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Selected Metrological Aspects in Truss Magnetoelastic Measurements

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This work presents the determination of the unbiased estimation of the standard deviation and magnetoelastic sensitivity for magnetoelastic measurements. The investigation was performed on trusses made of 13CrMo4-5 and X30Cr13 steel. Three central truss elements were designed as test samples constituting the tested magnetic circuit. Thirty interchangeable test samples were made to measure five sets for both materials. Based on the obtained characteristics, the unbiased estimation of the standard deviation and magnetoelastic sensitivity were determined. The percentages of the estimator indicate very low uncertainty in the assessment of stresses in the structure. High magnetoelastic sensitivity values indicate the possibility of using the developed method to assess the stress state in ferromagnetic structural elements.

topics: magnetoelastic measurements, magnetoelastic sensitivity, ferromagnetic materials

1. Introduction

The inspection of structural components is an important part of civil engineering. Determining their technical condition and detecting possible defects is crucial from the point of view of safety reasons. For this purpose, different types of investigations are conducted, such as thermal imaging of defects or stress testing of components in these structures [1–4]. An important piece of information about the tests is their accuracy. Another important factor in selecting a stress measurement method is the sensitivity value. The present work focuses on studying stresses by investigating the magnetic state of truss elements [5, 6].

2. Assumptions

The magnetoelastic method's applicability in stress assessment was validated on the model object. The following objectives should be followed for magnetoelastic measurements on the model object to be conclusive:

- the model object should represent a large group of real structures,
- the application of specific external forces must be ensured,
- the values of stress arising in the structure must be known,
- the structure must allow magnetoelastic characterization tests to be made [7].

Trusses were chosen as a model object. This type of structure is very often utilized in civil engineering. Bridges, columns, pylons, halls, and roofs are built from trusses. The truss also fulfills other assumptions necessary to verify the method. It allows external forces to be applied easily, and the stress arising in each element can be calculated. The design of the truss also makes it possible to measure magnetic characteristics.

3. Materials

Two ferromagnetic materials used in mechanical structures were selected for study. These materials are used, for example, in the construction of bridges, power poles, high-pressure boilers, etc. Tests were made on samples of 13CrMo4-5 and X30Cr13 steel.

X30Cr13 steel is a martensitic steel with enhanced corrosion resistance. The value of Young's modulus E ranges from 215 to 190 MPa in the temperature range from 20 to 400°C. The tensile strength R_m reaches a maximum of 740 MPa, and the yield strength Re_H is 345 MPa [8].

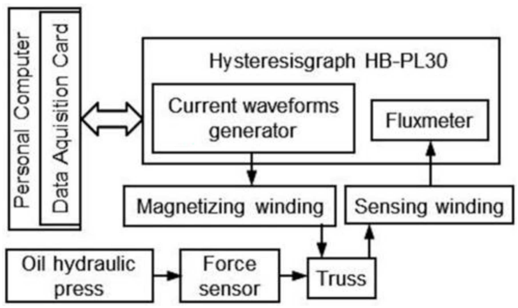

Fig. 1. Schematic block diagram of the measurement stand.

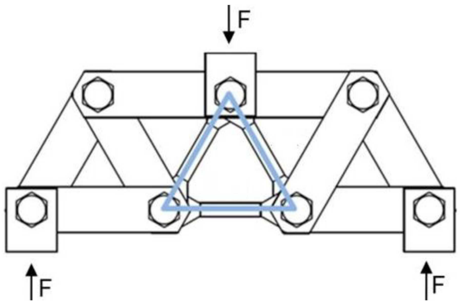

Fig. 2. Truss with the sample (blue line — magnetic circuit).

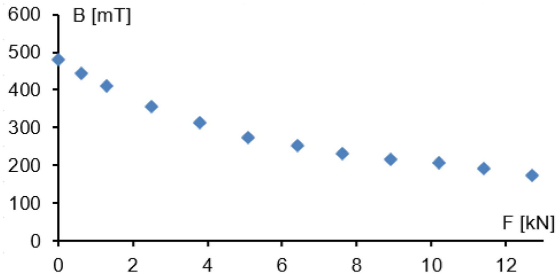

Fig. 3. Magnetoelastic characteristics $B_m(F)$ for a 13CrMo4-5 steel truss at a magnetizing field of $H_m = 350$ A/m.

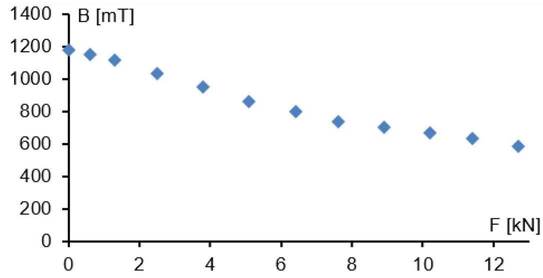

Fig. 4. Magnetoelastic characteristics $B_m(F)$ for a 13CrMo4-5 steel truss at a magnetizing field of $H_m = 655$ A/m.

TABLE I

Values of the unbiased estimation of the standard deviation for 13CrMo4-5 steel truss.

Steel	Tensile sample	Compressed sample
13CrMo4-5	300 MPa	200 MPa
X30Cr13	450 MPa	300 MPa

13CrMo4-5 steel is a chromium–molybdenum alloyed structural steel for use at elevated temperatures. The value of Young's modulus E ranges from 210 to 165 MPa in the temperature range from 20 to 500°C. The tensile strength R_m depends on the specimen thickness and takes values between 420 and 600 MPa. Similarly, the yield strength Re_H depends on the thickness of the specimen, and its values range from 245 to 300 MPa [9].

4. Method of investigation

The investigation was performed on a test stand adapted to study the $B_m(+\sigma, H)$ magnetoelastic characteristics of truss structures, as described in the articles [10–12].

Figure 1 shows a block diagram of the test stand for measuring magnetoelastic properties.

The truss used in the measurements is shown in Fig. 2.

The truss was designed so that the three central elements, i.e., the test samples, can be replaced [13]. These elements have a reduced cross-section, so they are only damaged when a force is applied, not the whole truss.

Thirty interchangeable test samples were made to measure five sets for both materials.

The measuring and magnetizing windings are wound uniformly over all samples so that the magnetic circuit closes through all three samples.

5. Results

The measurements of magnetic properties under stress were carried out for three different values of the magnetizing field for trusses made of steels 13CrMo4-5 and X30Cr13.

The calculated maximum stress to the samples is shown in Table I.

Figure 3 shows the magnetoelastic characteristics of the $B_m(F)$ truss at a magnetizing field of $H_m = 350$ A/m of truss of 13CrMo4-5 steel. The values presented in the graph are averages of 5 measurements.

Figure 4 shows the magnetoelastic characteristics of the $B_m(F)$ truss at a magnetizing field of $H_m = 655$ A/m of truss of 13CrMo4-5 steel. The values presented in the graph are averages of 5 measurements.

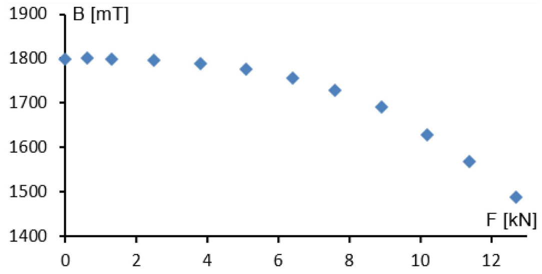

Fig. 5. Magnetoelastic characteristics $B_m(F)$ for a 13CrMo4-5 steel truss at a magnetizing field of $H_m = 2170$ A/m.

TABLE II

Values of the unbiased estimation of the standard deviation for 13CrMo4-5 steel truss.

Unbiased estimation of the standard deviation [%] for 13CrMo4-5 steel			
F [kN]	H		
	350 A/m	55 A/m	2170 A/m
0.0	6.1	5.6	4.3
0.6	5.0	4.8	4.1
1.3	4.6	4.5	4.0
2.5	3.8	4.0	4.3
3.8	3.3	3.5	4.1
5.1	2.7	2.6	3.9
6.4	3.4	3.5	3.9
7.6	3.8	3.6	3.7
8.9	3.9	3.8	3.8
10.2	4.8	4.5	4.4
11.4	5.7	5.1	4.5
12.7	6.3	5.9	6.8

Figure 5 shows the magnetoelastic characteristics $B_m(F)$ truss at a magnetizing field of $H_m = 2170$ A/m of a truss of 13CrMo4-5 steel. The values presented in the graph are averages of 5 measurements.

Figure 6 shows the magnetoelastic characteristics of the $B_m(F)$ truss at a magnetizing field of $H_m = 480$ A/m of truss of X30Cr13 steel. The values presented in the graph are averages of 5 measurements.

Figure 7 shows the magnetoelastic characteristics of the $B_m(F)$ truss at a magnetizing field of $H_m = 900$ A/m of truss of X30Cr13 steel. The values presented in the graph are averages of 5 measurements.

Figure 8 shows the magnetoelastic characteristics of the $B_m(F)$ truss at a magnetizing field of $H_m = 3000$ A/m of truss of X30Cr13 steel. The values presented in the graph are averages of 5 measurements.

An unbiased estimation of the standard deviation was calculated for the obtained results. The values of these estimators are included in Tables II and III.

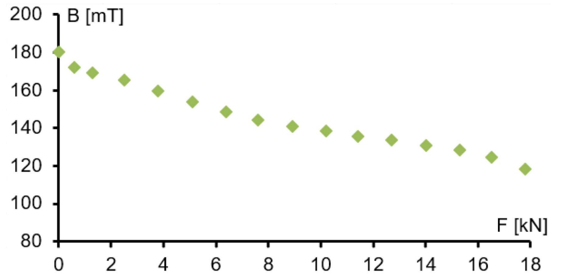

Fig. 6. Magnetoelastic characteristics $B_m(F)$ for a X30Cr13 steel truss at a magnetizing field of $H_m = 480$ A/m.

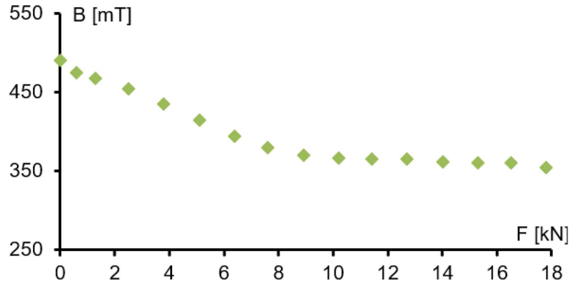

Fig. 7. Magnetoelastic characteristics $B_m(F)$ for a X30Cr13 steel truss at a magnetizing field of $H_m =$ 900 A/m.

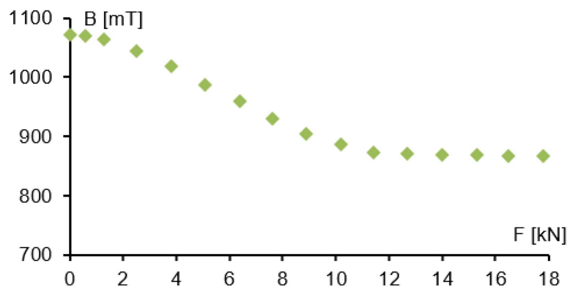

Fig. 8. Magnetoelastic characteristics $B_m(F)$ for a X30Cr13 steel truss at a magnetizing field of $H_m = 3000$ A/m.

The percentages of the estimator indicate very low uncertainty in the assessment of the stresses in the structure, considering that measurements were made on five independent sets of samples.

6. Magnetoelastic sensitivity

Based on the obtained characteristics, the magnetoelastic sensitivity was determined. This sensitivity can be described for the magnetoelastic characteristics $B_m(F)$ by the equation

$$k_F = \frac{\Delta B_m}{\Delta F}, \tag{1}$$

TABLE III

Values of the unbiased estimation of the standard deviation for X30Cr13 steel truss.

Unbiased estimation of the standard deviation [%] for X30Cr13 steel			
F [kN]	H		
	480 A/m	900 A/m	3000 A/m
0.0	4.7	3.4	2.7
0.6	4.4	3.5	2.7
1.3	4.0	3.4	2.7
2.5	3.2	2.9	2.7
3.8	2.7	2.7	2.8
5.1	2.6	2.6	2.9
6.4	2.4	2.3	2.9
7.6	2.3	1.9	2.9
8.9	2.5	1.6	3.0
10.2	2.6	1.8	2.5
11.4	3.3	2.2	2.3
12.7	3.8	2.5	2.1
14.0	4.0	2.5	1.9
15.3	3.7	2.2	1.9
16.5	2.9	1.8	1.9
17.8	7.5	6.8	4.7

TABLE IV

Values of the magnetoelastic sensitivity for 13CrMo4-5 steel truss.

	H_m [A/m]		
	350	655	2170
k_F [mT/kN]	29	34	37

TABLE V

Values of the magnetoelastic sensitivity for X30Cr13 steel truss.

	H_m [A/m]		
	480	900	3000
k_F [mT/kN]	4	10	14

where k_F is magnetoelastic sensitivity, ΔB_m — increase in maximum magnetic flux density, ΔF — increase in external force.

Tables IV and V show the maximum values of magnetoelastic sensitivity for the magnetic index of maximum B_m for the truss made of steel 13CrMo4-5 and X30Cr13.

The changes in flux density B due to stress depend on the value of the magnetizing field H at which the measurement was performed. The highest changes were observed at a magnetizing field of 2170 A/m for a truss made of 13CrMo4-5 steel, and the sensitivity obtained was 37 mT/kN.

7. Conclusions

In the research presented, the truss magnetic circuit is enclosed within three truss elements. This solution does not require holes drilled in the elements and is more convenient for use in existing structures. The maximum change in magnetic flux density value is 64%. The percentages of the estimator indicate a very low uncertainty. The high magnetoelastic sensitivity value of a maximum of 37 mT/kN was obtained.

The results confirm that the stress state assessment in structural components made of ferromagnetic steel can be performed using the magnetoelastic effect.

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