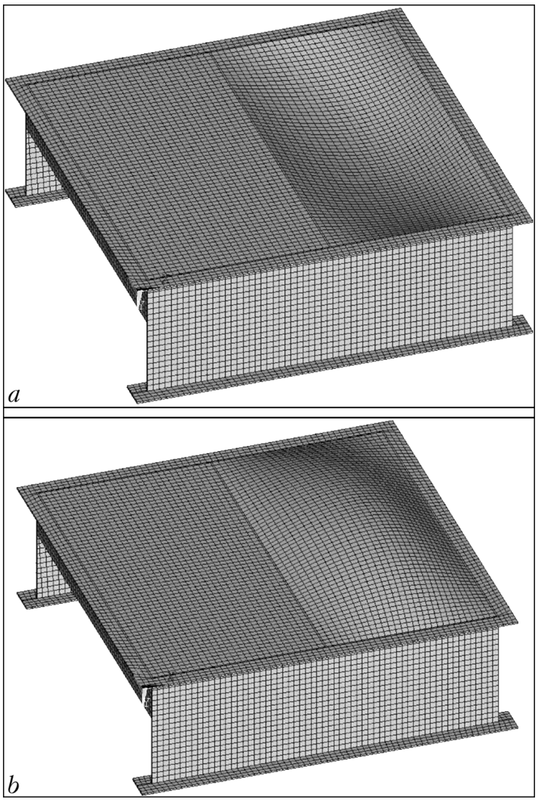

Figure 2. Finite element model of sample of a shipbuilding panel with buckling distortions of its skin: *a* — deflection; *b* — flexure

shrinkage in the sheet plane, but as a result of local bending deformations within the heating zone.

Modelling of the process of thermal straightening on the above experimental samples by using the ANSYS commercial software package was carried out to study this type of the problems. A model of the shipbuilding panel broken down into the finite elements (approximately 240,000 elements) is shown in Figure 2. Heatings were set in the form of additional shrinkage deformations in the skin sheet plane. A solution for general distortions and displacements of points of the skin sheet and stiffeners of a sample in a 3D statement of the problem was sought within the ranges of the elasticity theory by using the shrinkage function method, which is approximate and does not account for the history of formation and development of plastic deformations. Therefore, the developed model failed to determine the effect of a sequence of heatings on general distortions of a panel sample. Advantage of the shrinkage function method over the general thermoplasticity method is the possibility of obtaining a solution for general distortions of complex spatial structures with a large number of heatings.

Modelling of the process of thermal straightening on an experimental panel sample was performed when the skin of one panel had a buckling distortion, i.e. uniform deflection or flexure from the skin plane. Corresponding finite element models of a shipbuilding panel sample with buckling distortions are shown in Figure 3, *a, b*. Each model includes fixation of the sample at four points in corners along the contour against displacements from the skin sheet plane. Shrinkage deformations induced by heating of one strip 150 mm long were set equal to Δ_{tr} = 0.3 mm and Δ_l = 0.1 mm (in the transverse and longitudinal directions with respect to the heating strip), which approximately corresponded to real values in flame heating of such a strip [9, 10].

As shown by the calculation results, displacement of a skin sheet to 1.5 mm took place under the effect of shrinkage deformations induced by heating of one strip 150 mm long, located at the centre of a buckle

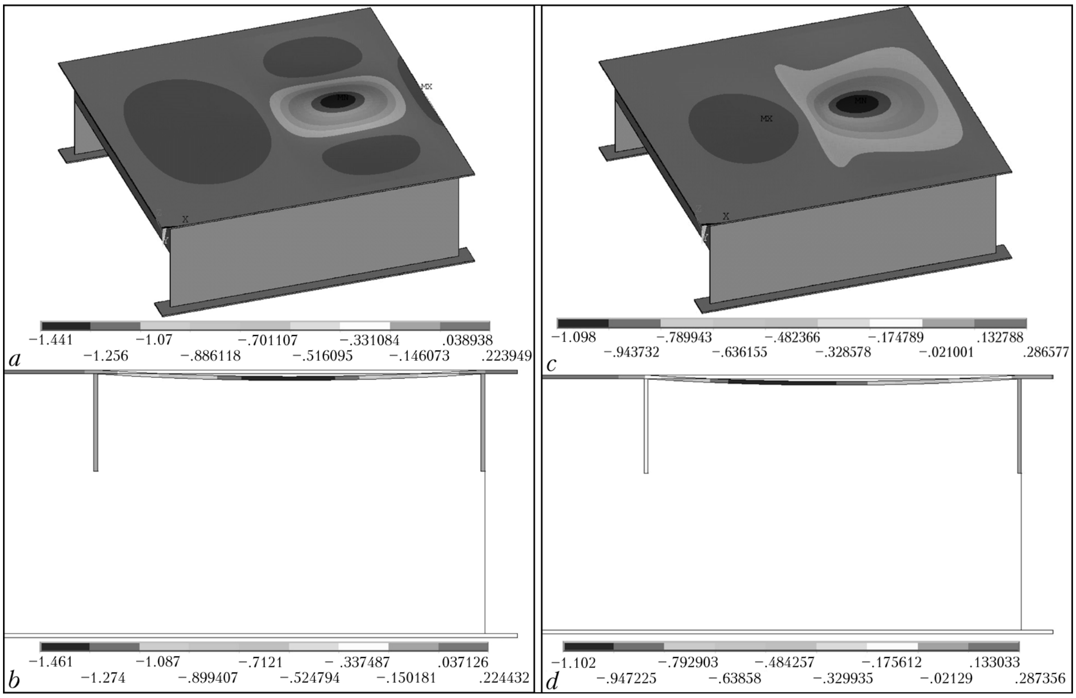

Figure 3. Displacements U_y (mm) from the skin sheet plane (decrease in buckling) under the effect of shrinkage deformations induced by heating of one strip 150 mm long: *a*, *b* — location at the centre of buckle; *c*, *d* — location at the end of buckle at a distance of 70 mm from stiffener; *a*, *c* — displacements on a general view of the panel sample; *b*, *d* — cross section at the centre of buckle

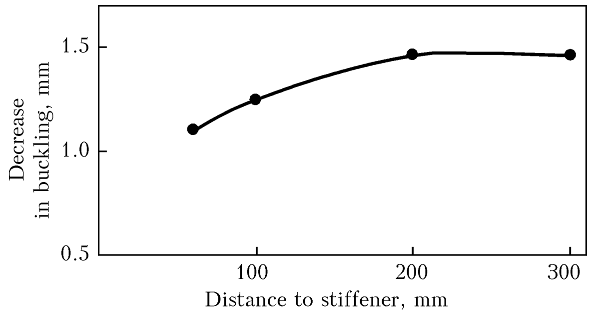

Figure 4. Decrease in the efficiency of straightening with displacement of a heating strip from the buckle centre to stiffener (framework)

(Figure 3, *a, b*), i.e. the buckling distortions decreased from 10 (initial value) to 8.5 mm. The calculations also showed that displacement of the heating strip from the centre of a buckle to a stiffener (to 70 mm from the framework) diminished the effect of straightening approximately by 25 % (Figure 3, *c, d*). Location of heating strips at the central part of a buckle is most efficient (Figure 4).

An important effect in terms of understanding of the thermal straightening process mechanism was revealed by calculation of decrease in buckling induced by one heating strip located at the centre of a buckle at different values of the initial buckling (2, 3, 5, 10, 15, 20 and 30 mm). The calculation results in Figure 5 show that the efficiency of straightening (decrease in buckling) first dramatically grows with increase in the initial value of buckling, then becomes constant, and further on decreases to some extent at high values of the buckling. At a zero buckling, i.e. in the absolutely plane sheet, the shrinkage due to heating in the sheet plane does not cause any displacement from the plane. This effect is in agreement with practical observations, i.e. it is more labour-consuming to straighten small buckles by the thermal method than big buckles. This effect can be explained by the fact that a decrease in buckling, i.e. bend of a sheet, depends upon the arm of application of shrinkage forces. The bigger the buckling, the higher the bending moment caused by shrinkage. At the same time, the skin sheet takes the spherical shape after the buckling reaches sufficiently high values, this leading to increase in bending resistance of the skin.

Therefore, as shown by the calculation results, straightening of buckling distortions under the effect of shrinkage deformations induced by heating of a

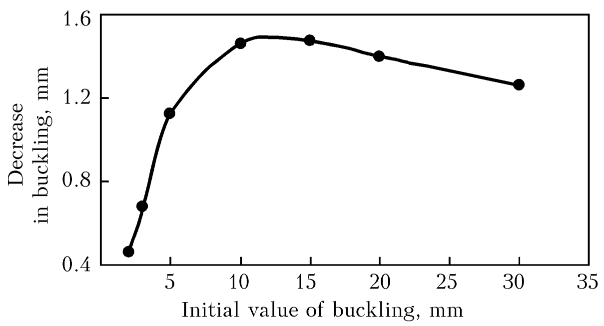

Figure 5. Dependence of the efficiency of straightening upon the value of buckling

strip features a marked efficiency for the shipbuilding panel sample under consideration. Moreover, this efficiency of straightening does not depend upon the sign (direction) of the initial buckling distortion. However, the calculations were made with no account for local bending deformations induced by non-uniformity of heating of the skin sheet. These bending deformations, which always cause deflection of the skin sheet, will contribute to decrease in buckling at the initial buckling distortion, while at the deflection buckling distortion they will partially or fully compensate for the effect of straightening due to shrinkage deformations. As bending deformations occur almost with any heat source, to ensure the efficiency of straightening it is necessary that the positive effect of shrinkage deformations in the sheet plane be much higher than the effect of bending deformations.

The numerical algorithm based on the thermoplasticity method, i.e. on tracing of temperature fields and evolution of elasto-plastic deformations in a sheet sample with a size of 500 × 500 mm and 6 mm thick in the 3D statement of a problem was used to determine residual shrinkage deformations and local angular deformations for the case of heating of a strip with a moving heat source (material — low-carbon steel).

The data on temperature fields were obtained by using the numerical method for solving the thermal conductivity problem within the limits of the 3D model for a range of $0 \le x \le 500$ mm, $0 \le y \le 500$ mm and $-\delta/2 \le z \le \delta/2$ at initial temperature $T_0 = 20$ °C, where heat transfer with an environment having a temperature of 20 °C, following the Newton's law, is set for all the surfaces at surface heat transfer coefficient $\alpha_h = 0.00004$ W/(mm^2·°C). The surface heat source with power Q_{eff}, distributed over the surface following the normal circular law, with concentration coefficient K, acts on surface $z = -\delta/2$. The centre of the source at a moment of $0 < t < t_0$ is located at a point of $x = x_0$, $y = y_0$, then it moves at speed v along axis x at $t > t_0$. The movement ends at $t - t_0 = L/v$, and levelling of the temperature takes place.

Numerical experiments were conducted by using the indirect-action plasma source, flame (acetylene) heat source, which is widely applied now, and laser heat source holding promise for application in the near future. Experimentally measured effective power $Q_{eff} = 1100$ W and concentration coefficient $K = 0.004$–0.010 1/mm^2 were set in the calculations for the plasma heat source. $Q_{eff} = 2500$ W and $K = 0.004$ 1/mm^2, corresponding to a torch employed for thermal straightening at a thickness of 6 mm, were set for flame heating. Effective power $Q_{eff} = 2800$ W and a uniform distribution of power in a round spot of the defocused laser beam with diameter $D_h = 24$ mm were set for the laser heat source.

The calculation results show that the temperature gradient through thickness of a sheet heated strongly depends upon power Q_{eff}, concentration coefficient K and the speed of movement of a heat source in heating of a strip with length $L = 150$ mm. For the plasma

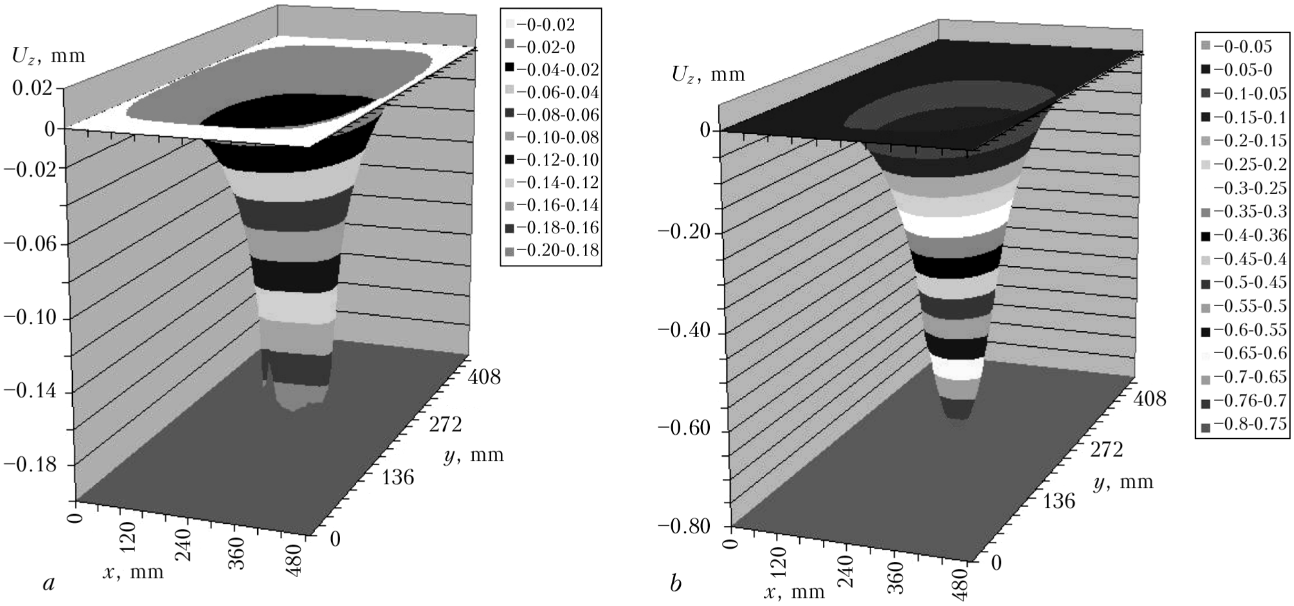

Figure 6. Distribution of residual deflections U_z (x, y) for flame (a) and laser (b) heat sources

heat source, the difference in heating temperatures at the upper and lower surfaces was approximately 40--60 °C, and maximal deflections were not in excess of 0.1 mm. The higher effective power (2--2.5 times) of the flame and laser heat sources, compared with the above plasma source, and, hence, the higher movement speeds of the sources cause a more substantial non-uniformity of distribution of temperature through thickness of the sheet. This explains the sufficiently high values of maximal deflections caused by local residual bending deformations. For the flame heat source, depending upon concentration coefficient K, the difference in heating temperatures on the upper and lower surfaces was approximately 100--160 °C, while for the laser heat source this difference amounted to 300 °C, depending upon its movement speed. Accordingly, maximal deflections U_z of local bending deformations were at a level of --0.2 mm (Figure 6, *a*) for flame heating, and --0.8 mm for laser heating (Figure 6, *b*).

Analysis of the calculation data given in the Table shows that flame heating is most efficient among the other heat sources under consideration for thermal straightening of buckling distortions in the proportions of values of the total volume of plastic shrinkage deformations V_p and maximal deflection U_z. The unexpectedly high values of bending deformations for the laser heat source, which is characterised by a uniform distribution of power in the spot with a diameter of 24 mm, might be explained by a sufficiently high reduced concentration coefficient K, obtained from a relatively small diameter of the heat input spot. When using the law of distribution of heating power from the formula

$$Q(r) = \frac{Q_{\rm eff}}{\pi R^2} e^{-Kr^2}$$

and regarding coordinate r as a boundary of the heat spot, for which the $Q(r)/Q_{\rm eff} = 0.1$ condition is met, the reduced concentration coefficient for the laser heat source at $R = 24/2$ mm will be $K = 0.009$ 1/mm^2. To compare, with the flame heat source at $K = 0.003$ and 0.005 1/mm^2 the heating spot sizes will be 41 and 32 mm, respectively.

To allow for local bending deformations caused by non-uniformity of heating of the skin sheet during heating, different values of shrinkage deformation on the upper and lower surfaces of a sheet were set in the developed finite element model of heating of a strip, based on the use of the shrinkage function method. This difference in shrinkages should correspond to angular deformations α according to the following dependence:

$$\alpha = \frac{(\Delta_{\rm tr}^{\rm up} - \Delta_{\rm tr}^{\rm low})}{\delta},$$

where $\Delta_{\rm tr}^{\rm up}$ and $\Delta_{\rm tr}^{\rm low}$ are the shrinkages on the upper and lower surfaces of the sheet, and δ is the sheet thickness.

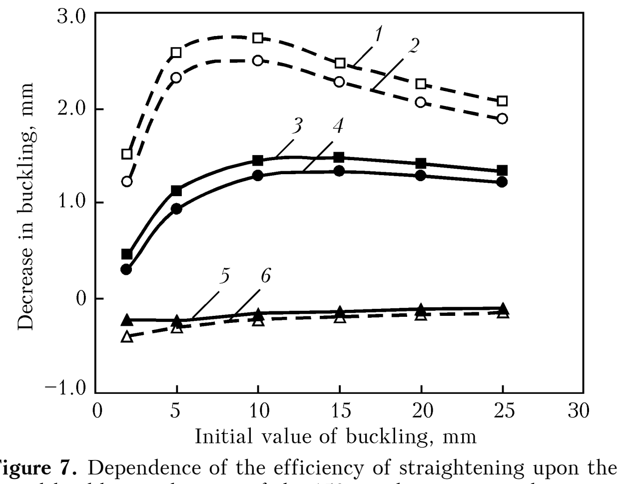

Figure 7. Dependence of the efficiency of straightening upon the initial buckling in heating of the 150 mm long strip at the centre of buckle of the skin sheet 6 mm (solid curve) and 3 mm thick (dashed curve), allowing for the effect of shrinkage in the sheet plane and angular deformations: *1, 3* --- shrinkage; *2, 4* --- shrinkage + angular deformations; *5, 6* --- angular deformations

Calculation data on heating of strip with L = 150 mm for a sheet sample 500 × 500 mm in size and 6 mm thick

Heat source	Q_{eff}, W	K, 1/mm^2	D_h, mm	v, mm/s	V_p, mm^2	U_z, mm
Plasma	1100	0.004	–	1.0	–119	–0.08
	1100	0.007	–	1.0	–128.9	–0.09
	1100	0.010	–	1.0	–132	–0.07
Flame	2500	0.003	–	2.0	–631	–0.18
	2500	0.005	–	2.0	–669	–0.20
Laser	2800	N/D	24	4.0	–390	–0.55
	2800	Same	24	6.0	–269	–0.80

In the calculations, the difference in shrinkages was selected so that deflection of a sheet caused by angular deformation was approximately U_x = 0.2 mm, this corresponding to the results of numerical estimation of local angular deformations for a heating strip 150 mm long in flame heating. The mean value of shrinkage was set to be Δ_{tr} = 0.1 mm and Δ_l = 0.1 mm (in the transverse and longitudinal directions with respect to the heating strip).

Figure 7 shows the calculation data for displacements U_y from the skin sheet plane depending upon the initial value of buckling of the skin sheet 6 and 3 mm thick, allowing for a separate and combined effect of shrinkage in the sheet plane and angular deformations. The results were obtained for the deflection buckling distortion, where angular deformations partially compensate for the efficiency of straightening of shrinkage deformations. With this relationship of shrinkage and angular deformations the effect of the latter on the efficiency of straightening, i.e. decrease in buckling, is insignificant. At higher values of angular deformations the efficiency of straightening will dramatically decrease.

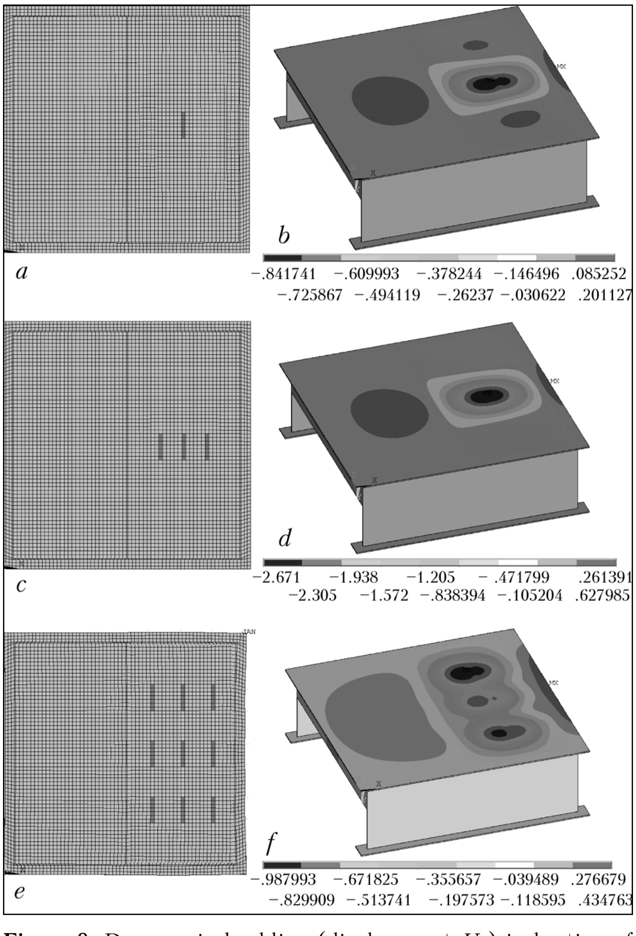

Figure 8. Decrease in buckling (displacement U_y) in heating of strips 150 mm long: *a, c, e* — scheme of heating of one, three and nine strips; *b, d, f* — corresponding distribution of displacements, mm

The results also show that the efficiency of straightening strongly depends upon the thickness of a skin sheet. Providing that the shrinkage characteristics are uniform at 3 mm thickness of the skin sheet, a decrease in buckling due to heating of a strip is 2 times as high as at 6 mm thickness. This is in good agreement with practical experience, where the application of thermal straightening of buckling distortions is most efficient at up to 4 mm thickness of the skin sheet.

The model developed made it possible to conduct numerical experiments to study the efficiency of straightening depending upon the quantity and arrangement of heatings. Figure 8 shows the calculation data on displacements U_y from the skin sheet plane for different variants of arrangement of the heating strips 150 mm long at a skin thickness of 6 mm. The initial values of buckling distortion was set equal to 5 mm. Displacements U_y under the combined effect of shrinkage deformations in plane and angular deformations were determined for each variant.

The results show (Figure 8, *a, b*) that a decrease of buckling in heating of a strip is of a local character and occurs in a zone limited by width of a buckle, and along the length of the buckle — approximately by two lengths of the heating strip. A small increase in this buckle, as well as in the neighbouring ones, takes place outside this zone. This effect is also confirmed by practical observations. Arrangement of several heating strips within one zone close to each other (Figure 8, *c, d*) provides a marked increase in the efficiency of straightening (decrease in buckling) within this zone. The uniform arrangement of the heating strips over the surface area of a buckle at a sufficient distance from each other (Figure 8, *e, f*) leads to a comparatively small decrease in buckling over the entire area of the buckle. This is attributable to a mutual effect of the zones of increase and decrease in buckling due to different heating strips. Therefore, the results of straightening at a large number of heatings must not be considered to be a simple sum of decreases in buckling due to individual heatings.

As seen from comparison of heating of strips and round spots (Figure 9), even at a set value of shrinkage a decrease in buckling (the initial value of a buckling distortion is 5 mm) in heating of round spots has a much lower effect than in heating of strips. This is associated with a lower total volume of plastic deformations formed in heating of round spots. In addition, all of the above peculiarities related to a local character of the efficiency of straightening and mutual effect of heatings on each other persist in this case.

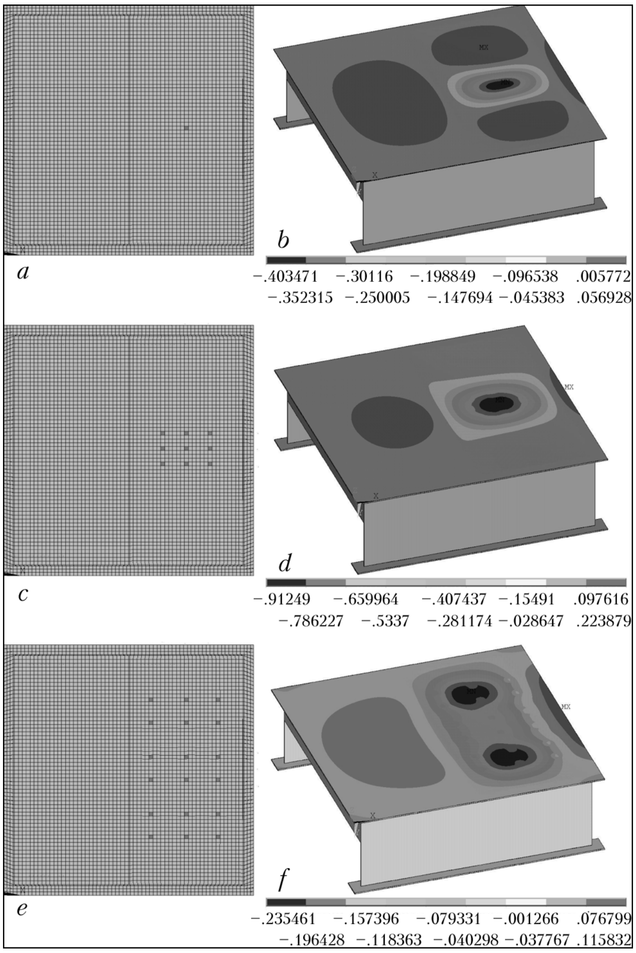

Figure 9. Decrease in buckling (displacement U_y) in heating of round spots: *a, c, e* — scheme of heating of one, nine and eighteen spots; *b, d, f* — corresponding distribution of displacements, mm

CONCLUSIONS

1. The efficiency of thermal straightening strongly depends upon the initial buckling, i.e. a decrease in buckling (in fact, bend of a sheet) depends upon the arm of application of shrinkage forces. At low initial values of buckling, or with decrease in buckling during the process of straightening its efficiency dramatically decreases.

2. The efficiency of thermal straightening is highly affected by thickness of a skin sheet. At a big thickness of the sheet (6 mm) the efficiency of straightening as a result of shrinkage deformation in the sheet plane greatly decreases. Additional bending deformations are formed at a big thickness, caused by non-uniformity of heating through thickness, which may substantially decrease the efficiency of straightening depending upon the sign (direction).

3. The result of thermal straightening depends to a considerably degree upon the quantity and location of heating spots and strips over the surface area of a buckle, and at their large quantity the efficiency of straightening cannot be considered to be a simple sum of decreases in buckling due to separate heatings. Decrease in buckling due to one heating is of a local character and occurs within the zone that is approximately equal in size to width of a buckle. Even a small increase in this buckle, as well as in the neighbouring ones takes place outside this zone. Therefore, thermal straightening should be performed by heating of spots or strips located within the zone of the maximal buckling.

4. The process of thermal straightening of buckling distortions has a number of objective factors that limit the efficiency of this technological operation, especially at big thicknesses of the skin sheets. The positive effect of straightening can be achieved only with the optimal selection of parameters and arrangement of heating spots.

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