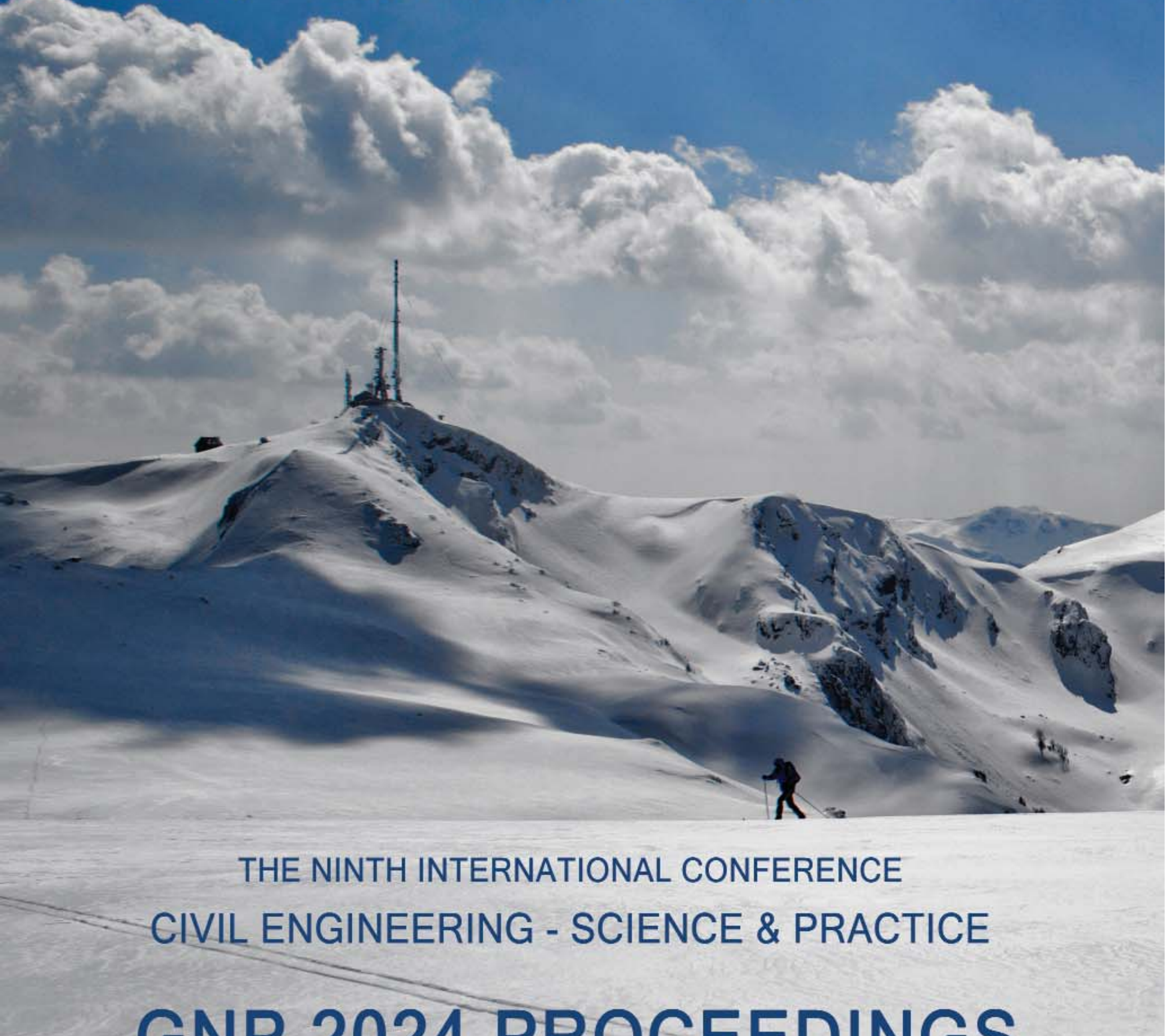
UNIVERSITY OF MONTENEGRO
FACULTY OF CIVIL ENGINEERING



THE NINTH INTERNATIONAL CONFERENCE

CIVIL ENGINEERING - SCIENCE & PRACTICE

GNP 2024 PROCEEDINGS

Kolašin, March 2024

UNIVERSITY OF MONTENEGRO

FACULTY OF CIVIL ENGINEERING

THE NINTH INTERNATIONAL CONFERENCE

CIVIL ENGINEERING - SCIENCE & PRACTICE

GNP 2024 PROCEEDINGS

KOLAŠIN, 5-9 MARCH 2024

GNP 2024 PROCEEDINGS

Publisher: **UNIVERSITY OF MONTENEGRO**
FACULTY OF CIVIL ENGINEERING

For Publisher: **Prof. dr Vladimir Božović**

CIP - Каталогизација у публикацији
Национална библиотека Црне Горе, Цетиње

ISBN 978-86-82707-36-3
COBISS.CG-ID 28528644

THE 9th INTERNATIONAL CONFERENCE
"CIVIL ENGINEERING – SCIENCE AND PRACTICE"

GNP 2024 – Kolašin, Montenegro, 5-9 March 2024

Ognjen Mijatović[1], Zoran Mišković[2], Ratko Salatić[3], Valentina Golubović - Bugarski[4], Matija Guzijan-Dilber[5]

DEVELOPMENT OF A TOOL FOR MEASURING THE EFFECT OF SURFACE ROUGHNESS ON STEEL STRUCTURAL RESPONSE

Abstract

Driven by the industry's needs to address energy dissipation issues in mechanical connections, the set goals of the global scientific community, and previous research efforts to interpret how the condition of contact surfaces between two bodies in contact can be significant, a unique experimental setup has been devised to study the impact of the state of contact interaction between two bodies on the system's response. The purpose of the designed experimental setup is to correlate the roughness of contact surfaces with the deformation of a specially designed experimental sample. The roughness of contact surfaces represents the most dominant influencing factor in the contact interaction of two bodies. In terms of scale, the study, measurement, and analysis of surface roughness fall under the micro and nano scales. On the other hand, the change in deformation of the experimental sample as a result of the change in roughness falls under the macro scale. Based on all the aforementioned, the fundamental idea of the designed experimental setup can be seen. Considering that it is not possible to enter into contact interaction and explicitly analyse the influence of roughness on the response of a mechanical connection, the idea in overall research is to consider the macro behaviour of a specially prepared experimental sample depending on the level of roughness of the contact interaction surfaces at the micro level. The aim of this paper is to present details and challenges in the construction of an instrument necessary for such precise examinations, named "Precision Press with Arcs".

Keywords

Experimental testing, Roughness, Micro scale, Friction, Mechanical joints

[1] *PhD student, CEng, University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Department of Mechanics and Theory of Structures, Faculty of Civil Engineering University of Belgrade, ognjen.mijatovic@aggf.unibl.org.*

[2] *Assoc. prof. PhD, CEng, Faculty of Civil Engineering University of Belgrade, zoran.miskovic@gmail.com.*

[3] *Full prof. PhD, CEng, Faculty of Civil Engineering University of Belgrade, ratko.salatic@gmail.com.*

[4] *Full prof. PhD, CEng, Faculty of Mechanical Engineering of University of Banja Luka, valentina.golubovic-bugarski@mf.unibl.org*

[5] *PhD student, CEng, Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya 29, 195251, St. Petersburg, Russia, nikobelic025@gmail.com.*

1. INTRODUCTION

The aim of the experiment is to determine how different conditions of contact interaction between the arc and the base plate will affect the overall deformation of the arc. It is important to note that the changes defined in the contact interaction are considered to be in the micro-scale range, representing a micro-level approach, while the changes occurring in the entire arc fall into the macro-scale range.

The significance of this research lies in establishing the relationship between changes in contact interaction, ranging from 10 to 670 nanometres, and the magnitudes of the overall arc deformation, which, depending on the contact interaction conditions, vary with average values ranging from 10 to 20 mm. The aim of the arc experiment is to examine the primary effects that can influence the contact interaction between two bodies, such as surface roughness, presence of contamination/lubrication, and corrosion.

2. DESCRIPTION OF THE BASIC PARTS OF PRECISE PRES WITH ARC AND MANUFACTURING PROCESS

As mentioned in the introduction, the aim of the arc experiment is to establish a correlation between changes in the contact interaction of two bodies at the micro/nanometre level and the overall deformation of the experimental sample. In this case, the sample is a semi-circular arc made of thin stainless steel strip, with a diameter of 200 mm, a width of 20 mm, and strip thickness of 0.8 mm. Importantly, for the accurate analysis of contact interactions at small scales, the construction of the experimental setup, namely the precision press, must be delicate and precise. Therefore, utmost precision was pursued during the construction of the precision press, employing CNC machine cutting and processing for the entire press to achieve maximum accuracy.

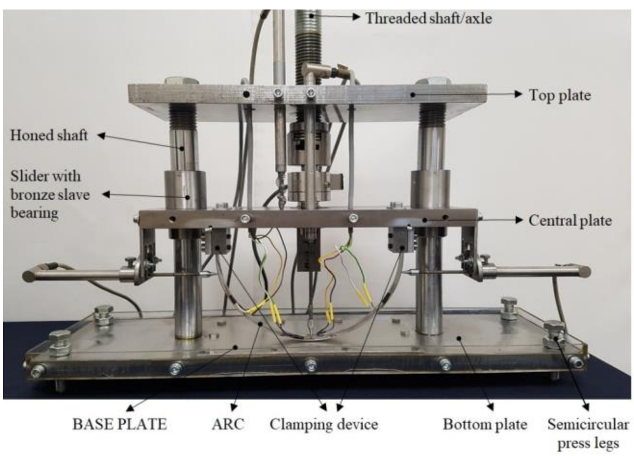


Figure 1. Main components of precise press.

The basic elements of the Precision press with the arc (PPA) are shown in Figure 1. The press is connected to the base via bottom plate which serves as a very rigid support structure. The central plate is vertically movable, while the top plate serves as a reinforcement for the press and ensures the required parallelism of all plates. It is also used as a support for the threaded shaft that pushes the central plate up and down. The top and bottom plates of the press are fixed and connected to form a frame using honed shafts/sliders. The guides, or honed shafts, have a fine surface finish (mirror-like) to ensure optimal fitting and sliding of the sliders. The movable central plate is positioned between the top and bottom plates of the press. It is connected through sliders that enable vertical movement along honed shafts along vertical axis. To ensure optimal fitting between the sliders and the honed shafts, sliders are lined with graphite bronze on their inner sides (from the inner side of the slider bronze sleeve bearings are installed), Figure 1. The vertical movement of the central plate is accomplished by a threaded shaft that has a threaded connection through the top plate. By rotating the threaded shaft through the thread on the top plate, the central plate can be moved up and down. To minimize resistance in the joint between the central plate and the threaded shaft, a torsional joint with an axial bearing is used. This design also provides easy access to install a force gauge.

The arc test samples are placed in the precision press using a clamping system that is specially designed to ensure the same initial conditions for all specimens, regardless of the number of tests. Importantly, the design and construction of the precision press are devise to enable identical boundary conditions for all test samples, regardless of their quantity. This will be discussed in more detail in the following chapter. Each arc (with specific surface roughness) will come into a contact with the base plate during deformation. The base plate and the arc are made of the same material and have the same surface roughness. The base plate is connected to the bottom plate of the precision press through a series of bolts. With each change of the arc, the supporting plate is also changed. Therefore, each test set consists of a semi-circular arc and a supporting/base plate with the same surface roughness.

In addition to the above, it is necessary to ensure consistent conditions during each testing phase. Therefore, all components of the precision press must be connected and fitted together using precision-profiled guides and assemblies that prevent any motion due to setting up the arcs and handling of the press during the experiment.

2.1. MANUFACTURING OF PRECISE PRESS

All components of the precision press were machined on appropriate CNC machines, and each element was manufactured within a tolerance range of 0.02 to 0.05 mm. In order to have the complete precision press within a tolerance of 0.2 mm, every part of it had to be manufactured with exceptional precision to account for an accumulation of imperfections during the machining and assembly of components.

Figure 2. Setting up and preparing a part of the precision press on the table of a four-axis CNC milling machine.

On Figure 2, it we shown the setup and preparation of a part of the precision press for machining on the worktable of a four-axis CNC milling machine.

To ensure consistent support conditions for each test and the placement of a new sample of the semi-circular arc, it was necessary to prevent rotations and movements of the clamp elements during the positioning and tightening of the bolts. Despite the precise drilling of holes for the bolts with tight tolerances, there is still a possibility of slight rotation of the clamp system relative to the surface of the central plate. In addition to the mentioned issue, a straightforward placing the arcs ends into the clamps and connecting them with bolts is not acceptable, as it may result in visible rotation of the arc ends within the clamps. In such cases, it cannot be guaranteed that the same boundary conditions will be maintained during successive tests.

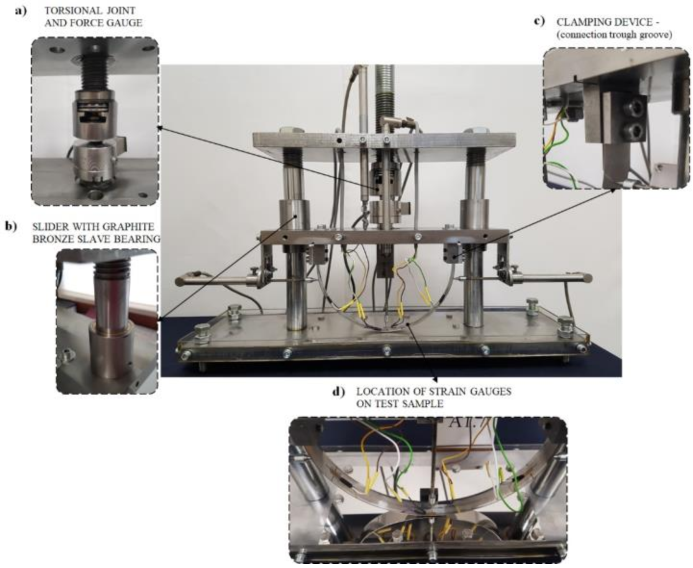


Figure 3. Precise press with details: a) torsional joint and force gauge, b) slider with graphite bronze slave bearing, c) clamping device, d) strain gauges.

During the tests, each sample of the semi-circular arc is placed in the press using clamps that are manufactured within tolerance so that the arc fits precisely within the clamp width. After tightening the clamps, any movement of the arc relative to the clamps is restrained. This can be seen in Figure 3c and Figure 4. The clamps are mounted on the central movable plate using bolts and grooves into which the clamps fit, preventing the clamps from moving when the bolts are tightened. In details shown in Figure 3c and Figure 4, we can observe that the package comprising one clamp is connected to the central plate using grooves and teeth that fit into the grooves. To ensure precise movement of the central plate along the honed shafts/guides, the sliders are coated with graphite bronze bearing to minimize friction and ensure better fit between the sliders and honed guides, as depicted in Figure 3b. Furthermore, Figure 3a shows the torsion joint and measuring cell that form the connection between the threaded shaft and the central movable plate. In addition, in Figure 3d, we can see the arc placed in the clamps and the base plate connected by a series of bolts to the bottom plate of the press, where the arc and base plate form one testing set.

Figure 4. Clamping device for installation of arcs

After the detailed construction and preparation of the precision press, the preparation of experimental samples was carried out, which included cutting stainless-steel strips from which arcs will be bent, cutting the base plates, achieving the appropriate roughness of the arcs and base plates, measuring the roughness, and bending the arcs. A series of trial tests were performed to identify any potential flaws in the experiment that needed to be addressed and resolved.

The tolerance for manufacturing the arcs (or the strips that will later be bent into arcs using a roller system) is between 0.05 mm and 0.1 mm over a length of 410.16 mm. This length corresponds to the size of one strip before bending and cutting the ends to the precise length of the arch, which is 314.2 mm, with a width of 20 mm. Considering the requirement for high precision and a need to avoid altering the material's physical and mechanical properties during and after cutting, laser cutting was not a feasible option for cutting the strips. If we consider that the stainless steel used for the arcs has a thickness of 0.8 mm and a width of 20 mm, laser cutting would result in an approximately 2 to 3 mm zone around the cutting area where the material's physical and mechanical characteristics would be compromised. Therefore, an alternative method that ensures minimal alteration of the material properties was necessary. Therefore, the cutting of the strips was carried out on a CNC milling machine. To avoid damaging and warping the base material, each stainless-steel plate was placed between two additional steel plates, creating a stack of sheets for cutting. This sandwich consists of an upper plate with a thickness of 1.5 mm and a lower plate with a thickness of 3 mm, while the stainless steel plate that need to be cut is placed in between. This procedure ensures the cutting of strips without unnecessary damage to the base material, Figure 5a.

Preparation of adequate and defined surface roughness is a challenging task for which were examined different procedures, recommendations, and steps [1-5]. The polishing of the arcs and base plates has been performed using a machine equipped with a cotton rotating disc and the appropriate stainless steel polishing pastes, Figure 5b. To achieve a uniform distribution of roughness in all directions without visible patterns or orientations, an eccentric rotary sander with suitable abrasive paper (sandpaper) was used for the roughening process. After polishing or roughening, depending on the desired sample, the prepared strips were bent into the desired semi-circular shape with a radius of 100 mm using rollers, as shown in Figure 5c. The cutting, polishing, and bending processes of the arcs are illustrated in Figure 5. Figure 6 displays the proper alignment of the bent arc with a schematic representation of the arc on paper.

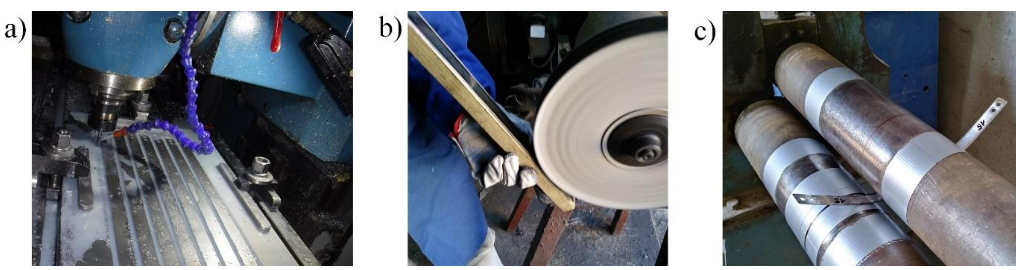


Figure 5. Stages of manufacturing the arcs for testing: a) Cutting strips for the arcs on a milling machine, b) Polishing of strips for the arcs on a cotton wheel, c) Bending the arcs on rollers.

Within the experiment, it was planned to conduct tests under five different conditions of contact interaction between the arc and the base plate, as illustrated in Table 1. The testing encompassed polished and rough arcs and base plates under both dry and lubricated conditions. Furthermore, a series of tests were carried out on arcs with 2R roughness under dry friction conditions.

Table 1. Different types of test specimens

Type of steel	Friction condition	Roughness Ra	Sample name	Sample mark
EN - SS1.4301	Dry friction	11 - 14 nm	Dry polished	**A1**
EN - SS1.4301	Friction with lubrication	11 - 14 nm	Greasy polished	**A2**
EN - SS1.4301	Dry friction	500 - 800 nm	Dry rough	**A3**
EN - SS1.4301	Friction with lubrication	500 - 800 nm	Greasy rough	**A4**
EN - SS1.4301	Dry friction	30 - 35 nm	2R	**A5**

Dray polished arcs and base plates refer to experimental samples with a surface roughness of approximately 12 nm. Dray rough samples, on the other hand, have a surface roughness of approximated 670 nm. The 2R roughness samples imply a roughness of approximately 35 nm. Different types of arc samples are represented in Figures 7.

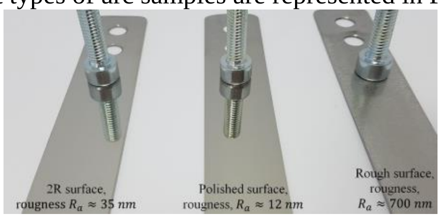


Figure 7. Different roughness: polished, rough, and 2R specimens prior to bending

4. EXPERIMENTAL SETUP

Until this point, construction of the press and the experimental samples has been explained. In this subsection, the positioning and application of measuring instruments, specifically displacement gauges, strain gauges, and force gauges, will be discussed. Figure 5 shows the complete experimental setup, which includes the following components:

- Data acquisition system: This system is used to collect and record data during the experiment. It enables precise monitoring of displacements, forces, and deformations.
- Two displacement gauges (HBM Inductive displacement transducers) with a capacity of 100 mm each: These gauges are used to measure the displacements and movements of specific components in the experiment.
- Two displacement gauges (HBM Inductive displacement transducers) with a capacity of 50 mm each: These gauges are also utilized to measure displacements, but with a smaller range.
- Force gauge with a capacity of 1000 N: This gauge is employed to measure the applied force during the experiment.
- Four strain gauges (Post-yield strain gauges YFLA-5) with dimensions of 5x5x1.9 mm and a strain limit of 15-20%: These gauges are attached to each of the experimental samples (arcs) to measure the strain and deformation.
- The experimental setup shown in Figure 14 illustrates the measuring system and the precision press with the arc positioned in the clamps, along with the displacement gauges and strain gauges.

Figure 5 provides a detailed depiction of the precision press with the installed experimental sample of a semicircular arc and the measuring instruments. The deflection measurement was performed using 4 electronic displacement gauges. Three displacement gauges were positioned along the axis of the arc. The left and right displacement gauges were fixed to the central plate and moved together with it to continuously monitor the lateral deformations of the arc. One displacement gauge was inserted through the central plate of the precision press to measure the deflection of the center of the arc during deformation – the central displacement gauge.

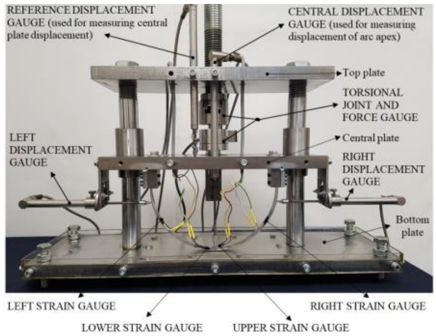


Figure 5. Arrangement of the precision press with measuring instruments

5. DISCUSSION

In the process of designing the experimental setup, the author primarily considered studies related to the first and second experimental setups of the Imperial College London, namely the |First and Second Generation Rig [6-8], and the experimental setup of the large mass device, named Big Mass Experiment [9]. By examining the methods and techniques employed in these studies, which clearly illustrated the impact of micro-effects related to the surface condition of bodies in contact, an experimental setup was devised with the aim that, as clearly and precisely as possible, the influence of the contact interaction condition on the behaviour of the entire system. After a thorough analysis of the effects that can influence the behaviour of the contact between two bodies, it was established that the roughness of contact surfaces during dry sliding friction is one of the most significant phenomena affecting contact interaction behaviour, [10-14]. Based on this conclusion, an experiment, or we can say a tool, was devised to investigate the influence of roughness on the deformation of the experimental sample, named Precision Press with Arcs (PPA).

As demonstrated in Chapters 2 and 3, when the goal is the comparison and analyse very small sizes at the micro or manometer level, challenges arise in how to conduct experiments without introducing small dimension irregularities during the experimental setup and manufactured procedures. Therefore, in the process of constructing the experimental setup, it is crucial to pay attention to the smallest details, continuously perform tests, and verify the required precision of the prepared experiment. The boundary conditions of samples, i.e., the placement of semi-circular arcs in the PPL and the contact interaction between the arc and the support plate, must be, figuratively speaking, of mathematical accuracy. This is essential to establish a consistent mathematical or numerical model based on experimentally obtained results.

6. CONCLUSIONS

The described method of constructing the PPL has achieved satisfactory precision of the entire arc testing mechanism. The precise fabrication of each element and the use of various fitting methods have prevented any form of displacement or rotation of one element relative to another. In this way, the same boundary conditions are ensured for each experimental sample placed and tested in the PPL. Compared to the flexibility of the test arcs, the PPL represents a rigid and stable structure that will not influence the measurement results of stress and deformation in the arcs based on the roughness of the contact surfaces, which was the main objective in the process of constructing the PPL

ACKNOWLEDGEMENTS

The authors express gratitude for the financial support from the Ministry of Education, Science and Technological Development of the Republic of Serbia, Grant no. 451-03-68/2020-14/200092 (University of Belgrade, Faculty of Civil Engineering).

LITERATURE

[1] K. J. Stout, E. J. Davis, and P. J. Sullivan, *Atlas of Machined Surfaces*. Dordrecht: Springer Netherlands, 1990. doi: 10.1007/978-94-011-7772-6.

[2] I. V. Kragelsk and V. V. Alisin, "Friction Wear Lubrication - 1st Edition." [Online]. Available: https://shop.elsevier.com/books/friction-wear-lubrication/kragelsky/978-0-08-027591-8

[3] M. Sahin, C. S. Çetinarslan, and H. E. Akata, "Effect of surface roughness on friction coefficients during upsetting processes for different materials," *Mater. Des.*, vol. 28, no. 2, pp. 633–640, Jan. 2007, doi: 10.1016/j.matdes.2005.07.019.

[4] G. Straffelini, *Friction and Wear: Methodologies for Design and Control*. in Springer Tracts in Mechanical Engineering. Cham: Springer International Publishing, 2015. doi: 10.1007/978-3-319-05894-8.

[5] Tom R Thomas, *Rough Surfaces*, 2nd Edition. World Scientific Publishing Company, 1998.

[6] M. R. W. Brake, Ed., *The Mechanics of Jointed Structures: Recent Research and Open Challenges for Developing Predictive Models for Structural Dynamics*, 1st ed. 2018 edition. New York, NY: Springer, 2017.

[7] C. W. Schwingshackl, E. P. Petrov, and D. J. Ewins, "Measured and Estimated Friction Interface Parameters in a Nonlinear Dynamic Analysis," *Mech. Syst. Signal Process.*, vol. 28, pp. 574–584, Apr. 2012, doi: 10.1016/j.ymssp.2011.10.005.

[8] A. Fantetti *et al.*, "The Impact of Fretting Wear on Structural Dynamics: Experiment and Simulation," *Tribol. Int.*, vol. 138, pp. 111–124, 2019, doi: 10.1016/j.triboint.2019.05.023.

[9] D. Segalman *et al.*, "Handbook on Dynamics of Jointed Structures.," Jul. 2009. doi: 10.2172/1028891.

[10] E. Rabinowicz, *Friction and Wear of Materials*, 2nd edition. New York: Wiley-Interscience, 1995.

[11] F. P. Bowden, "Friction," *Nature*, vol. 166, no. 4217, Art. no. 4217, Aug. 1950, doi: 10.1038/166330a0.

[12] F. P. Bowden and D. Tabor, *The Friction and Lubrication of Solids*, Revised ed. edition. Oxford : New York: Oxford University Press, 2001.

[13] V. A. Yastrebov, G. Anciaux, and J.-F. Molinari, "From Infinitesimal to Full Contact between Rough Surfaces: Evolution of the Contact Area," *Int. J. Solids Struct.*, vol. 52, pp. 83–102, Jan. 2015, doi: 10.1016/j.ijsolstr.2014.09.019.

[14] V. A. Yastrebov, J. Durand, H. Proudhon, and G. Cailletaud, "Rough surface contact analysis by means of the Finite Element Method and of a new reduced model," *Comptes Rendus Mécanique*, vol. 339, no. 7, pp. 473–490, Jul. 2011, doi: 10.1016/j.crme.2011.05.006.