Numerical and experimental study of cruciform specimens subjected to biaxial tensile test

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Abstract. Multiaxial stress states are very common in engineering applications. To obtain a plane stress state in a material are used different experimental procedures. Biaxial tensile tests of cruciform specimens represent one of the most versatile techniques with accurate results for a wide range of materials. Specimen geometry and size must be adapted to biaxial experiments that use devices attached to universal testing machine. Biaxial tensile tests are performed using cruciform specimens optimized by a numerical study through finite element analysis and a custom built attachable device developed. The results obtained show that the method proposed in this paper can be used with good results to characterize the behaviour of ductile materials.

1. Introduction

Structural and machine elements are subjected commonly to combined loading conditions during lifetime. This condition generates a complex state of strains and stresses in material. It is necessary to know behaviour and failure mechanisms of materials subjected to complex loading conditions. Multiaxial tests represent an important tool in this way. Parameters obtained through experiments are used in constitutive models. They are used to predict failure. Development of finite elements analysis codes, measurement techniques, and experimental procedures, coupled with a multidisciplinary approach are necessary in understanding materials behaviour. A step forward is the design of triaxial and biaxial testing machines and devices. In the last decades have been proposed different experimental setups/ facilities:

- Servo hydraulic triaxial testing machines [5].
- Electromechanical test frames [20], [22].
- Servo hydraulic biaxial testing machines [9].
- Custom-built biaxial testing machines [6],[12], [14], [16].
- Attachable devices [1], [2], [23].

Designing specimens subjected to multiaxial tests represents a major challenge. Concerning specimens used in triaxial testing of metallic materials, they are little known in the literature. [5], [8]

A particular case of multiaxial stress state is plane stress state. This can be obtained when materials are subjected to biaxial loading conditions (tension-tension, tension-compression, tension-torsion etc.).

Biaxial tensile test of cruciform specimens is the technique that provides the most accurate results. By the means of biaxial-planar servo hydraulic testing machine can be performed static and dynamic tests in all four quadrants: tension-tension, tension-compression, compression-tension, and compression-compression [9]. Ratio of biaxiality can be varied by modifying the proportion of the...
applied load or displacement. A review of planar biaxial tensile test systems and cruciform specimens, for sheet metal, was made by Hannon & Tiernan [21]. Biaxial tensile testing method using cruciform specimens made from sheet metals was standardized in 2014. [24]

Shape and dimensions of cruciform specimens depends by material nature, experiment type etc. and can be determined by individual numerical simulations (through finite element analysis) or by simulations coupled with different optimization techniques [3], [10], [11], [13], [16], [19]. Design of cruciform specimens is not an easy task. Because biaxial tensile test is a technique versatile, range of materials from which cruciform specimens are made is varied: metallic materials, composite materials [17], rubber [7] etc.

Cruciform specimens made from sheet metal can be subjected to complex strain paths through a multiaxial testing rig that allows performing in situ proportional and no proportional loading under neutron diffraction. [15]. Other applications of great importance of cruciform specimens are:
- materials behaviour study tested on elevated temperatures. [18]
- ductile failure study using cruciform specimens with notches [4], etc.

2. Finite element analysis
An elasto-plastic finite element analysis was performed to evaluate stress state from cruciform specimens. Different specimens were numerically investigated through FE simulations. Three principal conditions must be full field by cruciform specimens, when a finite element analysis is performed:
- existence of a uniform stress state plane in central zone with high values of von Mises stresses
- value of shear stresses must be minimum in central zone
- influence of stress concentrators must be insignificant

For this study was used only 1/8 of specimen due to symmetry. Stresses are recorded on the path at 45 degrees what begins from specimen centre and ends at the connection middle of two adjacent arms. Von Mises stresses in finite element analysis are calculated with relation:

$$\sigma_{VM} = \frac{1}{2\sqrt{2}} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2) \right]^{1/2}$$

In figure 1 is presented evolution of von Mises and shear stress for cruciform specimens subjected to uniaxial tensile test (1/8 of a sample).

Figure 1. Stress distribution in cruciform specimens subjected to uniaxial loading:
(a) von Mises stresses (b) Shear stresses.
This simulation assumes a ratio of biaxiality 1:0 ($F_z : F_x$), meaning that force is applied only on the vertical direction. In specimen central zone is a uniform plane stress with maximum values. Stress gradient is parallel with loading direction. Shear stresses are localized in connection zone of two adjacent arms and they are parallel with vertical axis of cruciform.

When cruciform specimens are subjected to uniaxial tensile test, for materials with ductile preponderantly behavior, failure is initiated by the action of shear stresses and will propagate in a direction at 45°, with respect to loading direction.

In figure 2 is presented evolution of von Mises and shear stress for cruciform specimens subjected to biaxial tensile test.

![Figure 2](image_url)

**Figure 2.** Stress distribution in cruciform specimens subjected to biaxial loading:
(a) von Mises stresses (b) Shear stresses.

Biaxiality ratio used for biaxial tensile test was 1:1.23 ($F_z : F_x$). von Mises stresses are maximum in specimen centre and shear stresses have maximum values in specimen corner zone on direction at 45°. Also in this case is present a stress gradient.

3. **Uniaxial and biaxial tests**

Cruciform specimens are made from Al 6082 T6, which is a material with ductile behaviour. Specimens are subjected to uniaxial and biaxial tensile tests (figure 3).

![Figure 3](image_url)

**Figure 3.** Force-elongation diagram for cruciform specimens (uniaxial and biaxial testing).
In figure 3 are presented force-elongation diagrams for cruciform specimens subjected to uniaxial and biaxial tensile test. Uniaxial tensile tests were performed on a universal testing machine Instron 8801.

Attachable device used in biaxial tensile tests is presented in figure 4c. A similar device, with very small dimensions [23], was used to test cruciform specimens. Measurements of strains are made with strain gauges (figure 4b) and recorded with a Vishay P3 Strain Indicator and Recorder.

![Figure 4](image)

*Figure 4. Vishay P3 Strain Indicator and Recorder (a) Strain gauges mounted on cruciform specimen (b) Attachable device for biaxial tensile test (c).*

In figure 5 is presented failure mode for cruciform specimens made from Al 6082 T6, subjected to biaxial tensile tests with a ratio of biaxiality 1:1.23.

Crack is initiated in central zone, up to thickness transition zone. Here the crack changes its path because of stress gradient. Finally, failure occurs due to shear stresses oriented at 45°.

![Figure 5](image)

*Figure 5. Cruciform specimen biaxial testing: (a) before; (b) during; (c) after experiment.*

4. Conclusions

Specimens shape and size have a significant role on normal and shear stresses distribution. Optimum cruciform specimen was obtained by combining various geometrical parameters. Specimens made from Al 6082 T6 subjected to uniaxial tensile test failed under the action of shear stresses. Shear stresses maximum values were in the middle of connection zone made from two adjacent arms. Failure is initiated from this region and its evolution is influenced by shear stress gradient on 45°.

Cruciform specimens subjected to biaxial tensile tests presents a uniform plane stress state in central part. Here von Mises stresses have maximum values. Crack initiation in central zone of
cruciform specimen has been well observed (onset of yielding was in the zone of interest). Von Mises stress gradient on direction at 45°. The proposed specimen shape and dimensions are validated by experiments. Numerical study has been validated by experiment for uniaxial and biaxial tests.

5. References

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