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DEVELOPMENT OF AUTONOMOUS EXPERIMENTAL SYSTEM TO ANALYSE YIELD SURFACES DISTORTION DUE TO MULTIAXIAL RATCHETING

Svárovský J.*, Parma S.*, Štefan J.*, Ciocanel C., Feigenbaum H. P.**, Marek R.*, Klepač V.*, Plešek J.***

Abstract: *Multiaxial ratcheting is a failure mode of structures characterized by the accumulation of plastic strain due to cyclic loading. Despite several models having been developed to predict multiaxial ratcheting, they often fail when validated with experimental data collected under a wide array of loading conditions. In this study, an experimental setup was developed and an autonomous testing procedure was used to experimentally analyze the evolution of the yield surface shape due to cyclic biaxial loading. Thin-walled tubular test specimens were made of 304L steel with a diameter of 40 mm and underwent axial-torsional testing using the Instron 8852 system. The total axial strain was increased from 0 to 1% while the total shear strain underwent 5 cycles with the strain amplitude of 0.5% and the mean strain of 0.5%. Three yield surfaces were measured after the straining sequence was completed. Results showed strong directional distortional hardening and good agreement between the flow vectors and the normals to the yield surface, lending support to the associative flow rule.*

Keywords: Yield Surface Distortion, Strain Hardening, Multiaxial Ratcheting, Flow Rule

1. Introduction

Multiaxial Ratcheting (MR) is characterized by the accumulation of plastic strain due to cyclic loading and is considered a failure mode of structures. Numerous models have been developed to predict MR, some of which were subsequently modified and refined. However, the models often fail when validated on experimental data sets collected under broad loading conditions, *e.g.*, various amplitudes, mean stresses, and loading path shapes. Although the majority of authors identified the kinematic hardening rule as a key feature to improve the predictive capabilities of models in MR simulations, there are several papers that call for improvement of the yield function, *cf.* Welling *et al.* (2017). In particular, the distortion of yield surfaces was observed in numerous experiments, as reported by Wu and Yeh (1991), Štefan *et al.* (2021), and Marek *et al.* (2022), among others. Also, numerous models have been developed to capture the phenomenon of yield surface distortion, *e.g.*, by Feigenbaum and Dafalias (2007) and Liu and Hong (2017). Note that some of the models from Feigenbaum–Dafalias family were implemented, calibrated, and used in multiaxial ratcheting simulations, as can be seen in Welling *et al.* (2017). Thus, an accurate description of the yield surface shape and, therefore, the plastic flow direction when using the associative flow rule (as is typical for metals), is expected to be crucial to improve MR models. Within this work, we aim to develop an experimental setup and an autonomous testing procedure to experimentally analyze the evolution of yield surface shape due to cyclic loading under biaxial loading mode, such as the work by Halama *et al.* (2019). Here, the long-term objective is to determine the mutual influence of yield surface shape evolution and MR.

* Ing. Jiří Svárovský, Ing. Slavomír Parma, Ph.D., Ing. Jan Štefan, Ph.D., Ing. René Marek, Ph.D., Ing. Vilém Klepač, Ing. Jiří Plešek, CSc.: Department D4 - Impact and Waves in Solids, Institute of Thermomechanics of the CAS, v. v. i., Dolejškova 1402/5; 182 00, Praha 8; CZ; {svarojir; parma; stefan; marek; plesek}@it.cas.cz

** Constantin Ciocanel, Ph.D., Heidi P. Feigenbaum, Ph.D.: Mechanical Engineering Department, Northern Arizona University, 15600 S. McConnell Dr. NAU; Flagstaff, AZ 86001-5600; US.

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2. Experimental Setup

The axial-torsional testing of the present study was executed utilizing the Instron 8852 system, which comprises of a universal hydraulic testing machine (UTM), a control unit, and a computer. The UTM, capable of applying axial loads of ± 100 kN and torques of ± 1000 Nm, was interfaced with the PC via the two-axis 8800MT digital controller and the Console software, enabling comprehensive system control from the computer. The Console software can also be utilized with other programs, including proprietary software by Instron (*e.g.,* WaveMatrix2, Bluehill Universal) and in-house software, through APIs. In the current experiment, a custom software was created using a visual programming environment to control the UTM during the Yield Surface (YS) tracing. The testing setup also includes a biaxial contact extensometer Epsilon Tech 3550, which was utilized to measure axial and shear strains on the test specimens. A more in-depth description of the experimental setup can be found in Štefan *et al.* (2021).

3. Material and Specimens

Thin-walled tubular test specimens (TS) fabricated from 304L steel round bars with a diameter of 40 mm underwent experimental testing and are shown in Fig. 1. The exterior of the TS underwent CNC machining and lapping for surface finish, while the inner bore was created through electrical discharge machining. Steel pin inserts were utilized to secure the TS end sections during the experiment, mitigating the risk for failure under hydraulic grip force.

4. Methodology

The procedure for tracing the Yield Surface involves measuring a set of yield points at specified combinations of axial load and torque. The act of measuring a single yield point is known as a probe, and the chosen probing system is depicted in Fig. 2. A slow, stress-controlled loading process is applied to the specimen from the center point, using the given normal and shear stress ratios defined by the probing system. The effective plastic strain accumulated in the specimen's testing section during a single probe reads

$$\varepsilon_{\text{eff}} = \sqrt{\left(\varepsilon^{\text{tot}} - \frac{4F}{\pi\left(D^2 - d^2\right)E} - \varepsilon^{(0)}\right)^2 + \frac{1}{3}\left(\gamma^{\text{tot}} - \frac{16DT}{\pi\left(D^4 - d^4\right)G} - \gamma^{(0)}\right)^2}, \tag{1}$$

where F and T are the axial load and torque, respectively; d and D are the inner and outer specimen's diameters, respectively; ε^{tot} and γ^{tot} are the axial and shear total strains, respectively; E and G are the Young's and shear moduli, respectively; and $\varepsilon^{(0)}$ and $\gamma^{(0)}$ are the axial and shear initial offsets, respectively. The yield condition is met as soon as the effective total strain reaches its threshold value of $50\,\mu\varepsilon$, which is taken after Dietrich and Kowalewski (1997). Thus, particular probe is terminated as soon as $\varepsilon_{\text{eff}} \geq 50\,\mu\varepsilon$.

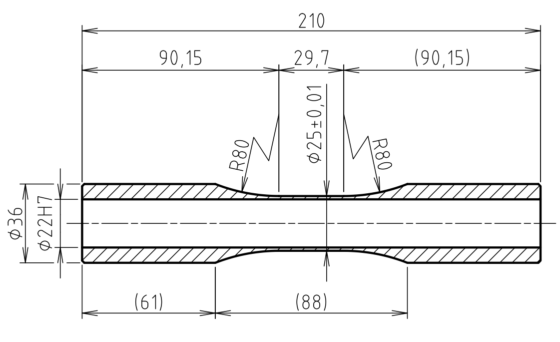

Fig. 1: Specimens' geometry.

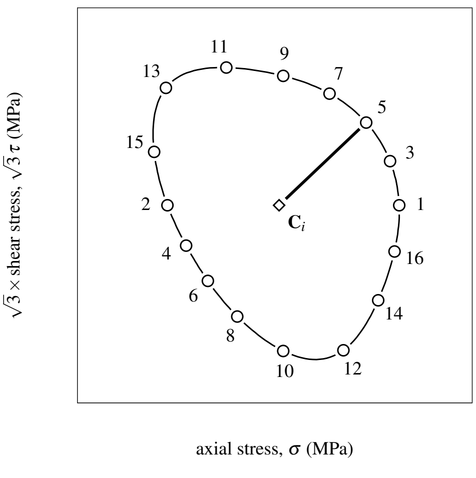

Fig. 2: Probing paths pattern after Dietrich and Kowalewski (1997) used to detect yield surfaces.

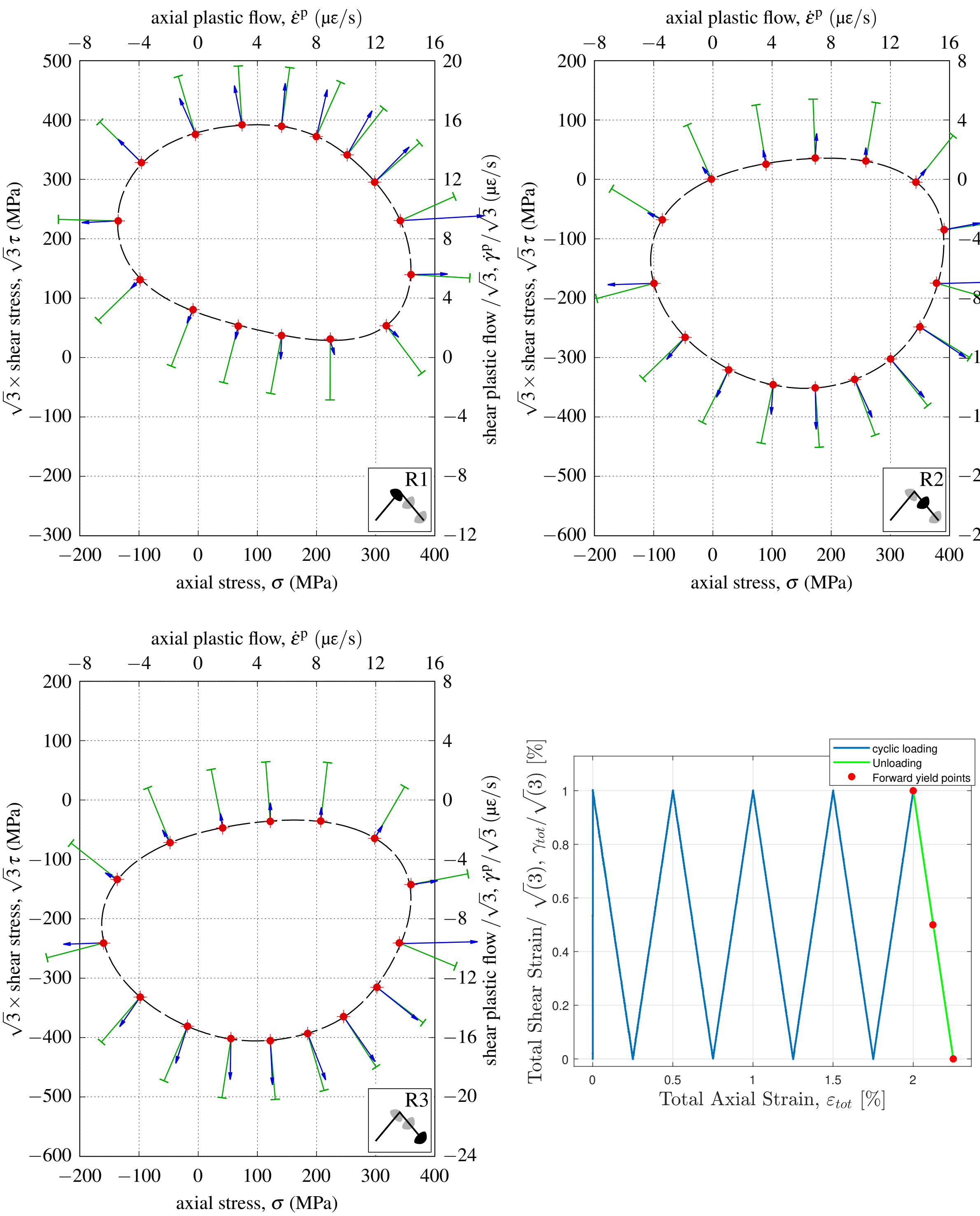

Fig. 3: Distortion of yield surfaces due to cyclic loading straining trajectory.

5. Results

The present study aimed to investigate the plastic behavior of material under multiaxial cyclic loading. The experiment was conducted in a strain-controlled mode on the biaxial testing machine, with the total axial strain linearly increasing from 0 to 1%. The total shear strain was subjected to 5 cycles with the strain amplitude of 0.5% and the mean strain of 0.5%. The cyclic straining path is shown in Fig. 3.

Following the cycling straining, three yield surfaces were measured. After the multiaxial cycling straining was completed, a 10-minute holding period was purposely implemented in which the test specimen was maintained at a constant strain level. The first YS was then measured at the point $\left(\varepsilon^{\mathrm{tot}}, \gamma^{\mathrm{tot}}/\sqrt{3}\right) = (2.000\%, 1.000\%)$. The second YS was measured at the point $(2.123\%, 0.500\%)$. Finally, the third YS was measured at the point $(2.250\%, 0.000\%)$. To ensure the accuracy and reliability of results, three repetitions were performed for each yield surface. The results shown in Fig. 3 are the average from the three readings.

6. Discussion

Three yield surfaces were successfully traced after a straightforward cyclic straining experiment was carried out. One of the key findings from this study is the observation of strong directional distortional hardening (DDH), which emphasizes the material's anisotropy under biaxial loading conditions. In addition to DDH, strong kinematic hardening was observed, in contrast to isotropic hardening, which was of little significance. Furthermore, the results from this study show that the flow vectors are in good agreement with the normals to the yield surface, lending support to the associative flow rule. This finding is particularly important for modeling the behavior of materials under multiaxial loading conditions, as it provides a useful tool for accurately predicting material behavior in a variety of loading paths.

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