System for Automated Fatigue Crack Growth Testing under Biaxial Loading

B.V. Ilchenko[1] ,K. Ramesh[2], V.N Shlyannikov[1], R.A. Sitdikov[1], R. Sunder[2+] and G. Vivek[2]

[1]Power Engineering Research Centre, Russian Academy of Sciences, P.B. 190, Kazan 420111, Russia.

[2]BiSS Research, 41A, 1A Cross, AECS 2nd Stage, Bangalore 560094, India.

[+]Corresponding author. Email: rs@biss.in. Authors listed in alphabetical order.

ABSTRACT. *A biaxial test system design was developed that is suitable for cruciform type test coupons with a center crack or notch. The objective behind this effort was to come up with a platform for experiments in biaxial fatigue that could proceed with the same degree of flexibility and performance as one experiences on conventional uniaxial test systems, but without diluting the sophistication required to faithfully reproduce the desired degree of biaxiality. The system is equipped with four independently controlled servohydraulic actuators, each equipped with a position and force transducer. The servo-control hardware provides for synchronous, in-phase and out-of-phase cycling at frequencies unrestricted by load biaxiality, under constant amplitude, programmed block and arbitrary (spectrum) loading with adaptive control to ensure adequate precision of peak-valley reproduction. All four grips are electrically insulated from the frame, providing for potential drop instrumentation for crack size measurement. COD instrumentation is also provided. The gripping arrangement provides for some lateral movement along both axes in order to avoid any side loads arising from misalignment. The cruciform specimen design was optimized for uniform stress distribution over the circle enclosed by the central section. A K-calibration was obtained by finite element analysis over this section.*

INTRODUCTION

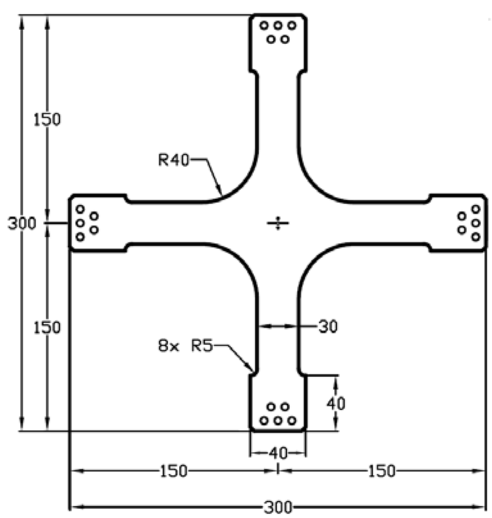
Most fatigue experiments are performed under uniaxial constant amplitude loading. However, most practical problems associated with metal fatigue in structural elements and machine components are associated with random service load conditions, often, under multi-axial loading. Automotive wheels see cyclic out-of-phase biaxial loading with sign reversal and with potential bending component from lateral loads. Turbine and compressor disks see equibiaxial loads arising from large centrifugal forces due to rotation and these can be made more complex by bending component. Pressure vessels always see biaxial loading and pressurized transport aircraft cabins see the superposed action of hoop and axial stress from internal pressure, combined with axial loads caused by gust loads on the aircraft wing. These examples cover different circumstances of cyclic nature of loading and also variations in biaxiality including in-phase versus out-of-phase, different ratios of biaxiality as well as the superposition of pseudo-random loading along one or both axes.

While considerable advances have been made in analytical modeling of stress response of cracked bodies under biaxial loading [1], fatigue under biaxial loading conditions remains very much an unexplored empirical science, demanding appropriate testing technology. Many test systems have been developed over the years to perform tests under static and cyclic biaxial loading using cruciform specimens [2]. To this end, a wide variety of cruciform specimens have also been developed [3-7]. Some of these systems (e.g. as in [3-5]) constitute simple and robust designs whose application using fewer actuators can realize a limited combination of biaxial loading conditions on sheet material.

The objective of this study was to configure a hardware and software platform around the 4-actuator scheme as in [6-7], that could serve a wide variety of biaxial loading conditions using cruciform type sheet specimens. The next section describes the test specimen, test setup, its features and how certain issues specific to biaxial testing were resolved. This is followed by sample fatigue crack growth test results obtained under in-phase and out-of-phase cyclic loading.

Experimental Setup

The Cruciform Specimen



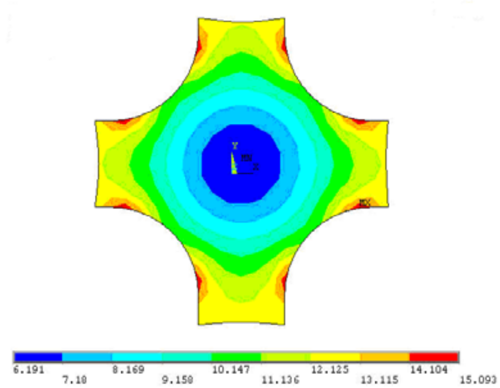


Figure 1. Cruciform specimen (Left) and stress distribution under equibiaxial loading (Right)

A symmetric cruciform specimen was specially designed to permit fatigue and fracture testing under a wide variety of cyclic tensile loading conditions. Using finite element analysis, the length of the four petals of the cruciform as well as the radius of the contours connecting them were optimized to obtain the largest enclosed circular gage area with least deviation of stress across it. Fig. 1 shows the resultant specimen and provides an idea of uniformity of load distribution across the gage area under axial and equi-biaxial loading.

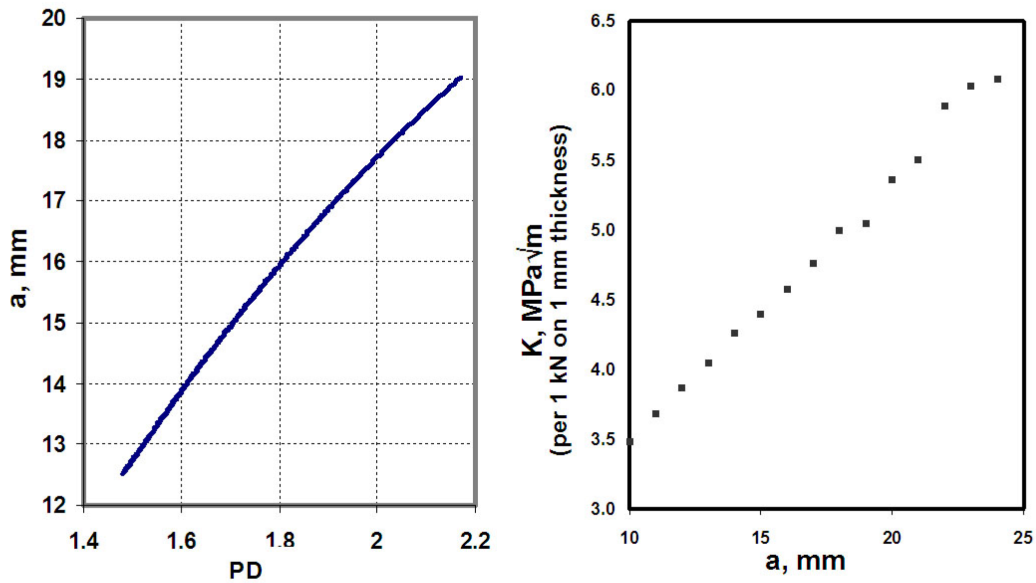


Figure 2. Potential drop and K-calibration functions for the cruciform specimen geometry

The cruciform specimen geometry shown in Fig. 1 may be used for both fatigue crack growth as well as notch fatigue response studies. The specimen may be instrumented for DC potential drop measurements, or COD, or both. Fig. 2 shows the potential drop calibration function established empirically. A polynomial approximation of this relationship may be fed into application software for automated crack growth testing including K-controlled biaxial crack growth. A finite element estimation of K-calibration function for this geometry also appears in Fig. 2. The computation assumes uniaxial loading normal to the crack plane.

Specimen Alignment

A cruciform specimen rigidly mounted onto four actuators constitutes a physically constrained geometry, whereby, any deviation of the specimen center from the intersection point of the two loading axes will induce undesirable shear stresses. Under quasi-static conditions the performance and quality of real-time digital servo-control may in principle satisfactory compliance with the demand of a stationary specimen center, by suitably correcting even miniscule errors in its location. However, under cyclic loading conditions, it is theoretically *impossible* to maintain a strictly stationary specimen center. As position correction is driven by error in the servo-loop, a time lag and therefore, finite displacement of center, becomes inevitable.

Shift of specimen center from load frame center carries several adverse implications. As the system is statically indeterminate, load seen by the opposite ends of the specimen will not be the same because part of the load is reacted by the lateral actuator bearing points. The resultant side loads will distort load cell readout. They can damage actuator seals. And they will impose shear stresses on the specimen gauge section that will in turn cause rotation of the crack plane if not fatigue/fracture at a location other than the intended one. The seriousness of these effects will increase with specimen lateral stiffness and axial compliance, with the latter becoming increasingly inevitable, even dominant, with crack extension. This problem may be somewhat relaxed by allowing individual actuators to pivot [6]. However, such a solution is only suitable where angles are marginal and loading frequency too small to cause inertia related issues.

In the present study, the specimen is mounted onto the four clevis grips using a pair of specially designed backing plates bolted onto each petal. Fig. 3 shows the backing plate. Note that load transfer is through a slot providing for up to +/- 1.5 mm lateral clearance on the loading pin. This provides limited lateral sliding capability in order to eliminate the possibility of transverse loads arising from limited movement of the specimen center.

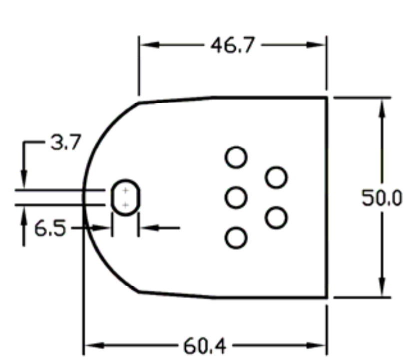


Figure 3. Backing (mounting) plate

As the backing plates do not add much mass to the load train, testing can be performed at frequencies in excess of 20 Hz without any fear of acceleration induced axial load distortion due to specimen or grip movement. Thanks to this arrangement, loading is strictly along the load cell axis, ensuring that force readouts cannot be distorted by side loads. This was confirmed by comparing force readouts from load cells on opposite actuators, which showed negligible difference in readout. The consequences of shift in actual loading axis of the specimen by up one mm away from the center are marginal as determined from recomputed stress distribution across the specimen. It must be noted that the above specimen mounting scheme restricts the test system to tension-tension load applications.

Test System Configuration

System design was to following specifications aimed at opening an avenue to sustainable long-term experimental research involving a testing process that to the operator does not appear much more complex than that associated with uniaxial servohydraulic test systems:

1. Independent digital control of the four servo-actuators with any desired servo-feedback including actuator stroke, force readout, local strain or displacement readout at the desired point on the gage area.
2. Ring-type fully self-reacting load frame permitting scale up in terms of size and force rating of future systems.
3. Single digital controller with capability of highly synchronized multi-channel servo-control, to perform as a single system with the same flexibility, performance and hardware components as conventional uniaxial test systems for ease of support and maintenance.
4. Unified, accessible and expandable software platform to permit ease of developing new test applications without the need to comprehend the complexity of a multi-channel control scheme. Thus, a new application to impose thermo-mechanical loading features can be added without changing software that controls other system functions.

Biaxial Load Frame

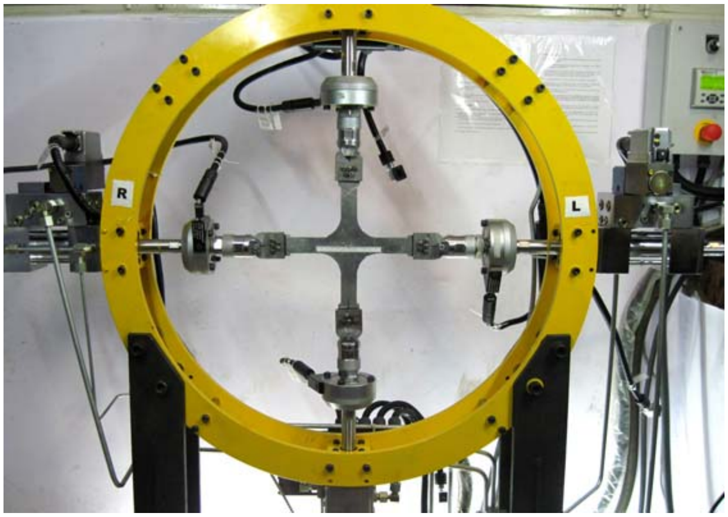


Figure 4. Biaxial test setup

The load frame (Fig. 4) is formed by a pair of parallel steel rings, mounted on rigid spacers including four radial mounted servo-controlled 5 kN, 50 mm stroke actuators. As the frame is totally self-reacting, only a stand is provided to retain the frame in the vertical position at a convenient height for the operator. The stiffness of the frame ensures diametral deflections less than 0.02 mm at maximum applied load. The four actuators are wired and controlled in much the same way as four independent uniaxial test systems. The pressure, return and drain lines from the actuators are hard piped to a common service manifold on the base stand at the foot of the load frame, which is equipped with components required to ensure safe and reliable operation of the actuators without noticeable cross-talk even under dynamic conditions.

Each actuator is equipped with a load cell and clevis grip, with the latter electrically insulated from the actuator in order to comply with the requirements of DC potential drop (PD) instrumentation. Lugs carrying the current for the PD measurement are fastened on opposing backing plates of the specimen along the loading axis perpendicular to the crack plane. The PD signal leads are spot welded about 2.5 mm above and below the specimen center.

Biaxial Control Implementation

Innumerable test control modes are possible on the system with each actuator capable of responding to either stroke, force or local displacement feedback. However, the following method appeared to be the most suitable.

One X and one Y actuator are in Stroke Control, while the other two are in Load Control. However, the load feedback of two actuators on the same axis are interchanged, i.e., the load cell mounted on the stationary actuator that is in Stroke Control provides the feedback for the actuator that is in Load Control and vice versa. As the actuator rod applying the load will see considerably greater movement than the one maintaining constant stroke, its own load cell readout may be distorted by inertial forces from its own mass as well as that of the gripping and the specimen assembly. By sensing force readout from the opposing actuator as feedback, the fidelity as well as accuracy of force response is maintained without the need for expensive acceleration compensated load cells at frequencies in excess of 10-25 Hz. The opposing actuator sees negligible reactive movement during dynamic cycling.

While mounting the specimen, all four actuators are kept in Stroke Control. Switch to Load Control on two of the actuators is performed after ensuring some tensile load is imposed in order to avoid backlash-induced damage to the specimen. At this point, the actuators in stroke control are moved so as to ensure sufficient clearance due to tensile motion on the backing plate slots. This is a manual adjustment that can be corrected at any time without test stoppage. In future, a local position feedback transducer may be introduced for automatic correction of specimen center location.

An important problem of biaxial loading is the inevitable cross-talk between axial and transverse servo-control loops, associated with the Poisson Ratio. This is manifest at frequencies in excess of a few Hz and can lead to a cyclic loading around existing mean on the transverse axis of up to 30% of axial force, and vice versa. This makes digital adaptive control an inevitable requirement for required quality and performance of biaxial cyclic testing. The problem can be somewhat reduced under quasi-static transverse loading by adding compliant links on the transverse axis to make it less sensitive to cross-talk.

Biaxial Test Applications

The application software permits biaxial tension-tension constant-amplitude fatigue cycling with user assigned test frequency, waveform, load/strain amplitude and load ratio, with synchronized waveform phase lag. It also permits axial spectrum loading with sustained or cyclic transverse load/strain.

Constant amplitude cycling is always performed under adaptive control in order to guarantee that cyclic loads are achieved within 2% of required amplitude. The control waveform for the two axes is digitally synthesized with the desired phase lag (in phase, out-of-phase, or some finite phase angle). In order to strictly impose the desired phase lag, a fast Fourier transform (FFT) based feedback waveform analysis is periodically performed and command waveform phase iteratively corrected. This scheme enables biaxial constant amplitude testing at frequencies up to 20-40 Hz. This opens up the possibility of carrying forward to biaxial conditions, such aspects of fatigue research as decreasing-K threshold studies in biaxial fatigue, that demands extended cycling intervals with automated crack size tracking.

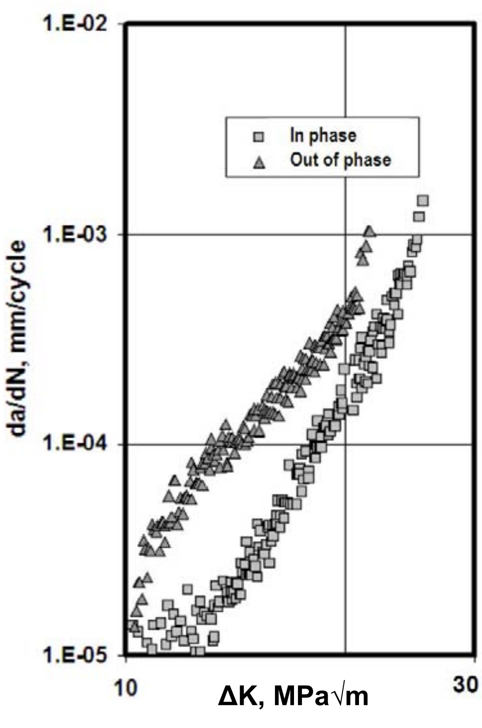


Figure 5. Sample crack growth rates obtained on 1 mm thick steel coupon with equibiaxed P_{max} = 4.5 kN and R = 0.3 at 10 Hz in phase and out of phase loading.

Fig. 5 shows crack growth rates obtained on 1 mm thick steel sheet material under in-phase and out-of-phase cycling, which show a noticeable effect of biaxiality on crack growth behaviour. The test system was also used to study fatigue crack growth under a transport wing load spectrum modified for biaxial loading [8].

CONCLUSIONS

1. A biaxial test system for cruciform geometry test specimens was developed to meet the requirements of routine fatigue research under biaxial loading.
2. The test system is virtually immune to problems associated with specimen misalignment and is capable of in-phase and out-of-phase synchronized constant amplitude as well as spectrum loading with adaptive load correction at test frequencies of the same order as those in conventional uniaxial test systems.
3. The system incorporates DC potential drop, crack opening displacement and other transducer inputs for automation of fatigue crack growth testing under biaxial loading.

Acknowledgement. The authors are grateful for support from BiSS Research and Kazan Energy Research Center that made it possible to develop the test coupon, test system and process described in this paper.

REFERENCES

1. Shlyannikov, V.N., Elastic-Plastic Mixed-Mode Fracture Criteria and Parameters, Lecture notes in applied mechanics, Springer-Verlag Berlin Heidelberg, 2003.
2. Lebedev, A.A., and Muzyka, N.R., Design of Cruciform specimens for fracture toughness tests in biaxial tension, Review paper, Strength of Materials, Vol 30, No 3, 1998 pp 243-254.
3. Muzyka, N.R., Equipment for testing sheet structural materials under biaxial loading, Part 2. Testing by biaxial loading in the plane of the sheet, Strength of Materials, No 2, Vol 34. 2002.
4. Radon, J.C., Leevers, P.S., Culver, L.E., A simple testing technique for fracture under biaxial stresses, J. Experimental Mechanics, June 1977, pp 228-232.
5. Wu, X.D., Wan, M., Zhou X.B., Biaxial tensile testing of cruciform specimen under complex loading, J. Materials Processing Technology, Vol 168, Issue 1, 2005, pp 181-183.
6. Liu, A.F., and Dittmer, D.F., Effect of multiaxial loading on crack growth, Vol 1 – Technical Summary, Air Force Flight Dynamics Laboratory Report AFFDL-TR-78-175 Volume 1, 1978.
7. Makinde, A., Thibodeau L., Neale, K.W., Development of an apparatus for biaxial testing using cruciform specimens, Experimental Mechanics, Vol 32, No 2, 1992.
8. Sunder, R., Fatigue Crack Growth under Flight Spectrum Loading with Superposed Fuselage Cabin Pressure (To be presented at the ICMFF9 Conference on biaxial fatigue, Parma, June 7-9, 2010)