Proceedings

The 6th International Congress
of Serbian Society of Mechanics

Tara, June 19-21, 2017

Edited by:

Mihailo Lazarević
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Ines Grozdanović
Nemanja Zorić
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Foreward

The present volume contains plenary lectures, abstracts and papers of young authors competing for the „Rastko Stojanović'' award at the 6th International Congress of Serbian Society of Mechanics. The objectives of this Congress, to be held at Mountain Tara during the period 19th -21th June 2017, are to review and discuss some of the latest trends in various fields of theoretical and applied mechanics as well as it aims to bring together the scientific communities of theoretical and applied mechanics in an effort to facilitate the exchange of ideas on topics of mutual interests, and to serve as a platform for establishing links between research groups with complementary activities.

We are happy to report that the number of accepted papers to be presented at the 6th Congress is 99. In addition, among them, 7 invited plenary lectures were presented by the authors from Rusia, USA, Greece, Germany, Serbia and BIH, Republika Srpska. These papers were grouped in the following sections General Mechanics, Fluid Mechanics, Mechanics of Solid Bodies, Control and Robotics, and Interdisciplinary and Multidisciplinary Areas. Also, the three Minisymposia were organized with following topics: Nonlinear Dynamics, Turbulence and Bioengineering.

The Editors would like to express their thanks to all participants for their scientific contribution to 6th Congress of Mechanics, as well as colleagues and friends who helped with the organization. Next, to the distinguished invited lecturers who kindly accepted the invitation to come to Congress and helped make it success. We owe great thanks to the reviewers of the papers, to the members of the Scientific and Organizing Committee, and to the organizers of the Mini-symposia on Nonlinear Dynamics, Turbulence and Bioengineering. The support of the members of Steering Committee of Serbian Society of Mechanics in organizing this event is also appreciated. Finally, special thanks are also due to those organizations which supported financially this Congress: Serbian Society of Mechanics, Ministry of Education, Science and Technological Development of the Republic of Serbia, and Faculty of Mechanical Engineering, University of Belgrade, Belgrade. It is our great pleasure to have you with us at the 6th Congress International Congress of Serbian Society of Mechanics.

We would like to wish all participants of this Congress a warm welcome to our country, our Serbian Society of Mechanics and Venue Congress place at Hotel Omorika, Tara, Serbia.

Tara, June, 2017

The Editors
Mihailo P. Lazarević
Damir Madjarević
Ines Grozdanović
Nemanja Zorić
Aleksandar Tomović

Technical program

SUNDAY, June 18, 2017

19:00 *Welcoming Coctail* (*Banquet hall*)

MONDAY, June 19, 2017

8:00 - 9:00 *Registration of participants* (*Main Hall*)

9:00 - 9:15 Welcome address: (*Forum Palace Hall*)
Professor M. P. Lazarević, the President of
Serbian Society of Mechanics

Plenary Lectures (*Forum Palace Hall*)
Chairman: Mihailo P. Lazarević

9:15 - 10:00 P-1 F. Chernousko
LOCOMOTION OF MOBILE ROBOTIC SYSTEMS: DYNAMICS AND OPTIMIZATION

10:00 - 10:45 P-2 P. Spanos
RANDOMLY EXCITED NONLINEAR DYNAMIC SYSTEMS ENDOWED WITH FRACTIONAL DERIVATIVES ELEMENTS

10:45 - 11:10 *Coffee Break* (*Main Hall*)

11:10 - 12:30 Parallel Sessions

Session	G1	S1	C1	F1
Hall	*Forum Palace*	*Banquet hall*	*Idea hall*	*Dialogue hall*
11:10	G1a	S1a	C1a	F1a
11:30	G1b	S1b	C1b	F1b
11:50	G1c	S1c	C1c	F1c
12:10	G1d	S1d	C1d	F1d

12:10 - 13:20 *Lunch* (*Restaurant*)

Plenary Lecture (*Forum Palace Hall*)

Chairman: Srboljub Simić

13:30 - 14:15 P-3 G. Saccomandi
UT VIS SIC TENSIO

14:20 -17:30 *Social program* (*excursion to Mokra Gora and train ride "Sargan Eight"*)

17:40 - 19:20 Parallel Sessions

Session	G2	S2	M1	C2
Hall	*Forum Palace*	*Banquet hall*	*Idea hall*	*Dialogue hall*
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18:00	G2b	S2b	M1b	C2b
18:20	G2c	S2c	M1c	C2c
18:40	G2d	S2d	M1d	C2d
19:00	G2e	S2e	M1e	

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PERSONALIZED SITE-SPECIFIC MODELS OF ATHEROSCLEROTIC PLAQUE PROGRESSION

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11:00 - 13:00 Parallel Sessions

Session	G3	M2	S3	M1
Hall	*Forum Palace*	*Banquet hall*	*Idea hall*	*Dialogue hall*
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11:40	G3c	M2c	S3c	M1h
12:00	G3d	M2d	S3d	M1i
12:20	G3e	M2e	S3e	M1j
12:40	G3f	M2f	S3f	M1k

13:00 - 14:20 *Lunch* (*Restaurant*)

Plenary Lecture (*Forum Palace Hall*)
Chairman: T. P. Exarchos

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15:40 - 17:20 Parallel Sessions

Session	S4	M2	C3	I1
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-modernization of teaching mechanics in higher education
(*Forum Palace Hall*)

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(*Forum Palace Hall*)

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WITH STRONG FIBERS

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Hall	*Banquet hall*	*Idea hall*	*Dialogue hall*	
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10:10	M3b	S5b	I2b	
10:30	M3c	S5c	I2c	
10:50	M3d	S5d	I2d	

11:10 - 11:40 *Coffee Break* (*Main Hall*)

11:40 - 12:40 Parallel Sessions

Session	M3	S6		
Hall	*Idea hall*	*Dialogue hall*		
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COMPUTATIONAL MODELING FOR PLAQUE PROGRESSION AND FRACTIONAL FLOW RESERVE IN THE CORONARY ARTERIES

of elasticity is present. This is mainly as a feedback from industry which have requirements toward mega and nanostructures.Corrosion represents an important limitation to the safe and reliable use of many alloys in various industries. Pitting corrosion is a form of serious damage on metals surface such as high-strength aluminum alloys and stainless steel, which are susceptible to pitting when exposed to a corrosive attack in aggressive environments. This is particularly valid for dynamic loaded structures. The subject of this paper is application of new method of determine length scale parameter for estimating the mechanistic aspect of corrosion pit under uniaxial/multiaxial high-cycle fatigue loading.

S2e: Vladimir Milovanović, Aleksandar Dišić, Nikola Jovanović, Gordana Jovičić, Miroslav Živković

EXPERIMENTAL STUDY OF DEFORMATION BEHAVIOR AND FATIGUE LIFE OF S355J2+N STEEL GRADE UNDER CYCLIC LOADING

Fatigue is a progressive, localized, permanent structural change that occurs in materials subjected to fluctuating stresses and strains that may result in cracks or fracture after a sufficient number of fluctuations. Fatigue fractures are caused by the simultaneous action of cyclic stress, tensile stress and plastic strain. If one of these three acting phenomena is not present, fatigue cracking will not initiate and propagate. In this paper, the cyclic deformation behavior and fatigue life of S355J2+N welding steel used for construction were studied experimentally. A complete cyclic characterization of the material is obtained, including new experimental ε–N fatigue curves for uniaxial tension–compression. The work has been developed using the experimental equipment and procedures available in Centre for engineering software and dynamic testing at Faculty of Engineering University of Kragujevac.

S3a: Slaviša Šalinić, Aleksandar Nikolić

DETERMINATION OF NATURAL FREQUENCIES OF A PLANAR SERIAL FLEXURE-HINGE MECHANISM USING A NEW PSEUDO-RIGID-BODY MODEL (PRBM) METHOD

This paper presents an approach to the free vibration analysis of planar serial flexure-hinge compliant mechanisms basing on a pseudo-rigid-body method with 3-DOF (degrees of freedom) joints. The considered type of compliant mechanisms contains rigid links interconnected by flexure hinges. It is assumed that the flexure hinges undergo small in-plane deformations. Also, the masses of flexure hinges are ignored with respect to the masses of rigid links. Two lateral and one rotational springs with corresponding stiffnesses are placed in each joint in the pseudo-rigid-body model of the considered type of compliant mechanisms. The circular hinge type of flexure hinges is considered. Theoretical considerations are accompanied by a numerical example. In the numerical example a RRR compliant micro-motion stage is analyzed. The influence of the spring stiffnesses determined based on various flexure hinge compliance equations available in the literature on the vibration frequencies of the compliant mechanism is studied. Also, the comparison of accuracy in the determination of vibration frequencies of the compliant mechanism between the proposed pseudo-rigid-body method and the classical pseudo-rigid-body method (with one-DOF revolute joints) is given.

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EXPERIMENTAL STUDY OF DEFORMATION BEHAVIOR AND FATIGUE LIFE OF S355J2+N STEEL GRADE UNDER CYCLIC LOADING

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Abstract:

Fatigue is a progressive, localized, permanent structural change that occurs in materials subjected to fluctuating stresses and strains that may result in cracks or fracture after a sufficient number of fluctuations. Fatigue fractures are caused by the simultaneous action of cyclic stress, tensile stress and plastic strain. If one of these three acting phenomena is not present, fatigue cracking will not initiate and propagate. In this paper, the cyclic deformation behavior and fatigue life of S355J2+N welding steel used for construction were studied experimentally. A complete cyclic characterization of the material is obtained, including new experimental *ε–N* fatigue curves for uniaxial tension–compression. The work has been developed using the experimental equipment and procedures available in Centre for engineering software and dynamic testing at Faculty of Engineering University of Kragujevac.

Key words: Structural fatigue tests, fatigue life, *ε–N* fatigue curves, S355J2+N steel grade

1. Introduction

There is no exact data, but many books and scientific articles have suggested that 50% to 90% of all mechanical failures are fatigue failures; and most of them usually are unexpected. It should be noted that for the difference of failure under static load, most fatigue failures occur without plastic deformation, whether regardless the materials are brittle or ductile [1]. Usually fatigue failure starts in the crystalline structure and becomes visible in a later stage by plastic deformation, forming of micro-cracks on slip bands, forming of macro cracks and finally propagation of a main crack. Fatigue of metals is a very complex phenomenon, which is still not fully understood and is also the topic of much active research. It can be defined as the failure of a component or material subjected to cyclic loads of which the resulting stresses are well under the yield or tensile strength of the particular material.

Many engineering components in different industries are operated in conditions in which they are subjected to low cycle fatigue at room and otherwise low or high temperatures. The material properties obtained from fully-reversed fatigue testing under total strain-controlled conditions are of the fundamental importance when designing components which are expected to working under repeated loads, during their service (fatigue) life. Many studies have been performed to investigate the cyclic response of materials subjected to cyclic loading [2], [3].

Today steels represent the most used group of mechanical materials. Steels are used in various branches of industry for constructing bridges, buildings, ships, cars, rail vehicles, railways. There are several thousand types of steel obtained by an appropriate combination of carbon and alloying elements of different characteristics. Because of good mechanical properties, good cutting, forming (forging, rolling, extrusion, pressing), good weldability and low prices, structural steels are widely used in industry. The most commonly used steel for producing carrying parts of structures, exposed to dynamic loads and low temperatures is medium-strength S355J2+N steel grade.

In this paper, the cyclic deformation behavior and fatigue life of S355J2+N steel grade without mean strains were studied experimentally.

2. Overview of current approaches to fatigue

The fatigue approaches may be divided into three classes (approaches): fatigue tests and stress-life (*S–N*) approach, cyclic deformation and the strain-life (ε–*N*) approach and linear elastic fracture mechanics based approach (LEFM) [1]. Stress-life (*S–N*) approaches are most useful at high cycle fatigue, where the applied stresses are elastic, and no plastic strain occurs anywhere other than at the tips of fatigue cracks. At low number of cycles, scatter in the fatigue data makes these methods increasingly less reliable. *S–N* approach is a global approach that relates the stress range (e.g. nominal, structural or geometric) applied to the component with the fatigue life [4]. The *S–N* approach is the basis of many standards for assessing the fatigue life, such as the Eurocode 3, part 1-9 [5]. For most stress-life calculations, the math is relatively easy, since there is only one stress component. In strain life calculations, the math is more difficult, as the elastic and plastic components of the strain must be dealt with separately.

Strain life (ε–*N*) approach and linear elastic fracture mechanics approach (LEFM) belong to local approach and it can be used for low cycle and high-cycle fatigue. The local approaches, recognizing the localized nature of the fatigue damage, propose the correlation of a local damage parameter (e.g. strain, energy) with the number of cycles required to initiate a macroscopic crack. LEFM approach represents an alternative approach to fatigue, based on the fatigue crack propagation phenomena [6], [7]. This approach is based on crack propagation laws, with Paris' law [8] and residual life computation of a structural component with an initial crack.

In ε–*N* approach loading is a combination of elastic and plastic deformation on the macro scale. In low cycle region, the plastic strain component is dominant, whereas in the high-cycle region the elastic strain component is dominant. ε–*N* approach use cyclic strain-controlled tests because better characterize fatigue behavior of a material than cyclic stress-controlled tests, particularly in the low cycle fatigue region. Mathematical model used to describe fatigue behavior of material under cyclic strain-controlled tests to obtained cyclic stress-strain (σ-ε) curve is given by Ramberg–Osgood approach [9] presented by equation:

$$\varepsilon_a = \frac{\Delta\varepsilon}{2} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} . \qquad (1)$$

The total strain-life (ε-N_f curve) is therefore expressed as the sum of Basquin's and Manson-Coffin's part by equation [1]

$$\varepsilon_a = \frac{\Delta\varepsilon}{2} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c . \qquad (2)$$

In equations (1) and (2) $\varepsilon_a, \varepsilon_{a,e}, \varepsilon_{a,p}$ are, respectively, the total, elastic and plastic strain amplitude; K', n' are, respectively, cyclic strain coefficient and cyclic strain hardening exponent; σ'_f, b are, respectively, fatigue strength coefficient and fatigue strength exponent; ε'_f, c are, respectively, fatigue ductility coefficient and fatigue ductility exponent; $2N_f$ is the number of reversals to failure; σ_a is true stress amplitude; E is the Young's modulus. All constants in equations (1) and (2) will be determined from fatigue tests of smooth specimens under strain-controlled conditions.

3. Description of the strain controlled uniaxial tension-compression fatigue test

This section describes a complete fatigue characterization of S355J2+N steel grade, carried out according to the internal procedures of the Centre for engineering software and dynamic testing at Faculty of Engineering University of Kragujevac, based on the ASTM E468-90 [10] and ASTM E606-92 [11] standards.

Uniaxial tension–compression fatigue tests of the S355J2+N steel grade was done at room temperature ambient (23±5ºC) The material used in the test was S355J2+N steel grade according to the EN10025-2:2007 [12] with the monotonic mechanical properties (minimum yield stresses of 355 MPa, minimum tensile strength of 530 MPa, Young's modulus $2.1\text{x}10^5$ MPa) for thicknesses below 16 mm.

Uniaxial tension–compression fatigue tests were performed by applying a sinusoidal wave in a universal servo-hydraulic machine SHIMADZU Servopulser EV101K3-070-0A [13] (Figure 1.), with 100 kN of axial maximum force. The shape and dimensions one of tested specimens are shown on Figure 2., in accordance with standard ASTM E606-92 [11]. All specimens have finely polished to minimize surface roughness effects. The tests were strain controlled by means of an SHIMADZU DYNASTRAIN TCK-1-LH dynamic extensometer with a ±1 mm working range (Figure 3.).

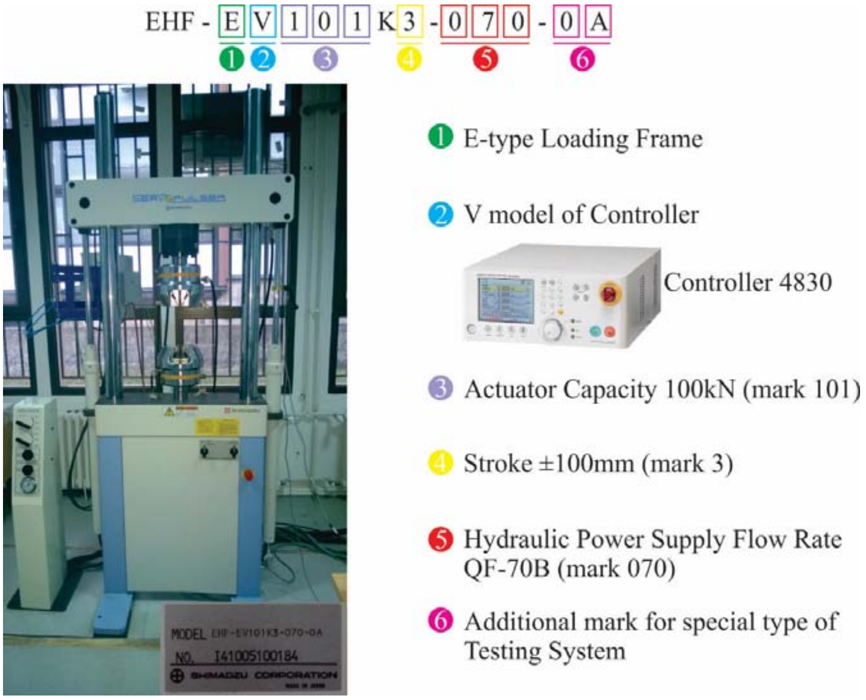

Fig. 1. SHIMADZU Servopulser EHFEV101K3-070-0A [13]

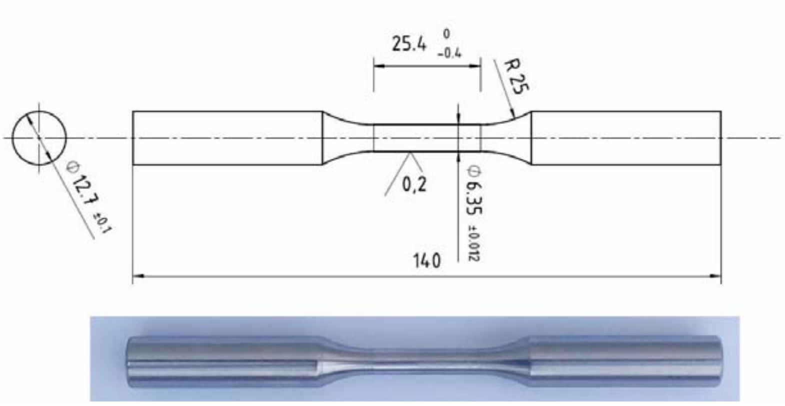

Fig. 2. Specimen for uniaxial tension–compression strain controlled fatigue test

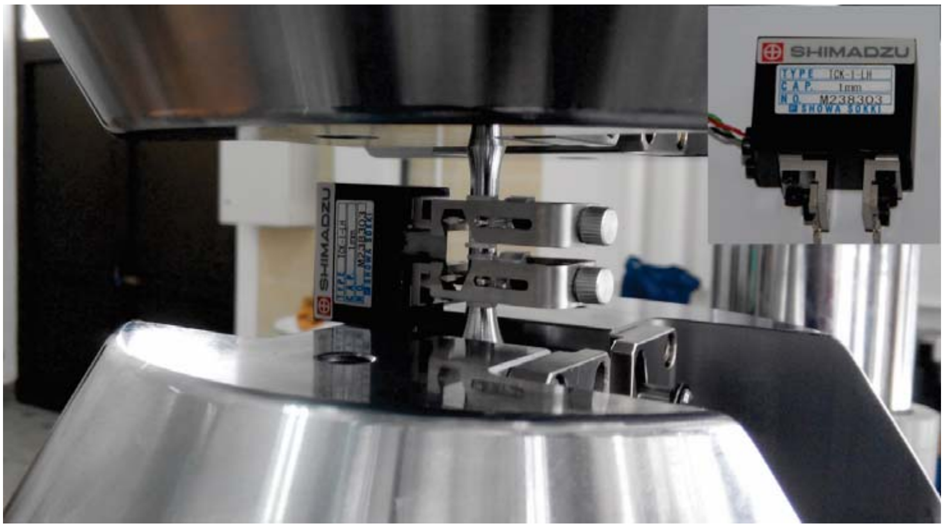

Fig. 3. SHIMADZU DYNASTRAIN TCK-1-LH dynamic extensometer

The strain levels used to control the fatigue tests were chosen from the previously performed monotonic material characterization. The selection criteria were to obtain fatigue life cycles between 10^4 and 10^6 cycles. The uniaxial tension-compression test planning (loading ratio $R=-1$, i.e. mean strain amplitude $\varepsilon_m=0\%$) is: five levels, three repetitions per level with a range of strain amplitude from 0.15% to 0.20%. The test frequency used in the characterization was in the range of 3–10 Hz, and the crack initiation criterion (failure criterion) was quick stiffness loss (load amplitude loss of about 10%).

4. Results and discussion

Table 1 shows the results of the uniaxial tension–compression strain controlled fatigue test. The normal stress amplitude σ_a were calculated by means of the maximum load applied to the medium life cycle in stable conditions divided by cross sectional area of the specimen at the beginning of the test.

Stabilized cyclic stress–strain hysteresis loops for one of the tested specimens, is shown in Figure 4. Stress-strain hysteresis loops for randomly chosen specimen show the effect of softening of S355J2+N steel grade under strain controlled fatigue test.

Mathematical model used to describe fatigue behaviour of the S355J2+N steel grade from uniaxial tension–compression fatigue tests, i.e. $\sigma - N$ cyclic curve, are created by taking Ramberg–Osgood's approach presented by equation (1). For description fatigue behaviour of the S355J2+N steel grade from uniaxial tension–compression fatigue tests, i.e. $\varepsilon - N$ cyclic curve equation (2), as the sum of Basquin's and Manson-Coffin's, part was used.

Specimen number	ε_a [%]	σ_a [MPa]	N_f
1-1	0.20	271.2	61900
1-2	0.20	270.5	50300
1-3	0.20	269.4	71000
2-1	0.18	254.1	92600
2-2	0.18	253.2	88300
2-3	0.18	253.2	103300
3-1	0.17	256.5	127600
3-2	0.17	250.4	109600
3-3	0.17	250.1	116000
4-1	0.16	243.1	310700
4-2	0.16	237.7	324700
4-3	0.16	234.3	257700
5-1	0.15	234.2	437500
5-2	0.15	233.0	1117200
5-3	0.15	238.2	389200

Table 1. Experimental uniaxial tension–compression strain controlled fatigue test results of S355J2+N steel grade

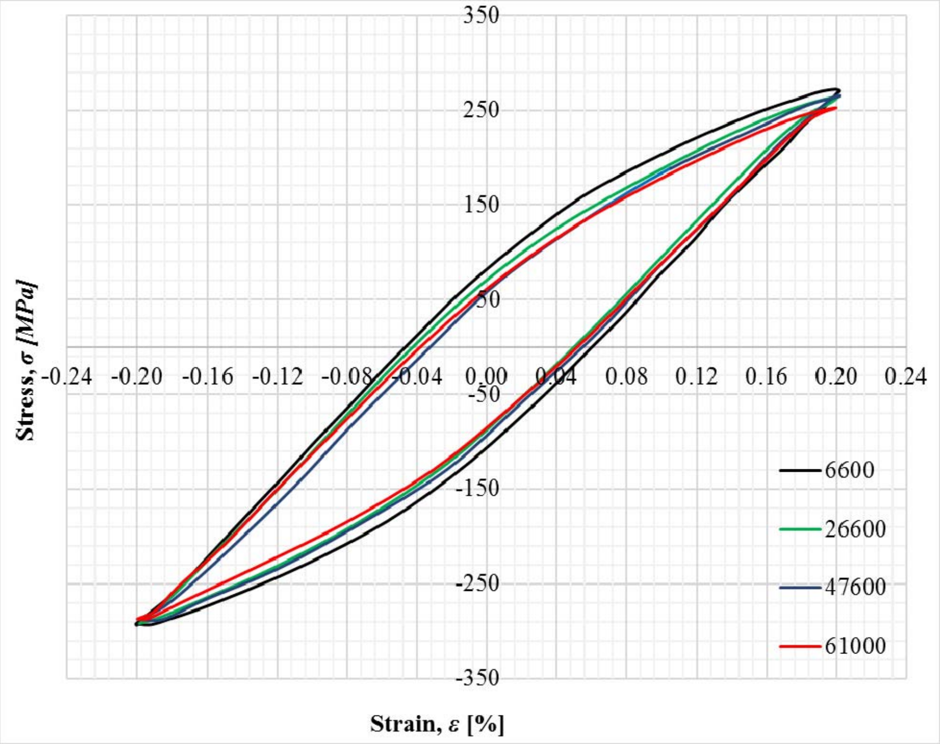

Fig. 4. Stabilized stress–strain hysteresis loops of tested specimen 1-1

Based on results shown in Table 1. and statistical analysis according to standard ASTM E739-91(2004) [14], uniaxial tension–compression strain controlled mechanical properties of S355J2+N steel grade have been shown in Table 2.

Uniaxial cyclic properties	Value
Cyclic strength coefficient, K’	1470.45 MPa
Cyclic strain hardening exponent, n’	0.2344
Cyclic yield strength, σy’	342.65 MPa
Fatigue strength coefficient, σf’	575.25 MPa
Fatigue strength exponent, b	-0.0656
Fatigue ductility coefficient, εf’	0.0182
Fatigue ductility exponent, c	-0.2087

Table 2. Uniaxial tension–compression strain controlled mechanical properties of S355J2+N steel grade

Based on experimentally obtained uniaxial tension–compression strain controlled mechanical properties of S355J2+N steel grade strain–life curve (log–log representation), have been determined and shown in Figure 5. Cyclic stress-strain curve from uniaxial tension–compression strain-controlled fatigue tests and graphical method for obtaining cyclic yield strength are shown in Figure 6.

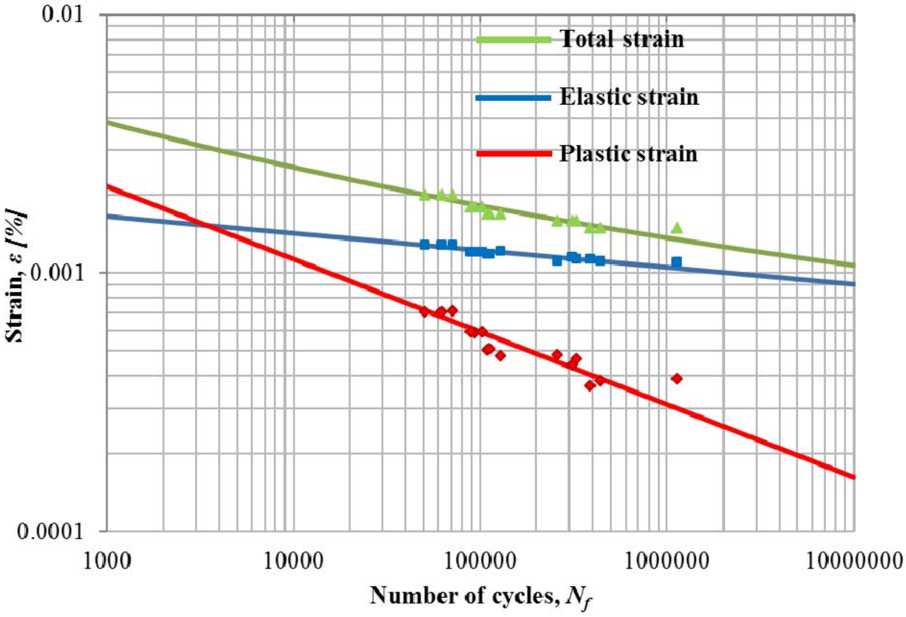

Fig. 5. Strain–life curve from uniaxial tension–compression strain controlled fatigue test of S355J2+N steel grade

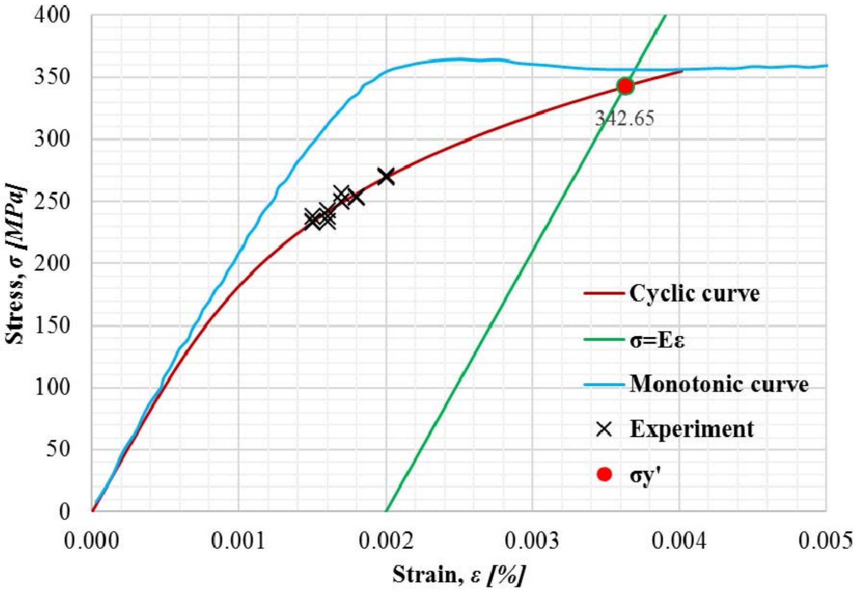

Fig. 6. Cyclic stress-strain curve from uniaxial tension–compression strain controlled fatigue test of S355J2+N steel grade

5. Conclusions

This paper has presented an experimental investigation into cyclic deformation behavior of S355J2+N steel grade. The hysteresis loop behavior, cyclic stress–strain response and strain-life curve determined by testing smooth specimens. A complete cyclic characterization of the material is obtained, including new experimental *ε–N* fatigue curves for uniaxial tension–compression strain controlled fatigue test. In relation to determine fatigue properties of material S355J2+N, the testing procedure was performed with help of special measurement device, servo-hydraulic SHIMADZU Servopulser EV101K3-070-0A. The cyclic curves exhibit the softening of the material in comparison with the monotonic curve. Obtained uniaxial tension–compression strain controlled mechanical properties and strain–life curve of S355J2+N steel grade show good correlations with results determined through another testing reported in literature. Experimental tests results have provided the basis for recommendation to use in fatigue life calculations the material cyclic properties determined in controlled conditions which are dominant during operation of machine components.

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