Multiaxial Fatigue and Deformation Testing Techniques

ASTM

STP 1280

Sreeramesh Kalluri and Peter J. Bonacuse, editors

STP 1280

Multiaxial Fatigue and Deformation Testing Techniques

Sreeramesh Kalluri and Peter J. Bonacuse, editors

ASTM Publication Code Number (PCN):
04-012800-30

ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959
Printed in the U.S.A.

Library of Congress Cataloging-in-Publication Data

Multiaxial fatigue and deformation testing techniques / Sreeramesh Kalluri and Peter J. Bonacuse, editors.
(STP ; 1280)
"ASTM STP publication code number (PCN): 04-012800-30."
Includes bibliographical references and index.
ISBN 0-8031-2045-1
1. Materials—Dynamic testing. 2. Materials—Fatigue.
3. Deformations (Mechanics) I. Kalluri, Sreeramesh. II. Bonacuse, Peter J., 1960– . III. Series : ASTM special technical publication ; 1280.
TA418.32.M85 1996
620.1'126—DC21 96-37368
CIP

Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

Printed in Philadelphia, PA
February 1997

Foreword

This publication, *Multiaxial Fatigue and Deformation Testing Techniques,* contains papers presented at the Symposium on Multiaxial Fatigue and Deformation Testing Techniques, which was held in Denver, Colorado, on 15 May 1995. The Symposium was sponsored by the ASTM Committee E8 on Fatigue and Fracture. Sreeramesh Kalluri, NYMA, Inc., NASA Lewis Research Center, and Peter J. Bonacuse, U.S. Army Research Laboratory, NASA Lewis Research Center, presided as symposium chairman and cochairman, respectively, and both were editors of this publication.

Contents

Overview 1

MULTIAXIAL TESTING FACILITIES

Testing Facilities for Multiaxial Loading of Tubular Specimens—F. ELLYIN AND J. WOLODKO 7

A Structural Test Facility for In-Plane Biaxial Testing of Advanced Materials—P. A. BARTOLOTTA, J. R. ELLIS, AND A. ABDUL-AZIZ 25

Adjustable Work Coil Fixture Facilitating the Use of Induction Heating in Mechanical Testing—J. R. ELLIS AND P. A. BARTOLOTTA 43

MULTIAXIAL DEFORMATION

Biaxial Deformation Experiments Over Multiple Strain Regimes—M. P. MILLER AND D. L. McDOWELL 65

Experimental Determination of Yield and Flow Surfaces Under Axial-Torsional Loading—C. J. LISSENDEN, B. A. LERCH, J. R. ELLIS, AND D. N. ROBINSON 92

Additional Hardening Due to Tension-Torsion Nonproportional Loadings: Influence of the Loading Path Shape—S. CALLOCH AND D. MARQUIS 113

Notch-Tip Stresses and Strains Under Nonproportional Loading—M. N. K. SINGH, G. GLINKA, AND R. N. DUBEY 131

MULTIAXIAL FATIGUE

Crack Initiation Life Behavior Under Biaxial Loading Conditions: Experimental Behavior and Prediction—H. NOWACK, D. HANSCHMANN, W. OTT, K.-H. TRAUTMANN, AND E. MALDFELD 159

An Axial-Torsional, Thermomechanical Fatigue Testing Technique—S. KALLURI AND P. J. BONACUSE 184

Fretting Fatigue Strength of Specimens Subjected to Combined Axial and Transversal Loading—W. SWITEK 208

Characterization of Ceramic Matrix Composite Tubes Under Uniaxial/Biaxial Monotonic and Cyclic Loading—K. LIAO, E. R. GEORGE, AND K. L. REIFSNIDER 224

STRUCTURAL FAILURE AND CRACK PROPAGATION UNDER MULTIAXIAL LOADING

Plane Stress Crack Resistance Curves of an Inclined Crack Under Biaxial Loading—C. DALLE DONNE AND H. DÖKER 243

Instability and Failure of Corrugated Core Sandwich Cylinders Under Combined Stress—P. PATEL, T. NORDSTRAND, AND L. A. CARLSSON 264

Crack Propagation in Cruciform IMI 834 Specimens Under Variable Biaxial Loading—K.-H. TRAUTMANN, E. MALDFELD, AND H. NOWACK 290

Overview

The importance of fatigue and deformation of materials under multiaxial loads has gained significant recognition over the last quarter century. The advances in sophisticated materials testing equipment and digital computer systems have enabled many researchers to explore a multitude of testing techniques to assess the behavior of materials and structural components. The result has been the evolution of several testing procedures and generation of indispensable multiaxial fatigue and deformation data on different types of materials. Theoretical models have been developed to estimate the deformation behavior and fatigue lives of materials under multiaxial loading conditions. Numerous conferences and symposia have been sponsored by various societies to document the technical achievements in the field. Two such ASTM sponsored symposia have resulted in the following valuable special technical publications: (1) *Multiaxial Fatigue (ASTM STP 853)* and (2) *Advances in Multiaxial Fatigue (ASTM STP 1191).* This special technical publication is the result of a third ASTM sponsored symposium on Multiaxial Fatigue and Deformation Testing Techniques, which was held on 15 May 1995 in Denver, Colorado.

The symposium on Multiaxial Fatigue and Deformation Testing Techniques was sponsored by the ASTM Committee E8 on Fatigue and Fracture and its Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation. The symposium's focus was on state-of-the-art testing techniques for characterizing the multiaxial fatigue and deformation behaviors of monolithic and composite materials. The main purpose of the symposium was to facilitate the development of standardized procedures for testing structural materials under multiaxial loading conditions.

This volume contains a set of fourteen papers, which were presented at the Symposium on Multiaxial Fatigue and Deformation Testing Techniques. These papers deal with both experimental and theoretical aspects of the multiaxial fatigue and deformation behaviors of structural materials. The papers are separated into the following categories: (1) Multiaxial Testing Facilities, (2) Multiaxial Deformation, (3) Multiaxial Fatigue, and (4) Structural Failure and Crack Propagation Under Multiaxial Loading. These four broad categories are intended to provide an orderly grouping of the presented papers.

Multiaxial Testing Facilities

Multiaxial testing is performed typically on tubular or cruciform specimens. The tubular specimens are employed for axial, torsional, internal pressure, external pressure, or combinations of these types of loads, whereas the cruciform specimens are used for biaxial tensile or compressive loads. The first paper in this category deals with the development of a multiaxial testing facility that is suitable for tubular specimens. The capability of this facility is demonstrated by testing composite specimens manufactured from glass-fiber reinforced epoxy tubes. The second paper describes a test facility that is designed to perform in-plane biaxial tests on cruciform specimens and on structural elements of advanced materials. Different features of the test facility include a digital controller and associated software to control four hydraulic actuators, a quartz lamp radiant furnace, an environmental chamber, and an in situ crack monitoring system. The third paper in this category illustrates the design and performance of a coil fixture for inductively heating cylindrical specimens during mechanical testing. This novel approach subdivides the induction coil into three individually adjustable segments. It is shown that temperature variation in the gage section of a large tubular specimen can be controlled to within 1% of the nominal test temperature with the adjustable induction coil fixture.

Multiaxial Deformation

Deformation of materials under monotonic and cyclic multiaxial loads has been the subject of many investigations in the last two to three decades. In particular, the shapes of the multiaxial load paths (proportional versus nonproportional) have been shown to have a significant influence on the hardening behavior of materials. Each of the four papers in this category addresses a different aspect of the multiaxial deformation behavior of materials. In the first paper, a succinct review of the research under large strain conditions is presented and the effects of large compressive and torsional prestrains on the subsequent large strain deformation behavior of 304L stainless steel are experimentally evaluated. In addition, experimental results depicting the influence of a large torsional prestrain on the subsequent small strain biaxial deformation behavior of the 304L stainless steel are illustrated, and issues for modeling the small strain deformation data are discussed. The second paper describes procedures for experimentally determining the room temperature yield and high temperature flow surfaces of 316 stainless steel under axial-torsional loading with a commercially available high temperature extensometer. An inelastic strain offset criterion is used to determine the yield surfaces, whereas a constant inelastic strain rate criterion is employed to establish the flow surfaces. The third paper addresses the influence of the loading path shape on the cyclic axial-torsional hardening behavior of 316 stainless steel. In this experimental investigation authors identify nonproportional loading paths that lead to higher levels of hardening than the conventional 90° out-of-phase axial-torsional loading. The final paper proposes two analytical models based on strain energy density to estimate the stresses and strains at the root of a notch under multiaxial nonproportional loading. In order to validate the models, results generated from the models are compared with stress-strain data obtained from finite element analyses.

Multiaxial Fatigue

Fatigue under multiaxial loads has been the topic of many investigations with emphasis both on experimental and theoretical aspects. Predicting the multiaxial fatigue crack initiation life requires complete knowledge of the cyclic stresses and strains and life prediction models that are appropriate for the damage mechanisms exhibited by the particular material under consideration. In this category, the first paper reports experimental results from a biaxial fatigue crack initiation study on cruciform specimens manufactured from an aluminum alloy. Fatigue lives under proportional and nonproportional loading histories are estimated with two incremental plastic work based fatigue life prediction approaches, which account for the influence of mean stresses. The second paper describes, in detail, a testing technique for performing strain-controlled, thermomechanical fatigue tests on thin-walled tubular specimens under combined axial-torsional loading conditions. Four types of axial-torsional, thermomechanical fatigue tests are described, and experimental results generated on a cobalt-base superalloy, Haynes 188, are discussed. The third paper deals with fretting fatigue of machine elements subjected to combined axial and transverse loading. Experimental results from fretting fatigue tests on normalized steel specimens are presented, and fracture mechanics is used to estimate fretting fatigue limits. The final paper in this category describes a technique for conducting monotonic and cyclic tests under uniaxial and biaxial loads on ceramic matrix composite tubes. Uniaxial and biaxial fatigue behaviors of a ceramic matrix composite and damage and failure modes exhibited by the composite under the investigated loading conditions are discussed.

Structural Failure and Crack Propagation Under Multiaxial Loading

The final category in this book contains three papers on the topics of structural failure and crack growth under multiaxial loading conditions. The first paper deals with crack growth under mixed Mode I and Mode II conditions in cruciform specimens made from an aluminum alloy and a structural steel. Crack resistance curves under mixed mode conditions, presented in terms of the magnitude of a crack tip displacement vector, are compared to the conventional R-curves obtained with compact-tension and center-cracked specimens. The second paper presents results from an experimental and analytical study on the structural failure of corrugated board cylinders. Failure data generated in experiments under compressive and torsional loads are compared to the failure envelope obtained with finite element analysis and Tsai-Wu criterion. In the third paper, experimental results obtained in a crack growth study on cruciform specimens made from a titanium alloy are reported. Block loading histories consisting of major and minor cycles are imposed on the cruciform specimens containing crack initiator sites prepared with electric spark discharge. The crack growth rates observed under different block loading histories are compared.

The experimental techniques presented in this book show some of the significant improvements that have occurred in the field of multiaxial testing during the past five to ten years. It is our sincere hope that the papers contained in this book will shed some light on multiaxial testing techniques and that this book will serve as a valuable technical resource. We would like to thank the authors and reviewers without whose contributions and meticulous efforts this book would not have been possible. We are grateful to the ASTM staff (Ms. Dorothy Savini, Hannah Sparks, Shannon Wainwright, Monica Siperko, Kathy Dernoga, and Helen Hoersch) for their professional assistance, cooperation, and patience.

Sreeramesh Kalluri
NYMA, Inc., NASA Lewis Research Center, Cleveland, Ohio; symposium chairman and editor.

Peter J. Bonacuse
U.S. Army Research Laboratory, NASA Lewis Research Center, Cleveland, Ohio; symposium cochairman and editor.

Multiaxial Testing Facilities

Fernand Ellyin[1] *and John D. Wolodko*[1]

Testing Facilities for Multiaxial Loading of Tubular Specimens

REFERENCE: Ellyin, F. and Wolodko, J. D., "**Testing Facilities for Multiaxial Loading of Tubular Specimens,**" *Multiaxial Fatigue and Deformation Testing Techniques, ASTM STP 1280*, S. Kalluri and P. J. Bonacuse, Eds., American Society for Testing and Materials, 1997, pp. 7–24.

ABSTRACT: The development of a new multiaxial testing machine is presented. The testing machine is capable of applying axial load, differential pressure, and torsion to a tubular specimen under independent servohydraulic control. Relative merits of various loading configurations are described. Stress/strain controlled, monotonic/cyclic, and in-phase/out-of-phase (nonproportional) tests under ambient temperature conditions can be performed with this system. The associated computer control hardware and software allows for a number of complex user-defined loading and acquisition schemes. Monotonic and cyclic tests on tubular specimens made of glass-fiber-reinforced epoxy with fiber orientations of ±45° and 0°, are presented. Details of the experimental apparatus and representative test results are discussed in this paper.

KEYWORDS: *multiaxial fatigue, biaxial fatigue, experimental methods, tubular specimens, composite materials, fatigue (materials) fracture (materials), testing, deformation (materials)*

Multiaxial stress and strain fields can occur in a component due to (1) applied multiaxial loadings (pressure vessels, shafts), (2) geometric discontinuities (notches, reinforcing plates), (3) material discontinuities (bonded structures), (4) material anisotropy (fiber-reinforced composites), and (5) hygrothermal gradients. The inability to predict multiaxial fatigue failures is primarily due to the lack of understanding of this extremely complex problem. It is for this reason that multiaxial fatigue topics are typically restricted to fundamental research or specialized engineering problems requiring advanced analysis techniques. Experimental multiaxial fatigue studies are typically conducted to investigate fatigue phenomena or to verify fatigue life, crack growth, or constitutive models. The current literature is devoid of valid experimental data for many emerging material groups. For example, experimental research in multiaxial fatigue of fiber-reinforced composites has not kept pace with the escalated usage of these materials. This is primarily due to the expense and required expertise in conducting such experimentations. The accumulation of an experimental database is a requirement for the future advancement of this topic.

Review of Multiaxial Testing Apparatus

Multiaxial testing machines are inherently designed around the geometry and loading requirements of the test specimen. The majority and most successful of these testing facilities

[1] Professor and graduate research assistant, respectively, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G8.

can be classified by one of two main test specimen geometries: (*a*) the cruciform (planar) specimen and (*b*) the thin-walled tubular specimen.

Cruciform Specimen Testing Machines

Cruciform testing machines typically consist of two sets of orthogonal actuating mechanisms that apply biaxial loads directly to the flat cruciform specimen in a single plane. The cruciform specimen is the preferred choice for crack growth studies as (1) the surface is accessible and visible, (2) long crack formation can be accomplished, and (3) there are no curvature effects.

The disadvantage with cruciform testing techniques is the difficulty in accurately determining the distribution of stresses in the specimen. This stress distribution is often determined using empirical or numerical methods, and is largely dependent upon the specimen design, configuration of the loading frame, specimen attachment, and actuation method. This accounts for the large number of variations in the reported testing apparatus. A discussion of these concerns and a review of cruciform testing machines can be found in recent papers by Makinde et al. [*1*] and Boehler et al. [*2*].

Tubular Specimen Testing Machines

The thin-walled tubular specimen has been shown to be the most versatile geometry available for characterizing biaxial properties in materials. A biaxial state of stress or strain can be imposed in the test specimen through the simultaneous application of one of three loading configurations: (*a*) axial force (tension-compression) and torsion, (*b*) axial force and differential pressure (internal-external), and (*c*) axial force, differential pressure, and torsion.

Axial Force and Torsion—Testing facilities that provide axial-torsion capabilities are the most common, due to their relatively low cost and availability from commercial vendors. A biaxial state of stress or strain is generated by the simultaneous application of shear (torsion) and normal stresses (axial force) in the material element. Since the biaxial state is created by a superposition of shear and normal loading components, the direction of the principal stresses and strains will change as the biaxiality ratio changes. This may be insignificant for tests on isotropic materials, but may be limiting for materials with directional properties (anisotropic). The tube surface is readily accessible during testing, which is extremely beneficial for investigating crack growth phenomena [*3,4*] and high temperature material response under fatigue loading [*5–7*].

The major disadvantage of axial-torsion testing is its limited range of attainable principal stress and strain ratios (Fig. 1*a*). A thorough review of fatigue life investigations using axial-torsion fatigue is given by Kalluri and Bonacuse [*8*].

Axial Force and Differential Pressure—Differential pressurization of a thin-walled tubular specimen induces a circumferential and radial stress component in the test material. Because of the thin-walled geometry, the radial component is typically much smaller than the in-plane components and can be ignored. By independently varying the applied axial load and differential pressure, a biaxial state of stress or strain with any biaxiality ratio can be attained (Fig. 1*b*). Since the applied loading is parallel and perpendicular to the specimen axis, the principal loading direction is fixed for all biaxiality ratios.

Axial-differential pressure testing apparatus are not common since they are typically more expensive to implement and require a controlled (safe) pressurized environment. Access to the specimen surface is not available during the test, and due to the pressurizing media, high temperature testing is difficult.

The use of thick-walled tubular specimens provides the ability to perform limited triaxial testing. The radial stress component is dependent on the specimen geometry and the applied

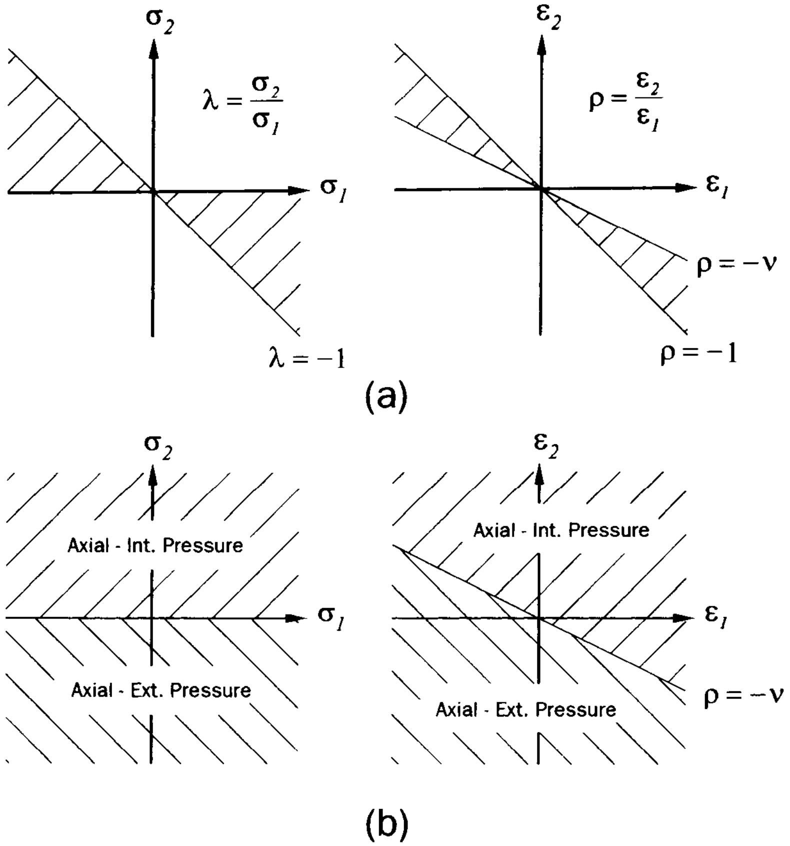

FIG. 1—*In-plane biaxiality regimes in terms of the principal stress and strain for various applied loading configurations:* (a) *axial-torsion and* (b) *axial-pressure, where ν is the Poisson's ratio.*

pressure. The radial-to-circumferential loading ratios are fixed by the specimen wall thickness and diameter with the resulting states of stress being nonuniform.

Crack studies using internally pressurized tubular specimens can only be accomplished with the use of liners or pressure containment sleeves to bridge crack formation. The use of liners is a common practice in the testing of tubular specimens made of fiber-reinforced polymeric composites [*9,10*]. These materials often possess brittle matrices that experience extensive cracking under multiaxial loading.

In biaxial testing machines with pressure capabilities, dependent and independent load control capabilities have been reported. Testing apparatus with dependent loading schemes have been built in which the axial force applied to the specimen is serviced by the same pressure source supplied internally or externally to the specimen [*10,11*]. Though these systems are relatively simple to develop and require only one control system, the applied biaxiality ratio is fixed by the relationship between specimen diameters and axial actuating piston sizes. Furthermore, high pressures, resulting in a significant out-of-plane stress component, may be required to achieve adequate axial forces.

Investigations using testing machines with strictly independent axial and differential pressure capabilities can be found in the literature [*12–14*].

Axial Force, Differential Pressure, and Torsion—The combination of axial load, differential pressure, and torsion results in the most versatile testing apparatus for tubular specimens. This combination offers the advantages of the two previous loading schemes described. Due to the axial load and differential pressure, all principal stress or strain ratios are attainable (Fig. 1*b*). Due to the addition of an applied shear component (torsion), the direction of the applied principal stresses and strains can now be varied. This is extremely advantageous for the testing of anisotropic materials where material properties are directionally dependent.

A large number of testing machines capable of axial, torsion, and pressure loading have been reported in the literature [*15–24*]. These have been used to conduct studies on a wide range of metallic [*15,20,21*] and nonmetallic [*16–19,22–24*] materials. Even though most testing machines reported have extended loading capabilities, very limited loading schemes have been implemented to date.

The development of a multiaxial testing machine with the capability of applying monotonic and cyclic axial load, differential pressure, and torsion to a tubular specimen under independent control is described in this paper. Tubular specimen development and preliminary test results are also presented.

Apparatus Description

The rationale for developing the testing machine described in this paper is to provide a precise, yet flexible, environment to conduct complex multiaxial tests on tubular specimens. A photograph of the servohydraulic multiaxial testing machine, described herein, is shown in Fig. 2.

The main elements in the testing machine design are: (1) the structural components, (2) the

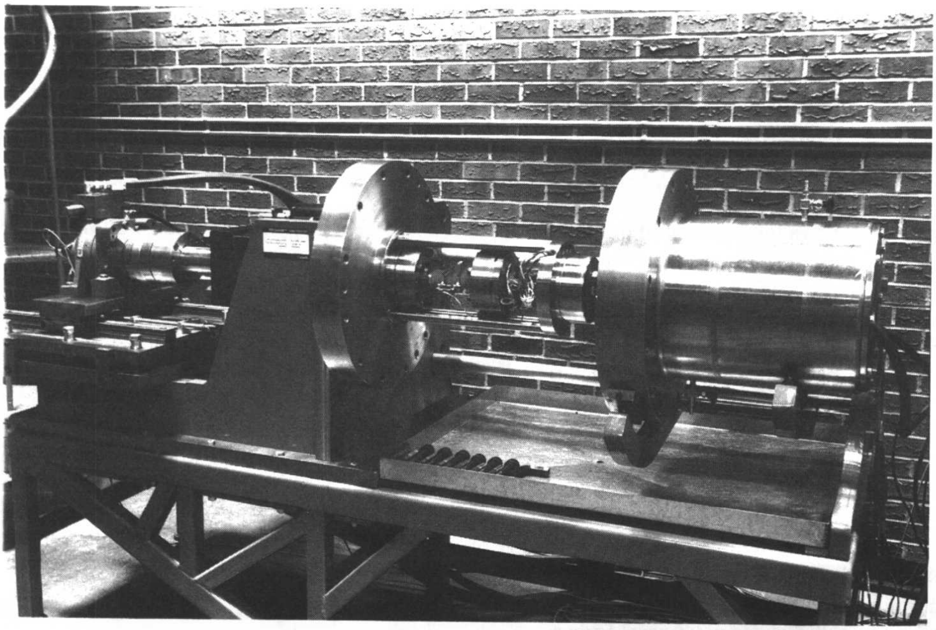

FIG. 2—*View of the multiaxial testing machine.*

servohydraulic system, (3) the feedback and control system, and (4) computer data acquisition and control. These elements will be described in the following sections.

Structural Components

Referring to Fig. 3, the testing machine structure is comprised of three subsystems: (1) the load train, (2) external pressure containment, and (3) the support structure.

Load Train—The load train consists of a linear series of components whose purpose is to provide axial force and torque to the specimen while maintaining transverse constraint. It consists of the rotary and linear hydraulic actuators in series with the grips, the specimen, and the load cell. The rotary actuator is connected to the linear actuator rod with a keyed compression coupling.

The actuated portion of the load train assembly is supported at two locations by separate bearing systems. At the entrance to the chamber, a bronze bushing bearing located in the mounting plate supports the actuator rod. At the other end, a pair of linear track bearings supports the rotary actuator assembly. Linear track bearings provide excellent lateral stiffness, good maintainability, easy installation, and relatively low friction.

The grip assembly transfers axial and in-plane shear forces to the specimen without slippage and supplies pressure to the interior of the specimen. The gripping system consists of two independent gripping units, one for each opposite end of the specimen. The units are identical except for the addition of a check valve mechanism in the grip attached to the load cell. This mechanism is required to facilitate internal pressurization of the specimen. The gripping units consist of three parts: (1) the tapered collet, (2) the flanged hub, and (3) the pre-loading plug.

The purpose of the tapered collet is to provide the necessary clamping force to the specimen during testing. The flanged conical hub provides the restraining force necessary to activate the collet and is used to locate and attach the grips to the testing machine. Matching pairs of the tapered collets and hubs were machined with the same tool setup to ensure compatibility between the mating parts. The hubs can accommodate specimen end sizes up to 64 mm (2.5 in.) in diameter.

The purpose of the pre-load plug is to apply the necessary force to activate the collet and to lock the collet into place. The pre-load plug consists of a cylindrical plug integrated onto a flat plate with extending teeth. These extending sections are used to bolt the plug to the flange hub. Torsional forces are transferred to the specimen by collet friction and a locking key located in the plug.

Internal pressure is supplied to the specimen through a specially designed tube assembly. The tube assembly is inserted into the grip assembly through the center of the load cell and is sealed and threaded externally to the vessel service manifold. Insertion of the tube into the grip cavity forces the check valve to open, resulting in direct and sealed pressurization of the inside of the specimen.

Once the specimen, and grips have been assembled and pre-loaded, the unit is mounted on locators in the testing machine and bolted into place. Since the specimen is mounted horizontally, the specimen-grip assembly must be filled with fluid and bled prior to mounting in the machine. If the interaction of hydraulic fluid with the specimen is not desirable [*23*], the right grip can be fitted with a threaded nipple (poppet insert) that can be used to attach an expendable elastomeric membrane with small hose clamps.

External Pressure Containment—The pressure vessel provides three functions: (1) to contain the pressure applied externally to the specimen, (2) to provide a safety barrier for internal pressure tests, and (3) to provide optimal stiffness for torsional loading. This thick-walled vessel is made from low-temperature, A350-LF3, pressure vessel steel and was machined from a solid forged piece so as to eliminate any welded joints in the vessel structure. The vessel has an