Insitu determination of continuous evolution in space and during the strain fields on steel plate with the stress concentrator

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Abstract. The article represents the results of the experimental research of the evolution of strain fields of a steel plate with a stress concentrator by the correlation method of digital images. The obtained results reflect elaborately the evolution of the distribution of isofields towards the strains on the surface of the steel plate and the behavior of their distributions, which corresponds to each stage of the stress-strain curve under uniaxial tension.

1. Introduction
For the reliable stress assessment of substructures and structural components as well as for the predictive modeling of their residual lifetime, the reliable experimental data on the distribution of stress-strain states are required in the field of stress concentrators. The bearing capacity of structural elements is determined...
by the distribution of stresses and strength conditions in the places with the maximum stress value, since
the destruction occurs particularly there [1].

The development of adequate ideas and making the correct calculation models used in the design of
reliable structures are impossible without the detailed experimental data on the stress-strain states of stress
concentrator fields under conditions of elasticity, ductility, creeping and damage. Recently, such data have
been successfully obtained using in situ studies of displacement and strain fields with the using the Vic-
3DCorrelatedSolutions digital optical system [2-7]. The developed ideas are successfully used in modeling
the processes of strain effects on the structural elements with stress concentrators, which have been made
of various metallic and non-metallic materials.

The aim of the current work is to study the continuous in situ evolution in space and during the
distribution of stress-strain states of structural elements in the field of stress concentrators under the
tension of plates made of 09G2S structural steel.

2. Material and methodology

![Figure 1](image1.png)

**Figure 1.** The scheme for the image registration from a speckle pattern on a plate with the symmetrical undercuts
during the tensile strain is presented: 1 – steel plates; 2 – undercut; 3 – holes; K1 and K2 – digital cameras; P - applied
load.

![Figure 2](image2.png)

**Figure 2.** The picture of the central part of the sample is shown before testing (a) with a stress concentrator
and after the testing (b).

The prototype models of the plates were made of 09G2S structural steel with a ferritic-bainitic-martensitic
structure that combines a complex of mechanical properties. The choice of steel grade is justified by the
wide practical application in the capacities of the petrochemical industry, operated in Siberia and the Far
North [8]. The chemical composition of steel is shown in the table 1.

![Table 1](image3.png)

**Table 1.** The chemical composition of 09G2S steel (weight %).
The tensile testing of the samples was carried out on an "INSTRON 3386" testing machine with a constant strain rate of 0.0021 s\(^{-1}\). The experimental design is shown in figure 1.

To study the continuous evolution in space and during the strain pattern, a speckle structure was created on the surface of the sample, which was obtained by applying the white and black finely dispersed contrastive aerosol paints to the surface of the sample. This allowed us to create a variety of contrasting irregularly located points on the surface.

The surface strain of a steel plate was measured by using a Vic-3D digital optical system based on the correlation method of digital stereoscopic images. By the process of testing, the VicSnap program allows to record synchronously the images from two cameras (figure 1), which are processed by the VIC-3D program. As a result, the geometrical parameters of the surface are calculated (\(X, Y, Z\) coordinates for each analyzed point), as well as the relative strains (\(\varepsilon_{xx}\) – along the \(OX\) axis, \(\varepsilon_{yy}\) – along the \(OY\)).

3. Results and discussion

The application of the VIC-3D system allows obtaining the patterns, which elaborately reflect the continuous evolution in space and during the distribution of isofields of relative strains on the surface of steel plates, as well as the nature of the distribution of deformation fields at each stage of the stress-strain curve (figure 4-6).

The stage I of the stress-strain curve (figure 3) corresponds to the patterns of horizontal relative strains.

![Figure 3](image_url)

**Figure 3.** The full stress-strain tensile curve of the steel plate with an artificial stress concentrator (a) and a fragment of the stress-strain curve in the first strain stage (b).\[\varepsilon_{XX}\], in which the distribution of strain fields is characterized by the chaotic arrangement of the plastic compressive strain zones (figure 4, pattern (a)). The local zones of plastic strain are stretched along the...
axis of stretching (OY axis, figure 1). It corresponds to the strain geometry of the sample. During the stretching of the platelike sample, the elongation along the OY axis and the compression in the horizontal direction along the OX axis occur. Thus, the compression stresses along the OX axis lead to compression of the plastic strain zones. For this purpose, the zones of plastic strain are grouped into two wedge-shaped areas with the base of the wedges in the upper and lower edges of the plate and the tip of the wedges in the central part of the sample. In the neck formed by the undercuts between the stress concentrators, a deformation zone is formed by compression.

![Figure 4](image1.png)

**Figure 4.** The patterns of distributions of horizontal relative strains $\varepsilon_{XX}$ on the sample surface of 09G2S steel with a stress concentrator in the center of the sample: (a) $\varepsilon = 0.10\%$; (b) $\varepsilon = 0.15\%$; (c) $\varepsilon = 0.61\%$; (d) $\varepsilon = 1.00\%$; (e) $\varepsilon = 2.33\%$; (f) $\varepsilon = 2.91\%$. The points (a)–(h) of the stress-strain curve in figure 3 correspond to these patterns.

In the patterns of the distributions of the relative longitudinal strains $\varepsilon_{YY}$ along the tensile axis at the stage I, the zones of plastic strain are elongated along the OX axis, which is perpendicular to the tensile direction of the sample. In this case, in the local zone of the stress concentrator, the material is stretched with the local strain, which exceeds more than twice the magnitude of the highest average strain over the entire sample (figure 5, pattern (a)).

![Figure 5](image2.png)

**Figure 5.** The patterns of the distributions of vertical relative strains $\varepsilon_{YY}$ on the sample surface of 09G2S steel with a stress concentrator in the center of the sample: (a) $\varepsilon = 0.10\%$; (b) $\varepsilon = 0.15\%$; (c) $\varepsilon = 0.61\%$; (d) $\varepsilon = 1.00\%$; (e) $\varepsilon = 2.33\%$; (f) $\varepsilon = 2.91\%$. The points (a)–(h) of the stress-strain curve in figure 3 correspond to these patterns.

When the sample is stretched, the distribution of the relative tangential strains $\varepsilon_{XY}$ at the stage I is characterized by the chaotic arrangement of the zones of plastic strain, and the asymmetric one in reference to the sign of strain of the longitudinal and transverse axes of the sample (figure 6, pattern (b)).

At the stage I' (figure 3) of elastic-plastic transition from the elastic to plastic strain in the patterns of horizontal relative strains $\varepsilon_{XX}$, a decrease of the density zones of plastic compression strain is observed.
A combined zone of plastic strain, consisted of the tension field along the axis $OX$, is formed in the neck.

Figure 5. The patterns of the vertical relative strains $\varepsilon_{YY}$ on the surface of the sample of 09G2S steel with a stress concentrator in the center of the sample: (a) $\varepsilon = 0.10\%$; (b) $\varepsilon = 0.15\%$; (c) $\varepsilon = 0.61\%$; (d) $\varepsilon = 1.0\%$; (e) $\varepsilon = 2.33\%$; (f) $\varepsilon = 2.91\%$. The points (a)–(h) of the stress-strain curve in figure 3 correspond to these patterns.

At the stage I' (figure 3), in the patterns of the vertical relative strains $\varepsilon_{YY}$, one can observe the de-emphasis of the strain difference between the zones of plastic strain and background strain over the whole sample are with the exception of the zone of stress concentrator (figure 5, pattern (b)). In the neck formed by the undercuts, a tension field is observed, where the strain is more than 6 times higher than the average strain of the sample. At this stage, the system is practically in a weakly stable condition of the transition from the elastic strain to the plastic one. The importance of this stage is emphasized.

The distribution of the relative tangential $\varepsilon_{XY}$ strains at stage I' is characterized by a chaotic alternation of local zones of compressive and stretching plastic strains. In the neck at an angle of 45°, a zone of plastic strain is formed, made by the areas of compression and tension (figure 6, pattern (b)).

At the stage II of the stress-strain curve (figure 3), it can be seen that the whole plastic strain is localized in the zone of the stress concentrator and is characterized by the significant compressive strain ($\varepsilon_{XX} < 0$) in the patterns of transverse relative strains $\varepsilon_{XX}$. In this case, the isofields are redistributed in the upper and lower parts of the sample, and it is characterized by the homogeneous strain with the value by an order less than in the zone of the stress concentrator. Almost complete disappearance of the plastic strain zones is observed (figure 4, patterns (c)-(f)).

The analysis of the strain patterns of vertical relative $\varepsilon_{YY}$ strains at stage II shows that the whole plastic strain is localized in the zone of the stress concentrator and is characterized by the significant tensile strain ($\varepsilon_{YY} > 0$) with smaller and homogeneously distributed strains in the upper and lower parts of the sample (figure 5, patterns (c)-(f)).

A similar change in the behavior of the distributions of strain fields on the sample surface during the transition to stage II is observed in the distributions patterns of tangential strains $\varepsilon_{XY}$ (figure 6, patterns (c)-(f)).

4. Conclusion
1. It is evaluated that each stage in the diagram of the stress-strain curve $\sigma = f(\varepsilon)$ of tension of the steel sample from 09G2S steel with a stress concentrator in the center of the plate corresponds to its own distribution of strain fields on the surface of steel samples. In this case, there is a continuous evolution in space and during the distributions of stress-strain states of structural elements in the zone of stress concentrators under the tension of the plate.
2. It was evaluated that the behavior of the change in the diagram $\sigma - \varepsilon$ is determined mainly by the steel strain in the local zone of the stress concentrator at the stage of plastic strain.

3. The elastic-plastic strain processes occur at the stage $I'$. The distinction of a narrow stage $I'$ on the stress-strain curve is due to the transition from the elastic strain to the plastic one. At this stage, the system is practically in a weakly stable condition of the transition from the elastic strain to the plastic one. The importance of this stage is emphasized.

4. The experimentally obtained strain diagrams and their corresponding representations and patterns of the distribution of isofields can be used to verify the finite-element models when performing numerical investigations.

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