Investigations of the stress-strain state of a compressed steel concrete column using digital image correlation method

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Abstract. The results of the investigation of deformation during axial compression of a steel-concrete round column with dimensions of 1000×102 mm on the testing machine Universal Testing Machine 4500 using a digital optical system Vic-3D are presented. The patterns of the evolution of strain field distributions on the surface of the steel shell of the column are obtained. A deformation diagram indicating the transition stages of elastic strains to inelastic ones is constructed. A jump-like dependence of the Poisson's ratio on the longitudinal relative strain of the steel concrete column during deformation of the steel concrete column is established. This phenomenon is explained under the assumption that the deformation process involves redistribution of the forces (deformations) among the components of the composite system at the stage of joint operation before separation of the steel/concrete media and operation of concrete beyond elastic strain under conditions of volumetric compression.

1. Introduction
The use of complex structures perceiving compression, such as steel-concrete and those consisting of a jointly operating steel shell of a concrete core, has several advantages as compared to reinforced concrete structures [1-3]. The strength of a concrete body pressed by a steel shell exceeds the strength of 2 times. A positive effect of increasing strength characteristics of the concrete core is observed under both static and dynamic loads. As compared to conventional reinforced concrete structures, the use of steel-concrete allows reducing the material consumption of steel-concrete in 1.5–2 times, and, therefore, the mass of structures [4,5]. These and other positive qualities allow the effective use of steel-concrete structures as columns of high-rise buildings [6,7], as well as the use in seismic regions and regions of the far north. The behavior of the “shell-core” system operating under conditions of the volumetric compression is of great interest to researchers in this field. The study of the distribution of surface deformation of the steel shell and the deformation curve of the entire sample can clarify the redistribution of forces among the components of the system. One method for analyzing deformation of a steel-concrete column at mesoscale and macroscale levels is the digital image correlation method.

Despite numerous studies conducted by domestic and foreign authors, steel-concrete structures are not widely used in Russia. One of the reasons is the lack of regulatory documents and calculation methods that allow normalizing the limiting state of a steel-concrete structure. Verification of the
calculation model with the results of experimental studies will improve the accuracy of calculations and ensure the reliability.

The purpose of the paper is to identify features during compression strain of a steel-concrete column based on experimental studies of the distributions of relative longitudinal and transverse straining the near-surface layers of a steel pipe.

2. Materials and methods
Steel-concrete columns were used as prototypes for studying the stress-strain state of the “shell-core” system. The clip was made of a steel pipe with a height of 1000 mm, a diameter of 102 mm, and a wall thickness of 3 mm. The concrete core filling the inner space of the shell was made of monolithic fine-grained heavy concrete. The proportion of the components of the concrete core was taken in the ratio by weight of 2.35:1:5.5 cement: sand: screening. The screening with a fraction size of 5 mm was taken as a filler. The accepted water-cement ratio was W/C=0.46. The prismatic strength of control concrete samples at the time of testing was 27.1 MPa.

![Figure 1](image1.png)

**Figure 1.** Scheme for recording images from a speckle pattern on the surface of a steel-concrete column under compression: $K_1$ and $K_2$ are digital cameras; $P$ is the applied load.

The tests samples of steel-concrete columns were subjected to static axial compression. The columns were deformed using the UTM-4500 hydraulic unit at a speed of 2 mm/s. The test program provided for stepwise loading of columns. A predetermined level of compressive force was held for 5 minutes in order to redistribute stresses along the sample surface. Each stage of the test corresponded to an increase in the compressive strength of 60 kN. The Vic-3D stereoscopic measuring system was used to register the evolution of relative and absolute strain of steel-concrete columns, [8, 9]. Figure 1 shows the test scheme. Synchronous fixing of speckle-patterns from the surface of the columns was carried out using two cameras and the VicSnap software.

The operation principle of the Vic3D digital optical system is correlation of digital stereoscopic images. The measurement results have allowed obtaining data on the displacement of microvolumes in a three-dimensional space. The resulting patterns of displacement fields are projections of the displacements of local surface areas along the OX axis “transverse strain”, along the OY axis “longitudinal strain”, and along the OZ axis “transverse strain” (figure 1). The deformation pattern of the steel shell surface is obtained as a result of combining changes in microregions. The speckle-structure in the form of randomly distributed points on the sample surface was ensured by spraying a contrast finely dispersed aerosol paint.
3. Results and discussion

Figure 2 presents the deformation curves in $\sigma=f(\varepsilon_{yy})$ and $\sigma=f(\varepsilon_{xx})$ obtained under static compression of the samples of steel-concrete columns. It is seen that the elastic section is present on the deformation curves (AB sections in figure 2). Then, an increase in the applied load leads to plastic strain of the column (sections BC in figure 2). Further deformation of the column is accompanied by localization of strain fields in the central part of the column indicating a loss of stability due to longitudinal bending. This is very clearly seen in the three-dimensional distribution of longitudinal relative strain of the steel-concrete column surface (figure 3).

![Figure 2](image.png)

**Figure 2**: Deformation diagram of the steel-concrete column in the longitudinal (a) and transverse (b) directions. The numbers correspond to the position on the curve of the patterns of deformation structures (figure 3 and 4). AB is the elastic strain stage; BC is the non-elastic strain stage.

The results of experimental studies of the axial compression of the column have allowed obtaining distribution patterns of strain fields on the surface of the steel-concrete column in the longitudinal (figure 4) and transverse (figure 5) directions. On the presented patterns of longitudinal distributions of strain fields on the surface of the column, it is seen that distribution patterns of the deformation along the surface of the column are heterogeneous from the beginning of loading until the moment of the stability loss. An increase in the load leads to redistribution of strain fields and formation of local strain foci.

In the elastic stage of compression, the density of local strain foci in the supporting zones of the column is higher than in the middle part of the column. Local foci with positive and negative values of longitudinal strains are formed in the lower part of the column (section AB, points 1 and 2 in figure 2). Whereas strain foci with negative values are formed in the upper part of the column from the very beginning of compression. Such a noticeable heterogeneity in distribution of strain foci is not observed in the patterns of transverse strain fields (patterns 1 and 2 in figure 5).

Transition from the elastic stage to the region of inelastic strain of the column (figure 2, section of the BC curve, points 3 and 4) is reflected in the distribution patterns of strain fields in the appearance of local...
plastic strain foci on the surface of the column in its central part (figure 4 and 5). This is clearly seen in the schematically presented distribution patterns of longitudinal strain fields in the upper part of the column (figure 6). A decrease in the regions (regions with $\varepsilon_{yy}$) with highest strain values takes place in the region of the upper punch of the testing machine on the surface of the steel shell (figure 4, 5, regions with $\varepsilon_{yy}$ figure 6). This indicates that stresses are transferred from contact areas of the column with the punches of the testing machine to the central region of the column. Moreover, distribution patterns of strain fields show that this stage includes a complete disappearance of local strain foci with positive values in upper and lower parts of the column during deformation in the longitudinal direction.

Figure 4. Distribution patterns of longitudinal relative deformations $\varepsilon_{yy}$ of the steel-concrete column surface. The numbers on the diagram in figure 2 show the corresponding strain-strain states of the column during the test.

Fusion of local strain foci into vast areas is observed in upper and lower parts of the column in the patterns of transverse and longitudinal strain fields. Local fields with lower deformation values are formed inside these vast areas (figure 4, 6). Local areas with deformation $\varepsilon_1$ are shown in figure 6. The size and concentration of these areas increase with increasing external stress (pattern 3–5 figure 6). The appearance of local areas with lower deformations on the surface of the steel shell is associated with redistribution of stresses in the steel shell due to its expansion by the concrete core [6].

An asymmetric distribution of plastic strain foci relative to the longitudinal axial line of the column takes place in the central part of the column. Subsequently, an increase in the applied external load leads to a
longitudinal bending of the column in the central part. This phenomenon indicates a loss of stability of the column.

The Poisson's ratio \( \mu \) plays an important role in studying the deformation effect on solids when their linear and/or volumetric dimensions are changed. This parameter characterizes the property of a solid to retain its initial volume at the elastic stage of deformation. Calculation of the Poisson's ratio under uniaxial tension is determined by the ratio of the transverse strain of the sample \( \varepsilon_{XX} = \Delta h / h_0 \) to its longitudinal elongation \( \varepsilon_{YY} = \Delta l / l_0 \) according to the formula [10]:

\[
\mu = \frac{\varepsilon_{XX}}{\varepsilon_{YY}}. \tag{1}
\]

Where \( h_0 \) is the initial width of the sample, \( \Delta h \) is the change in the width of the sample during deformation, \( l_0 \) is the initial length of the sample, and \( \Delta l \) is the change in the length of the sample during deformation.
The dependence of the Poisson’s ratio on the longitudinal relative strain $\varepsilon_{yy}$ on the surface of the steel-concrete column has been obtained using the above mentioned dependences in figure 2 using the formula (1) (figure 7). The jump-like nature of deformation (section AB, figure 7) is very well pronounced in the dependence $\mu=f(\varepsilon_{yy})$ at the initial stage of deformation of the steel-concrete strut in the elastic region under low external applied stresses. The jump-like behavior of the deformation ends at the BC stage of inelastic strain. Then, deformation of the steel-concrete column in the CD section is accompanied by a longitudinal bending of the column. At this stage, deformation of the column occurs smoothly. This nature of the jump-like reaction of the steel-concrete column to the deformation effect is conditioned upon its compositional structure: a concrete core isolated by metal sheathing. Compression strain of such a composite material with different values of the Poisson’s ratio of the core and shell materials leads to failure of the adhesive bond at the concrete/steel interface, and manifests itself in the form of a jump-like nature of deformation curves.

The Poisson's ratio in the elastic strain region on average coincides with the Poisson's ratio for steel (figure 7). Upon transition to the BC stage, the value of the Poisson’s ration begins to increase, and then at the CD stage, a further increase in $\mu$ values takes place. This indicates that external mechanical stresses have led to a transition to the region of plastic strains with a change in the volume of the composite material.

4. Conclusion
The analysis of the obtained distribution patterns of strain fields, as well as deformation diagrams of steel concrete columns has shown that the compression of the concrete core with the steel shell prevents formation of microcracks and leads to an increase in the ultimate elastoplastic deformation. Since stresses in the
Concrete core exceed its prismatic strength, the value of the yield strength of a steel pipe can be taken as the value of critical stresses, taking into account elastoplastic deformation.

It has been established that elastic operation of the steel-concrete strut continues up to compressive stresses not exceeding 50 GPa. Further loading is accompanied by development of inelastic strain until stresses of 63 GPa are reached, corresponding to a loss of stability due to formation of a longitudinal bending of the rack.

The jump-like dependence of the Poisson’s ratio on the longitudinal relative strain $\varepsilon_{yy}$ of the steel-concrete column indicates redistribution of forces (deformations) among the components of the system at the stage of joint operation until separation of steel-concrete media and operation of concrete beyond elastic strain under volumetric compression.

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