APPARATUS FOR BIAXIAL FATIGUE TESTING

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ABSTRACT

The increasing sophistication in aircraft designs has necessitated the development of more descriptive - and complex - material and component models. Effective validation of these complex models, however, requires manufacturers to pursue far more realistic simulations of airframe and turbine operating environments. Employing uni-axial testing technology to validate complex models yields less than accurate results, while full-scale tests with spinning components are expensive when evaluating design iterations. Therefore, achieving truly accurate and affordable simulation of these environments requires the use of multiaxial loading technology. This paper will review materials behavior models and fatigue damage theories and map these against required testing methodologies for validation. An integrated system with planar biaxial tension and compression loading and torsional loading capacity is reviewed as an apparatus for validation of advanced models under multiaxial loading. This new frame technology allows for efficient and accurate testing that can bridge the gap between traditional methods of uni-axial and full scale tests.

KEYWORDS

Advanced Materials, Multiaxial Loading, Damage Theories, Validation Testing

INTRODUCTION

Most mechanical components in aerospace structures, naval navigation, army weapon systems and ground vehicles, among others, are complex two- and three-dimensional structures capable of carrying complex, non-proportional multiaxial loads. Under these complex loads, the ability to successfully model the behavior of materials for optimum use in structures depends on reliable constitutive relations and failure criteria that can be employed in analytical and numerical formulations [1, 2]. Material behavior has typically been characterized under uniaxial loads with increasing accuracy. As a result, test methods to characterize the same materials under multiaxial, or even biaxial, stress states have not been used widely. However, to ensure that a constitutive model adequately describes the behavior of a material under a variety of complex loading conditions, it is necessary to conduct rigorous experimental characterization to obtain enough data to formulate proper constitutive and damage laws [1]. Nonetheless, recent developments on the understanding of inelastic material behavior and damage [1, 3, 4], indicate that the extension of uniaxial test results to predict failure for multiaxial stress states can be inadequate, although numerous failure theories have been proposed to predict the response of materials under general stress conditions based solely on uniaxial test results [1]. Therefore, a lack of reliable multiaxial/biaxial experimental data can prevent the development of more accurate constitutive and failure theories under multiaxial stresses [1].

Basically, there are two categories of experimental techniques and specimens for testing under 2-D stress states [5, 6]: (i) tests using a single loading system; (ii) tests using two or more independent loading systems. Examples of the first category are bending tests on cantilever beams, anticlastic bending tests of flat plates, bulge tests and tests using special fixtures [7]. In this kind of test device, the biaxial stress ratio depends on the specimen geometry or the loading fixture configuration. Examples of the second category are a round bar specimen under torsion combined with bending, thin-wall tube specimen subjected to a combination of tension/compression and torsion or internal/external pressure, and cruciform specimens under in-plane biaxial loading. The technique with the thin-wall tube specimen is among the most popular [8], because it can change biaxial load ratio as the principal axes "rotate" when the loads are out of phase. The material and damage models that can be validated with these loading techniques and the features of the load frames will be discussed in this paper.

MATERIALS MODEL

Material behavior

The cruciform specimen can indeed be used to investigate material behavior under in-plane stress states; therefore, it has been of interest to many researchers. In particular, behavior of materials with plastic anisotropy induced by processing, such as metallic parts [9] needs to be studied with multiaxial loading techniques. Note that classical continuum plasticity, which has been a very successful theory, consists primarily of a yield criterion, a plastic potential, a flow rule and evolution laws to describe isotropic and kinematic hardening [9]. The determination of the appropriate material constants needed to formulate all these "components" of classical models requires extensive testing, particularly for anisotropic behavior. In this sense, biaxial (and triaxial) loading is ideal to probe interactions that result from the simultaneous presence of load along different directions, which are impossible to evaluate with uniaxial tests.

Furthermore, recent work has shown that the yielding behavior of what would normally be considered isotropic polycrystals can be affected by stress triaxiality, due to basic asymmetries on the glide of dislocations due to core spreading [3]. These effects, which can be quite pronounced on BCC metals, can only be evaluated effectively when stresses can be applied and controlled along more than one axis. One particularly interesting consequence of this phenomenon is that the plasticity model needs to be non-associative, since the yield criterion and the plastic potential cannot longer be the same, as it is typically assumed in classical plasticity [9].

Another important factor on the evaluation of material models under multiaxial stresses is related the evolution of hardening as loads change in magnitude and direction as a function of time. In this regard, it has been reported that metallic materials exhibit additional cyclic hardening under non-proportional loading, i.e., loading with changing directions of the principal stresses, and that the degree of additional hardening is related to the loading path [1]. A survey of the performance of several kinematic hardening rules for multiaxial cyclic loading was presented in [10]. The results indicate that many well-known rules cannot account well for multiaxial load conditions, which emphasizes the need to perform accurate multiaxial loading experiments to validate and calibrate models used to describe material behavior.

Inelastic material behavior is intimately linked to the evolution of damage in a large variety of materials, since the typical equations that describe damage evolution contain parameters related to the evolution of inelastic strain. Therefore, multiaxial testing is also required to evaluate damage theories, which will be discussed in the next section.

Damage Theories

Damage evolution under multiaxial loads is more complicated due to the complex stress states and histories as well as varied orientations of cracks and their paths. Differences were observed between biaxial and uniaxial tests on the nucleation of fatigue damage on a C36 steel by Billaudeau *et al* [11]. These differences were: (1) under dominant torsion cyclic loading, stage I fatigue cracks can propagate in several grains before branching into stage II; (2) several cracks can be observed close to the fatigue limit in axial/torsion cyclic loading while only a few cracks are present under uniaxial cyclic loading. It has also been confirmed [8] that short crack propagation under multiaxial cyclic loading is a discontinuous process. Another important fact is that classical strength hypotheses are not applicable for the calculation of the fatigue limit under multiaxial non-proportional loading. Reviews and comparisons of existing multiaxial fatigue models are reported in [12]. In this regard, the importance of fatigue under multiaxial, non-proportional cyclic loading has been recognized in recent years. Substantial investigations have been performed by [13, 14]. Socie [15] reported that fatigue lives of 304 stainless steels were reduced by 90% under 90°-out-of-phase loading, compared with those under proportional loading.

Regarding crack propagation, high-strength low-hardening aluminum alloy specimens with middle-cracks at various in-plane constraint states were tested under uniaxial and biaxial tensile loading by [16]. The results indicate that the crack tip opening displacement, crack tip opening angle, and energy release rate depend on the load biaxiality ratio. Biaxial fatigue tests were performed by Kane and Doquet [17] to study the growth of semi-elliptical fatigue cracks in 304 L stainless steel. It was found that the growth rate of surface cracks is increased by a non-singular compressive stress and reduced by a tensile stress when $R = 0$, as compared to through-cracks under uniaxial loading.

Validation Requirements

In order to validate material and damage models a test apparatus has to fulfill the following requirements:

> Capability to use cruciform specimens, to apply uniform stress on the gauge section.
>
> Capability to induce non-proportional loading: in cruciform specimens the principal axes of stress are fixed, preventing the application of non-proportional loading. To overcome this limitation the capability to apply simultaneous axial and torsion loads is also required.

TEST MACHINE DESIGN

Load Application and Reaction Apparatus

Frame and load train stiffness are extremely important for specimen performance during low cycle fatigue tests. Actuator characteristics impact stiffness, performance, wave shape fidelity, and alignment. High frequency testing can produce inertial errors that must be compensated for. Specimen failures can apply loads and moment that can potentially damage equipment. Alignment characteristics impact test results and influence specimen failures in fatigue testing. With all of the constraints placed on the equipment, as much flexibility as possible must be designed in for future specimen configurations and tests.

For this paper, the force axes in a planar biaxial frame are x-horizontal, y-vertical, and z-normal to the plane. During a typical planar biaxial test, the x and y forces are balanced and controlled by the test controller with a matrix control mode that will be discussed later. Under ideal conditions, z plane forces do not exist. Z plane forces, unless intentionally applied, are the result of specimen buckling. Testing with fully reversed loads in a planar biaxial frame requires high load train lateral stiffness due to the potentially high compressive strains experienced in the test. Tension only tests, including monotonic and tension-tension fatigue tests, are less demanding in terms of lateral stiffness.

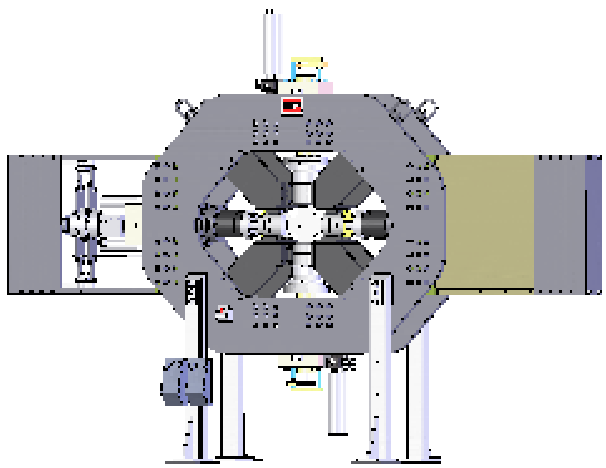

Figure 1: Biaxial Load frame design with torsion on the horizontal axis.

The shown design for planar biaxial frame incorporates both linear and axial torsional actuators bolted to stiff side plates. With the actuators bolted this way, they become an integral part of the reaction structure. The load train comprised of a grip/specimen fixture, force transducer, alignment fixture, and the actuator piston rod is optimized to reduce the overall length from the actuator bearing to the specimen with the goal of increasing the lateral stiffness. This is accomplished by using large diameter piston rods with actively fed hydrostatic bearings, an oversized low profile force transducer, a grip/specimen test fixture, and integrated preloaded joints to remove backlash.

Two sources of loads to the system that require special design consideration are specimen leg failure and z-axis buckling induced loads. In the event that limits in the control system are not set properly, specimen leg failure on one axis can produce side load to the other axis. This side load can potentially be the full force capacity of an actuator. This load applied through the specimen will apply an overturning moment to the force transducers and the actuator pistons of the affected axis. Likewise, z-axis buckling loads apply similar overturning moments to the same sensitive components. The design path chosen reduces the load train length from the specimen to the actuator bearing. There are also adjustable devices that do not contact the load train unless a side load is applied to carry any induced side load.

The actuators used in the biaxial frame are specially designed for this type of application. Specific design attributes are low friction, actively fed hydrostatic bearings, alignment characteristics, low internal oil volume, and reduced cross piston leakage.

A load cell is mounted to each actuator and therefore has the potential to experience inertial loading. An accelerometer is mounted inside of the load train and is used to acceleration compensate the load signal.

A frame of this type has limited test space flexibility. The reaction structure is designed from the specimen out. If a specimen geometry and gripping solution has been chosen, then the test space will be defined by these requirements and the optimal actuator stroke for this configuration. If the geometry of the specimen is not known or if the system is to be used for general research, then a test space envelope will be assumed. The use of hydraulic wedge grips provides the most flexibility in this case for mounting a variety of specimen configurations.

This frame design has a modular nature. Because of the bolt together design and the use of the actuators as structural members, the actuators can be mated with the side reaction plates for various test spaces and force combinations.

Control Technology

For multiaxial load application the effect of one channel of load or displacement onto the other channels needs to be considered also, the following scenarios exist:

> Rigid body motions, where the specimen moves but is not strained, in a planar biaxial environment with torque this requires that opposing actuators are moving in the same direction.
>
> Mean or offset or pre-load application. Each axis of control can be pre-loaded (or strained) by commanding opposing actuators to move in opposite direction of each other to a fixed position.
>
> Cyclic or fatigue loads are applied by commanding opposing actuators to move in opposite direction of each other but with a time varying amplitude.
>
> Centroid control is a scheme where it is desired to displace or keep constant the location of the center of the specimen. The latter is a requirement for planar biaxial tests where the displacement of one axis may not introduce unwanted bending of the other axis. Furthermore, keeping the centroid makes visual monitoring (e.g. via video or laser extensometry) possible.

The above load combinations can be achieved inside a digital servo controller through the notion of calculated variables by creating two new control loops per axis of loading, namely specimen offset and specimen force [19]. Specimen displacement is calculated by taking the difference of two actuators' displacement along one axis, while the force can be calculated by taking the average of the load cell measurements across a loading axis. This type of control is also referred to as matrix control.

CONCLUSIONS

Increasingly complex material models require test machines that can verify material behavior in more than one direction simultaneously. Machine design needs to take into account application specific requirements as tradeoffs in test space opening vs. load train stiffness and force capability vs. signal resolution must be made.

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