

The application of finite element analysis during development of the Integral Strain Gauges calibration method for the study of the welded construction

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Abstract. Destruction of welds in metalwork is caused, in most cases, by low-cyclic fatigue. Among the wide spectrum of existing fatigue gauges, the Integral Strain Gauges are widely adopted in practice of experimental researches of different machine parts and carrying systems of vehicles. The paper proposes a new method based on finite element analysis of calibrating dependence establishment for ISG placed on the weld material by the use of few welded specimens of special geometrical shape providing the obtainment of several points of the calibrating curve in the tests process. Calibrating dependences allow determining the stress value σ_x in places of accumulated fatigue damages concentration which is used for serviceability estimation of welded joints by traditional techniques.

1. Introduction

It is known that destruction of welds in metalwork is caused, in most cases, by low-cyclic fatigue. Up to the present time, a wide range of the experimental methods allowing us to estimate the quality of welds is developed for prevention of emergencies [1-3]. However, these methods provide only detection of welds defects, without solution of the main problem: how detected defects will affect the fatigue durability of a construction. Among the wide spectrum of existing fatigue gauges [4-6], the Integral Strain Gauges [7-8] were widely adopted in practice of experimental researches of different machine parts and carrying systems of vehicles [8-9].

Operation, necessary for the use of ISG, is their calibration which is carried out by cyclic deforming of specimens with the pasted ISGs under the known stress-strain condition of specimens [8]. As a result of ISG calibrating, the dependence connecting the amplitude of the cyclic stresses (strains) with the number of loading cycles in accordance with one criterion of the ISG reaction (first 'dark spots' on the ISG surface, the relative area of 'dark spots' and others) is established. When using ISG for accumulated fatigue damages control of welds, it is necessary to get the calibrating dependences not only on the main material, but also on zone of thermal influence and on weld zone because the fatigue processes in these zones differ.

ISG calibrating can be carried out on standard plane specimens with a cross weld under conditions of cyclic tensile stress and compression. However, in this case, after testing of one specimen, only one experimental point of calibrating dependence will be established. And for obtaining the whole set of points, it is necessary to test several specimens under load varying.



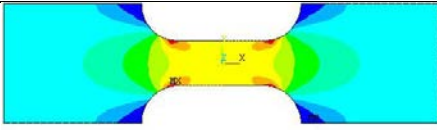

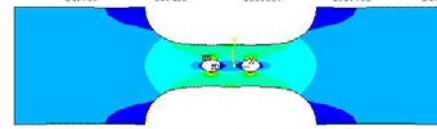

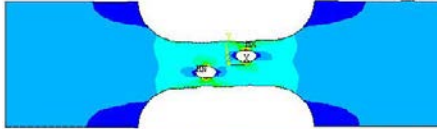

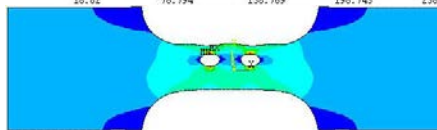

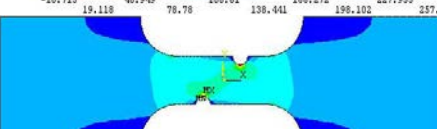

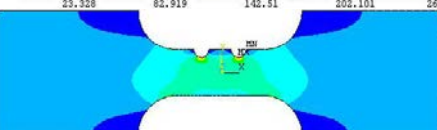

This paper offers a new method of calibrating dependence establishment for ISG placed on the weld material by the use of few welded specimens of special geometrical shape providing the obtainment of several points of the calibrating curve in the tests process.

2. The task of the choice of an optimum geometrical shape of the specimen

At the first stage, the task of determination of an optimum geometrical shape of the test specimen is solved. Table 1 presents both the results of the stress-strain conditions calculation of different variants of specimens and the stress distribution diagram on the weld length.

In middle section (where the weld is placed) of the test specimen of traditional shape, the stress distribution diagram is close to uniform. To obtain the irregular distribution law of stress, the different concentrators were made on specimens 2 ... 6.

Table 1. Influence of concentrators on the stress distribution law in the welded specimen

№	Stress von Mises distribution picture	Stress distribution diagram (σ_x) along the weld, MPa	Tensile force, kN
1			90
2			37
3			30
4			33
5			39
6			40

Analyzing results of stress calculation in the place of a weld presented in Table 1, it is easy to see that concentrators significantly change the picture of stress distribution. Among researched specimens, specimen № 5 is of the greatest interest, because it is characterized by the optimum stress distribution

law (close to parabolic) along the weld. The value of the maximum stress (88 MPa) exceeds the level of the minimum stress (39 MPa) approximately twice. It allows one to carry out the calibration of ISG in this stress range by using only one test specimen.

3. Analysis of the stress-strain condition of a three-dimensional welded specimen

At the second stage, computer simulation for the stress-strain condition calculation of the calibrating specimen of the geometrical shape chosen at the first stage (specimen №5) is carried out by Finite Element Method [1, 6, 10-11]. The finite element structured mesh [12] of the calibrating specimen is shown in Figure 1. The calibrating specimens material [9] was described by steel 14HGS, Russian State Standard 19282-73 (yield strength is 343.4 MPa, tensile strength is 490.5 MPa). For the analysis, the elastic material model was used. For the analysis of the influence of different boundary conditions on experiment results, the authors have considered 7 loading cases which are characterized by different boundary conditions (Table 2).

For quality estimation of the finite element mesh, the method described in works [8, 13] was used. Relative accuracy between nodal and element results was less than 7% that testifies to sufficient quality of the finite element mesh of the researched model.

The executed calculations have shown that the most rational loading cases for establishment of calibrating dependences for ISG are loading cases № 5, 6, 7 (Figures 3 and 4): tensile force varying at a fixed value of the vice lock on the pulsating stand. These test modes will allow carrying out the calibration of ISG in three ranges of stress variation by using only one calibrating specimen.

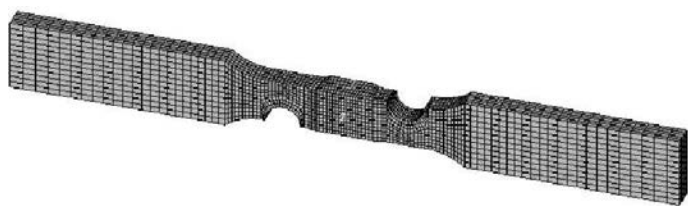


Figure 1. The finite element model of calibrating specimen №6

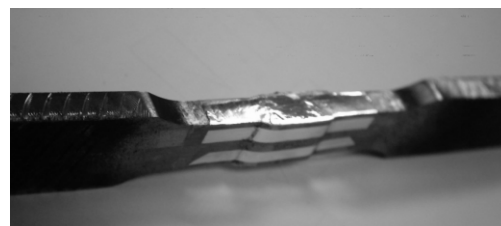


Figure 2. Calibrating specimen №1 with placed ISG

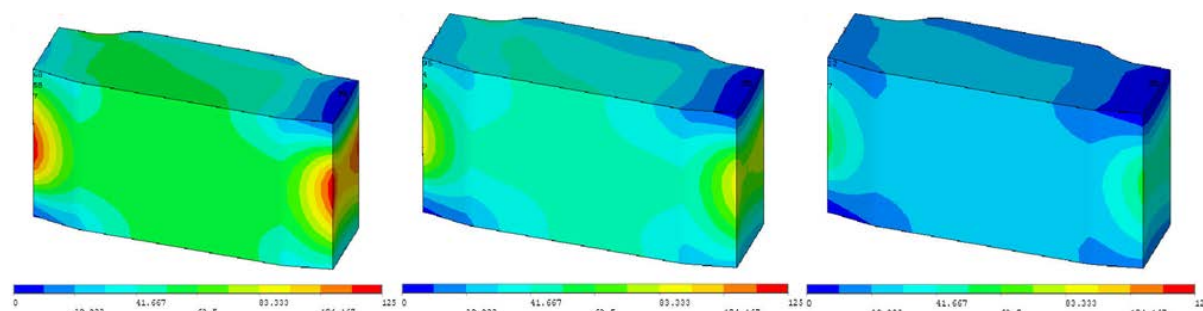


Figure 3. The stress von Mises distribution law in the weld material for loading cases №5, 6, 7

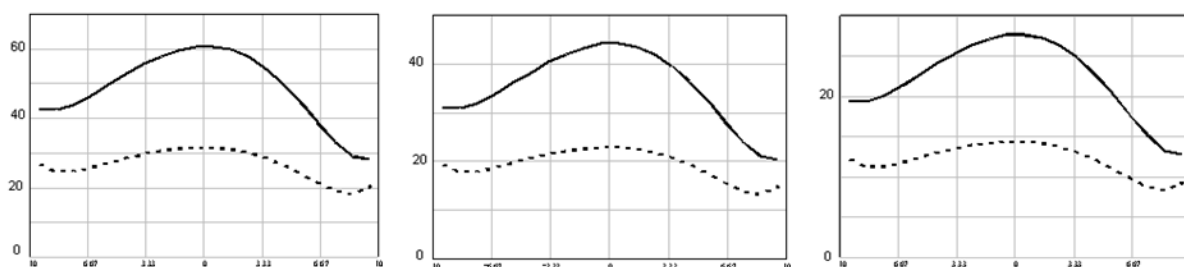


Figure 4. The stress von Mises distribution diagram along the strengthening edge of the weld

for loading cases № 5, 6, 7 (solid curve – weld upper surface, dotted curve – weld lower surface)

Table 2. Boundary conditions for different loading cases of specimens

Loading case	Type of specimen	Tensile force F , N	Value of vice lock on pulsating stand L , mm
1	Welded	10000	40
2	Solid	10000	40
3	Welded	9700	10
4	Welded	13000	80
5	Welded	11000	50
6	Welded	8000	50
7	Welded	5000	50

4. The method of establishment of calibrating dependence

We will illustrate the realization of the developed method of calibrating dependence establishment for a welded specimen corresponding to the fixed number of loading cycles.

The welded specimens (Figure 2) made of a welded pipe were object of the experiment. The pipe material: 14HGS. The specimen on the pulsating stand [14] was subjected to deforming under the conditions of stretching at constant amplitude ($F_{min} = 6\ 000\text{ N}$, $F_{max} = 35\ 000\text{ N}$) during 80 000 cycles [9]. After $N=20\ 000$ cycles, the crack was registered and the experiment was interrupted. Using the photo camera, the digital pictures of the ISG reaction were obtained at different places of the specimen. Figure 5 illustrates the ISG reaction on the face surface of the welded specimen (a – the face crack, b - the upper weld in the weld zone with the main metal, c - the lower weld in the zone of thermal influence, d - the lower weld in the weld zone with the main metal). Figure 6 shows the ISG reaction on the lower surface of the weld (a - on the weld boundary, b, c, d – different zones of the main metal) [9]. The analysis of the achieved information gives evidence of the fact that the intensity of the ISG reaction in various zones of the weld differs significantly. The greatest ISG reaction was registered on a surface of the lower weld on the weld boundary (Figure 6a). The maximum ISG reaction testifies to stress (strains) concentration in the researched place and, accordingly, the greatest accumulated fatigue damage. Confirmation of the described fact is a fatigue crack initiation on the welded specimen in the zone of the weld boundary of the lower weld with the main metal (Figure 5a). The obtained photos of the ISG reaction (similar to the data of work [6]) show that stress distribution (accumulated during cyclic deforming of the specimen) on the surface of the welded specimen in its different zones (weld, zone of thermal influence, main metal, weld boundary) is very heterogeneous. Difficulty of serviceability forecasting of welded joints and constructions is explained by this circumstance.

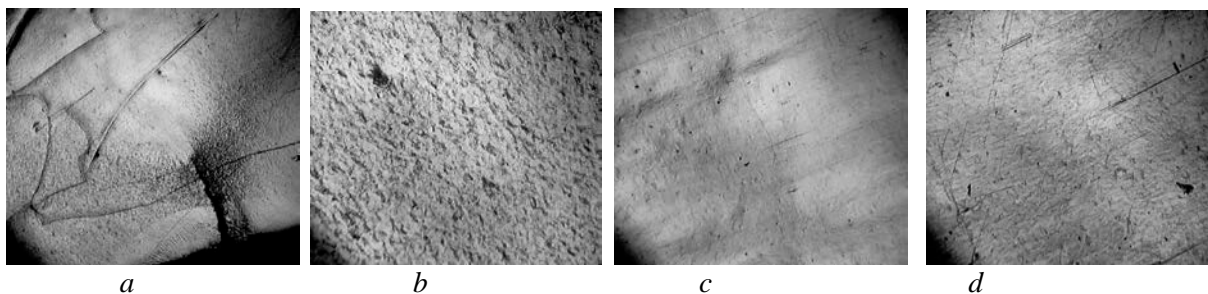


Figure 5. The ISG reaction in different face regions of the welded specimen after 20000 cycles, $\times 200$

For interpretation of the ISG reaction, the stress-strain condition estimation of the researched welded specimen was carried out by the finite element method during its stretching by axial force $F = 35000\text{ N}$. Values of the calculated stresses for 8 regions of the welded specimen are presented in the

last column of Table 3, and the results obtained during processing of photos of the same ISG regions by the histogram method with the help of the special software [8] are shown in the second and third columns of Table 3.

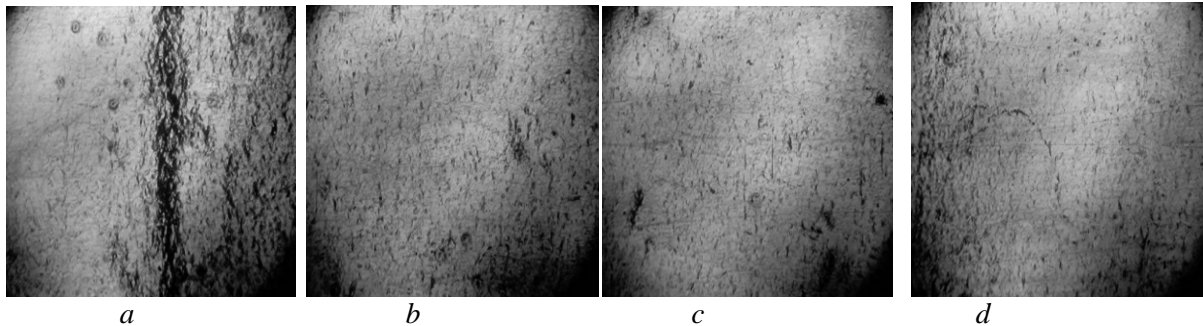


Figure 6. The ISG reaction on the lower surface of the weld after 20000 cycles, $\times 200$

Using the value of criteria (D and δ) of the ISG reaction estimation and calculated stress value, we shall obtain experimental points of calibrating dependence for the loading cycles number, $N=20000$, in coordinates $D-\sigma_x$ (Figure 7) or $\delta-\sigma_x$. After approximation of experimental data by the linear model, the required calibrating dependence can be presented as function:

$$D(\sigma_x, N=\text{const}) = 22.21 \cdot \sigma_x - 4.16 \cdot 10^3 \quad (1)$$

$$\text{or } \delta(\sigma_x, N=\text{const}) = 1.539 \cdot \sigma_x - 293.895 \quad (2)$$

The use of dependences (1) and (2) for experimental researches of welded joints with the help of ISG consists in the following. ISG are placed on the surface of welds, on the weld boundary and on the main metal; the specimen is subjected to cyclic deforming during $N=20000$ cycles. After that, the regions of ISG with the greatest reaction are photographed and the obtained information is processed by the developed software [8].

Table 3. The results of computer processing of the ISG reaction

Photo of ISG reaction	Relative area of 'dark spots' δ , %	D -criteria (dispersion) of ISG reaction	Stress σ_x , MPa by FEM
Figure 5a	53.4	833	220.5
Figure 5b	29.0	517	212.33
Figure 5c	28.3	556	212.33
Figure 5d	27.4	464	212.33
Figure 6a	38.2	598	215.2
Figure 6b	13.2	327	199.67
Figure 6c	15.5	332	199.67
Figure 6d	16.9	282	199.67



Figure 7. Experimental points and calibrating dependence on the base of the linear model in accordance with D -criteria of the ISG reaction.

5. Conclusion

Values D or δ obtained as a result of processing of calibrating dependences (1) or (2) allow determining the stress value σ_x in places of accumulated fatigue damages concentration which is used for serviceability estimation of welded joints by traditional techniques. It is easy to see that similar calibrating dependences can be established for any other numbers of loading cycles.

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