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Metallic materials — Principles and designs for multiaxial fatigue testing

Matériaux métalliques — Principes et conceptions associés aux essais de fatigue multiaxiale

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Foreword

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This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Fatigue, fracture and toughness testing*.

Introduction

Structural components in industry are frequently subject to some form of multiaxial stressing. Fatigue cracks generally initiate from surface defects or discontinuities and are thus primarily influenced by the surface biaxial stress system. This can vary from equibiaxial, where surface principal stresses are equal in magnitude and sign (present under conditions of pressurization, rotation and thermal loading) to pure shear where surface stresses are equal in magnitude, opposite in sign (as in shafts and shear panels).

The majority of fatigue test data gathered worldwide have been and will continue to be under uniaxial conditions for reasons of simplicity and cost. A secondary goal of multiaxial testing is therefore to develop behavioural models which relate failure under specified multiaxial conditions to established uniaxial cases.

This document utilizes data gathered from the past 80 years spanning most multiaxial fatigue research. It can be of interest to new researchers in the field and form a basis for full International Standards as the need arises.

Metallic materials — Principles and designs for multiaxial fatigue testing

1 Scope

This document discusses the general principles of multiaxial fatigue testing and the design recommendations for specific classes of multiaxial testing machines and test specimens.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
biaxial strain ratio
ϕ
ratio of the surface principal strains, smaller/larger

3.2
biaxial stress ratio
ψ
ratio of the surface principal stresses, smaller/larger

3.3
principal strains
$\varepsilon_1 > \varepsilon_2 > \varepsilon_3$
principal direct strains at a point in a multiaxial strain field

3.4
principal stresses
$\sigma_1 > \sigma_2 > \sigma_3$
principal direct stresses at a point in a multiaxial strain field

3.5
Poisson's ratio
ν
negative ratio of transverse to longitudinal strain under uniaxial tensile stressing

3.6
specimen diameter
d
diameter of a cylindrical tubular specimen

Note 1 to entry: The symbols d_0, d_i and d_m are used to express outside, inside and mean diameters, respectively.

3.7
parallel length
l_p
parallel length of a cylindrical tubular specimen

3.8
fillet radius
r
fillet radius of a cylindrical tubular specimen

3.9
directional suffix
suffix identifying a direction in a cylindrical tubular specimen

Note 1 to entry: The suffixes z, r and θ are used to express axial, radial and circumferential directions, respectively.

3.10
strain component suffix
suffix identifying a strain component

Note 1 to entry: The suffixes e, p and t are used for elastic, plastic and total strain components, respectively.

3.11
internal pressure
P
internal pressure within a cylindrical tubular specimen

4 General principles

4.1 Methodology

Multi-axial fatigue testing sets out to simulate the dynamic stress-strain conditions at key locations on components, on test specimens of constant geometry for a given test series, and to determine the cyclic stress-strain history, crack initiation and propagation behaviour, fatigue life and failure mode.

Dependent on the level of geometric constraint in the real component, it can be more useful to test specimens under stress or strain control, e.g. a test specimen representative of a relatively unconstrained gas turbine blade can be tested in stress control whereas it can be more relevant to utilize strain control for a test specimen simulating part of a steam turbine disc subject to thermal straining during start-up.

Further, where stress amplitudes are sufficient to take test specimen materials well into the region of cyclic plasticity (LCF), it can be preferable to employ strain control in order to better control cyclic amplitude during the test and failure at end of test.

4.2 Historical development

Multiaxial fatigue has been addressed since the 1930s. Initially, testing machine and specimen designs were created to address specific biaxial stress conditions, e.g. torsion, bending + torsion, cantilever bending, anticlastic bending and plate pressurization. However, a criticism of much of the early research was that specimen design had to change in order to change the biaxial stress or strain ratio, leading to uncertainty in the interpretation of results.

The benefit of being able to test a single specimen design over a wide range of biaxiality led to the choice of two generic specimen types, tubular and cruciform, together with associated multi-axis testing machine designs.

Table 1[5] summarizes the attributes of the different test methods applicable to tubular and plate specimens.

Biaxiality is shown in terms of the range of surface strains with ε_1 held constant. Only cruciforms and systems employing axial force plus internal and external pressure are capable of applying fully reversed fatigue cycles over the full range of biaxiality ($-1 \leq \phi \leq +1$) to test specimens.

Buckling is a key concern in the design of effective LCF specimens.

A reasonable gauge area of essentially constant strain is beneficial.

Ideally, strain should be constant through the thickness.

If all the applied forces are carried by the gauge area, then all stresses and strains can be determined; otherwise, only total (not plastic) strains can be measured.

The ability to visually observe the specimen is useful especially for surface crack monitoring.

Some designs are suitable for high temperature and thermo-mechanical fatigue (TMF) testing.

Systems involving torsion cause the principal axes to rotate up to 45°.

System cost can be scaled by the number of actuators, and therefore closed servo-loops, in the design.

Table 1 — Multiaxial test methods for tubular and plate specimens

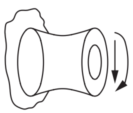
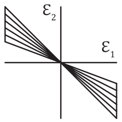
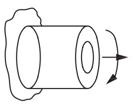
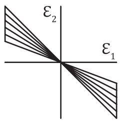
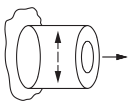
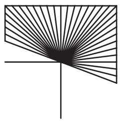
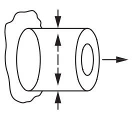
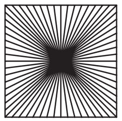
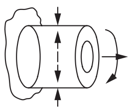
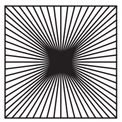
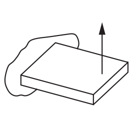
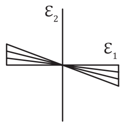
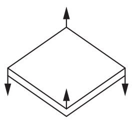
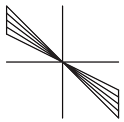
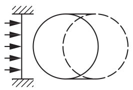
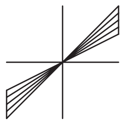
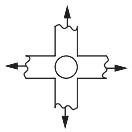
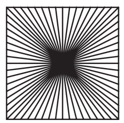
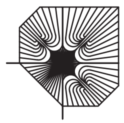
	Biaxial specimen schematics and modes of loading	Range of surface principal strains	Single geometry	Immune to buckling	Invariant σ and ε on gauge area	Min. ε-gradient through thickness	Monitoring biaxial σ and ε_P	Specimen observation	Crack growth studies	High temperature capability	TMF studies	Rotation of principal stresses	No. of actuators proportional to cost
Bending + torsion			√	√		√		√				√	1
Axial + torsion			√		√	√	√	√	√	√	√	√	2
Axial + P_{int}			√		√	√	√	√		√			2
Axial + P_{int} + constant + P_{ext}			√		√	√	√			√			2
Axial + P_{int} + P_{ext} + torsion			√		√	√	√					√	4

Table 1 *(continued)*

	Biaxial specimen schematics and modes of loading	Range of surface principal strains	Single geometry	Immune to buckling	Invariant σ and ε on gauge area	Min. ε-gradient through thickness	Monitoring biaxial σ and εP	Specimen observation	Crack growth studies	High temperature capability	TMF studies	Rotation of principal stresses	No. of actuators proportional to cost
Cantilever bend				√	√			√		√			1
Anticlastic bend				√	√			√	√	√			1
Plate pressurization				√	√								1
Cruciform LCF			√			√		√		√	√		4
Cruciform crack growth			√		√	√	√	√	√	√	√		4

4.3 Specific multiaxial test methods

4.3.1 Bending + torsion[6]

This was the first technique used to apply combined stresses in high cycle fatigue (HCF) at room temperature. Oscillating vertical forces were applied to a horizontally clamped cylindrical specimen which could be rotated by up to 90° in the horizontal plane so as to introduce bending, bending + torsion, or torsion in the waisted centre section. Specimens were either solid or hollow. A number of these electro-mechanical testing machines were built between 1930 and 1950 to investigate fatigue of aero-engine steels, especially for crankshaft applications.

4.3.2 Axial + torsion[7]

This popular technique employs a single tubular specimen design with a gauge length over which stress and strain are substantially invariant and access for strain measurement and crack monitoring. The principal stress and strain directions progressively rotate through 45° as the test moves from uniaxial to torsion. Elevated temperature testing and thermo-mechanical fatigue (TMF) are achievable with relevant accessories and control software. Despite a limited range of strain biaxiality ($-\nu \geq \phi \geq -1$), this approach is widespread and standard testing machines with dual servo-hydraulic actuators are available from commercial manufacturers.

4.3.3 Axial + internal pressure[8]

This approach permits a single tubular specimen design with essentially invariant stress and strain over the gauge length. Crack studies are difficult as maximum stress occurs at the bore, so cracks can only be visible after penetration of the wall shortly prior to failure. In addition, cyclic plasticity results in strain ratchetting as external radial compression cannot be applied to fully reverse the stress — strain cycle. Hence this approach is essentially restricted to elastic HCF studies. The testing machine typically utilizes a dual actuator servo-hydraulic design.

4.3.4 Axial + internal + external pressure[9]

This design enables fully reversed cycling without ratchetting because radial compression can be applied. Axial and circumferential stresses and strains are measurable, enabling LCF hysteresis loops on both surface axes, which makes the approach suitable for fundamental behavioural studies. Because a pressure vessel is located around the specimen, visual observations are difficult. Also elevated temperature testing above about 200 °C requires gas pressurization which presents safety issues. By employing variable internal pressure and fixed external pressure, a design with just 2 servo-hydraulic actuators is achievable.

4.3.5 Axial + internal + external pressure + torsion[10]

The addition of torsion introduces rotation of principal stress or strain axes which allows, in principle, material anisotropy and the effects of the different symmetries (in the axial and circumferential directions) to be investigated. The mechanical design is complex with 4 servo-hydraulic actuators, but has been successfully achieved.

NOTE Multiaxial testing machines featuring axial force and differential pressure are typically used for academic research or specific R&D applications, and are usually designed and manufactured to order.

4.3.6 Cruciform — LCF[11]

Four orthogonal loading arms apply biaxial strain to a central circular gauge area on the specimen. This area is usually spherically recessed on both sides in order to resist buckling and ensure that cracks initiate near the centre. In consequence, the gauge area does not support all the applied forces, i.e. some of the force is shunted around the outside. As a result, stresses and plastic strains are not readily determinable. However, visual observation of developing fatigue cracks is straightforward and elevated temperature testing, including TMF, is readily achievable.

4.3.7 Cruciform — Crack growth[12]

The four orthogonal arms are slotted to minimize grip constraint. A central square, constant thickness, gauge area typically features a central hole stress raiser to initiate fatigue cracks. There is a large region of essentially constant biaxial strain ideal for crack initiation and propagation studies. Elevated temperature testing, including TMF, is achievable. Maximum compressive strains are limited to avoid buckling in the gauge area and arms.

NOTE Cruciform designs provide the opportunity for testing single geometry plate specimens with dual symmetry over the range of surface biaxiality. Testing systems employ 4 servo-hydraulic actuators within an annular frame and are typically specified according to application and manufactured to order.

4.4 Multiaxial fatigue analysis

4.4.1 Computer aided design

In the design of structural components subject to multiaxial fatigue, it is common to use finite element analysis (FEA) to determine stresses and strains. For elastic behaviour, such analyses are useful to predict stress concentrations and local yield in order to evolve specimen designs.

4.4.2 Fatigue life prediction

Yield criteria such as Tresca (maximum shear), Von Mises or octahedral shear strain, coupled with the Palmgren-Miner linear damage hypothesis, are frequently employed to predict “multiaxial fatigue life”. However, research evidence does not necessarily support this approach.

Multiaxial LCF fatigue studies[13][14] on specimens capable of being tested over the full biaxial range showed that Tresca and Von Mises did not correlate all the fatigue life data, especially over the range between uniaxial and torsion, i.e. $(0 \geq \psi \geq -1)$ and $(-\nu \geq \phi \geq -1)$.

For example, in Figure 1, Mohr’s strain circles drawn with principal strain (ε_1) constant and Poisson’s ratio = 0,5, show that the maximum shear strain (γ_{max}) is the lowest in the uniaxial stress ($\phi = -\nu$) case. However, ranking these biaxial fatigue cases from most to least damaging, the order was equibiaxial strain ($\phi = +1$), plane strain ($\phi = 0$), uniaxial stress ($\phi = -\nu$) and pure shear ($\phi = -1$).

Current consensus[15] indicates that a critical shear plane analysis including, as a modifier, the direct stress or strain acting normal to that plane, offers the best approach to correlating multiaxial fatigue behaviour across the complete range of applied biaxial surface stresses or strains.