Experimental characterization of materials subjected to combined loading conditions

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Abstract. In real life experience, machine and structure elements are subjected to complex loading history. Combined loading testes facilitate the understanding of materials behavior subjected to multiaxial stress state. In this paper are presented experimental investigations used to evaluate the influence of an initial type of loading on material properties which will be subsequently tested through another load type. Initial tests are tension tests, by different elongations, and subsequent tests are torsion tests, until break. Circular cross section specimens will be used in these tests. Tension tests have been performed on a universal testing machine. Subsequently torsion tests have been conducted through an attachable device. It was found that the energy associated with plastic deformation obtained by subsequent torsional tests has the dominant influence on the material total plastic energy, although initial test was tension.

1. Introduction
Knowing and understanding materials behavior under multiaxial stress state has a major theoretical and practical importance. By the means of combined loadings can be imposed a multiaxial stress state. Combined loadings can be used to validate failure criteria [1] and also presents a significant practical interest (shafts, fasteners, blade turbine etc.). Tension-torsion test represents a particular case of combined loadings.

Combined axial/ torsional loadings can be realized with two types of specimens:
• Tubular.
• Circular solid.

Different materials are subjected to combined tension–torsion deformation for micro-structural evaluation: pure copper [6], [12], polymers [17] etc. Torsion of ductile materials allows obtaining large plastic deformations. This test can be performed either with devices attached to universal testing machines [2] or using individual machines [3], [13]. In torsion tests, when axial displacements are allowed, shortening or lengthening of material occurs. This phenomenon has been studied for the first time by Swift [8].

Combined loadings can be realized with different experimental setups:
• With one loading system (custom-built [7] and axial-torsional servo hydraulic fatigue testing machines [5]).
• With individual systems for each test (tension and torsion) including machines and devices.
Independent machines have active control systems (servo hydraulic, electrical) while devices depends on their geometry and construction to vary the loading. Axial and torsional strains can be controlled and measured precise with a bi-axial extensometer when a servo-controlled machine is used.

With respect to end conditions, torsion test can be divided in:
- Torsion with fixed-end [11], [14], [15].
- Torsion with free-end [4], [9], [10], [16].

Axial load and torsion can be applied through:
- Successive combined loading.
- Simultaneous loading (axial/torsional, varying the ratio between them).

Successive combined loading can be realized by two distinct loading paths:
- Initial torsion and subsequent axial load.
- Initial axial load and subsequent torsion.

Through tensile-torsion tests will be evaluated the influence of initial plastic deformation produced by tensile test on some mechanical properties such as hardness, yield limit etc., obtained by subsequent torsion test.

2. Materials and Methods

In this paper is investigated behavior of a ductile material subjected to an initial tension test and a subsequent torsion test. These tests consisted in combined loading of specimens manufactured from structural steel S 235 JR. Specimens used are with circular cross section. Mechanical and elastic characteristics of material were determined by uniaxial tensile testing.

Combined loadings purpose is to evaluate each of the two tests (tension and torsion) influence on the material behavior. Tensile tests were conducted in the elastic-plastic domain. Initial tensile test of specimens with circular cross section was performed on Instron 8801 universal testing machine. Subsequent torsion test was made using an attachable device. By torsion test, torque-twist angle diagram is obtained.

The test cycle consisted from three phases:
- Preloading – when specimens are subjected to initial tensile test, by varying displacements;
- Elastic recovery - when specimens are unloaded;
- Reloading – when specimens are subjected to torsion test, until break.

There have been manufactured and tested a total of seven samples. One sample was tested until break and the results are used as reference in determining the value of elongation when each test will be stopped. Stress-strain diagrams for six specimens (noted P_A...P_F) are presented in figure 1.

Figure 1. Stress-strain diagrams (initial tensile test).
Maximum values of force and elongation, when tests have been stopped for each specimen, are presented in table 1.

**Table 1. Maximum values for displacement and force for each specimen.**

|     | Force [N] | Elongation [mm] |
|-----|-----------|-----------------|
| P_A | 36646.9   | 17.8            |
| P_B | 39106.1   | 14              |
| P_C | 40801.6   | 11              |
| P_D | 38515.22  | 8               |
| P_E | 35507.2   | 5               |
| P_F | 31937.9   | 2               |

After initial tensile test, Vickers hardness was determined on the generator of specimens. The interval between the indentation points is the same for all samples. It was used the average value of hardness obtained for each sample individually, to express the variation as function of plastic deformation energy. Distribution of hardness for each specimen is presented in figure 2.

![Figure 2. Vickers hardness evolution for six samples (after initial tensile test).](image)

For each specimen, Vickers hardness high values were correlated with areas where plastic deformation of the material was important.

Elastic strain energy and plastic deformation energy are determined from force-elongation diagram (figure 3), using equation (1) in the case of tensile test and from torque-twist angle diagram in the case of torsion test. The elastic part of energy is represented by the area to the right of the unloading line, at break (a triangle). The plastic energy is area under the curve, and can be expressed as:

$$E_p = \sum_i \left[ \frac{(F_{i+1} + F_i) \cdot (l_{i+1} - l_i)}{2} \right] - \frac{F_p \cdot l_e}{2}$$

(1)

where $l_i, l_{i+1}$ are displacements values given by testing machine in positions $i$ and $i+1$; $F_i, F_{i+1}$ represents forces values in positions $i$ and $i+1$; $F_p$ is ultimate value of force corresponding with curve end point and $l_e$ — represents values of displacement corresponding to elastic unloading area, at break.
Figure 3. Determination of deformation energies for tensile testing.

Total energy required to break specimens is determined with relation:

\[ E_t = E_{pT} + E_{pR} \]  \hspace{1cm} (2)

where: \( E_{pT} \) represents plastic deformation energy obtained through tension test and \( E_{pR} \) represents plastic deformation energy obtained through torsion test.

After initial tension test in the elastic-plastic domain, specimens were subjected to subsequent torsion test, until break. Control of twist angle has been imposed by adopting certain values of universal testing machine traverse stroke. Torque-twist angle diagram for each specimen subjected to subsequent torsion test is presented in figure 4.

Figure 4. Torque-twist angle diagram (subsequent torsion test).

3. Results and discussions
The variation of Vickers hardness as function of energy associated with plastic deformation from tensile test is presented in figure 5. Hardness values decrease with decreasing values of plastic deformation energies.
In Figure 5 is presented the evolution of hardness versus plastic deformation energy (initial tensile test). In Figure 6 is presented the variation of shear stresses as a function of plastic deformation energy assigned to the tension test. Specimen P_A is the sample with the largest elongation, while P_F is the sample with the smallest elongation. Specimen P_F has the highest value for ultimate shear stress (413 MPa). Specimen P_E has the highest value of yield limit (227 MPa). Starting with sample P_F, both ultimate shear stresses and yield limits show a decrease. Smallest values for yield limit are determined for P_F (182 MPa) and P_A (184 MPa).

In Figure 7 is presented the evolution of total energy for all six specimens subjected to initial tension test and subsequent torsion test until break.

Figure 5. Evolution of hardness versus plastic deformation energy (initial tensile test).

Figure 6. Variation of shear stresses as a function of plastic deformation energy assigned to tension test.

Figure 7. Evolution of total energy for all six specimens subjected to initial tension test and subsequent torsion test until break.
Figure 7. Evolution of total energy for tension-torsion combined loading.

Specimen P_F, with the smallest value of elongation, 2 mm (table 1), has the highest value of total plastic deformation energy, calculated with equation (2). Specimen P_A, with the highest value of elongation, 17.8 mm (table 1), has the smallest value of total deformation energy. Total plastic deformation energy increase due to influence of energy associated with plastic deformation from torsion test.

4. Conclusions
In this paper behaviour of S 235 JR structural steel subjected to complex loading conditions was studied. Circular cross specimens were subjected to an initial tensile test and a subsequent torsion test until break. High values of Vickers hardness are present in specimens were necking occurs, after initial tensile test. Specimens with highest values of plastic deformation energy, have higher values of ultimate shear stress. Starting from the most elongated specimen, both yield limit and ultimate shear stress increase due to influence of subsequent torsion test. Failure of material is influenced by the subsequent torsion test.

5. References
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