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DEVELOPMENT OF A DEFLECTION CONTROLLED MULTIAXIAL FATIGUE TESTING MACHINE

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This paper discusses the development of a multiaxial fatigue testig machine. The deflection controlled eccentric disk type testing machine produces mode Ⅰ, mode Ⅱ, or combination of both, of crack surface displacements on round or flat specimens. These loadings are necessary for research on complex multiaxial stresses which are common in engineering practice, such as crankshafts. This machine achieved the objective with very simple mechanisms(vector sum of two crank throws of eccentric disks yield bending moments; vector differences, twisting moments), but with more computation in setting the desired parameters. Bending data and torsion data produced by the machine were in good agreement with the data by a conventional fatigue testing machine. Multiaxial data produced by the machine were also in good agreement with the prediction by a well proved multiaxial fatigue theory. Applications of the multiaxial fatigue testing machine are described.

Key Words: Multiaxial Fatigue, Bending, Torsion, Out-of-Phase, Deflection Controlled, Testing Machine, Discriminating Specimen

NOMENCLATURE

A	: Phase plate adjusting angle between two eccentric disks.
b	: Bending fatigue strength
$\mathbf{B}$	: Bending deflection
F_A, F_B, F_C	: Load cell readings
$\mathbf{L}$	: Crank throws of left eccentric disk
M_x	: Bending moment
$\mathbf{R}$	: Crank throws of right eccentric disk
$SALT$	: Equivalent stress according to Langer criterion
$SEQA$	: Equivalent stress according to modified Langer criterion
$SLEE$	: Equivalent stress according to Lee's empirical criterion
$\mathbf{T}$	: Torsional deflection
t	: Torsional fatigue strength
T_m	: Twisting moment $T_m = 50\,\|F_A - F_B\|$
α	: $\alpha = 2\,(1 + \beta \sin\phi)$
β	: An empirical constant
σ	: Applied bending stress amplitude
τ	: Applied torsional shear stress amplitude
K	: $K = \frac{2\tau}{\sigma}$
ϕ	: Phase angle between bending and torsion

1. INTRODUCTION

Most engineering components suffer multiaxial cyclic loadings. Fatigue crack initiation and propagation under multiaxial loadings show different behavior from those of uniaxial loading. Fatigue life prediction of structures or machine parts under multiaxial loadings is essential to their reliable design and failure prevention. Such prediction was often based on simple laboratory data generated under cyclic uniaxial loading.

Research by Brown and Miller(1973), Krempl(1974), Lee (1980) and Garud(1981) indicated that uniaxial data alone cannot be applied directly to the practical situations of complex multiaxial fatigue, i.e., moving principal axes and non-proportional loading. Many fatigue theories or criteria have been proposed but none was generally accepted(Garud, 1981; Lee, 1985). Very little experimental work has been done in this field owing to the lack of proper multiaxial fatigue testing machines. Therefore reliable fatigue testing facilities are required for multiaxial fatigue research. Various types of multiaxial fatigue testing machines are possible such as servo-hydraulic axial-torsion system, or servo-hydraulic axial-torsion and internal/external pressure type system, servo-hydraulic cruciform specimen loading machine. However these servo-hydraulic systems are very expensive and moreover their load types may not be versatile. Therefore we designed a deflection controlled eccentric type multiaxial fatigue testing machine to produce a rather versatile loadings such as static and cyclic bending, static and cyclic torsion, and the combination of bending and torsion with any phase angle between them. Among the various loadings produced by the multiaxial fatigue testing machine, the cyclic bending and out-of-phase torsion load, which is commonly encountered in engineering practice, such as crankshafts in automobile industry, is an example of complex multiaxial loadings.

The construction of the multiaxial testing machine, some detailed descriptions of the frame and the driving mechanism, kinematic analysis of the machine, measurement of moments, and control devices will be described. To evaluate the multiaxial fatigue testing machine, the test data performed with the multiaxial fatigue testing machine were compared

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with the test data with a commonly used fatigue testing machine which can apply bending and torsion separately. Multiaxial fatigue data performed with the multiaxial fatigue testing machine were compared with the prediction of the well proved theory suggested by Lee (1985) for combined bending and out-of-phase torsion.

To show the applicability of the multiaxial fatigue testing machine in discriminating multiaxial fatigue criteria, a discriminating specimen was designed to be suitable for the multiaxial fatigue testing machine. Three multiaxial fatigue criteria suggested by Lee (1989) were chosen to be compared in the discriminating specimen. A typical application of the multiaxial fatigue testing machine to a structural member was also discussed.

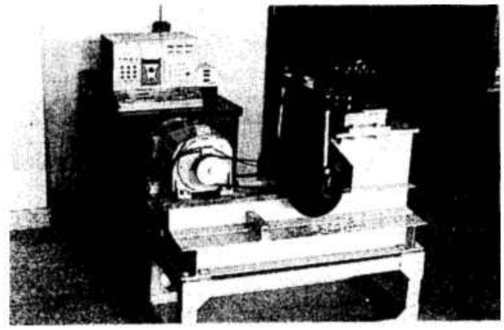

Fig. 1 An overall view of the multiaxial fatigue testing machine.

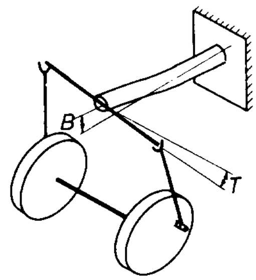

Fig. 2 A schematic diagram of the multiaxial fatigue testing machine.

2. DEVELOPMENT OF THE MACHINE

2.1 Construction

The purpose of the machine is to apply bending moments and twisting moments at the same frequency but with adjustable phase angles, amplitudes, and mean values. The multiaxial fatigue testing machine was constructed as shown in Fig. 1. The machine achieved the objectives with simple mechanisms, but with more computation in setting the desired parameters. The schematic diagram of the multiaxial fatigue testing machine is shown in Fig. 2. There are two eccentric cranks which move the two ends of a symmetric cross beam attached to the moving end of a cantilever specimen. The eccentric cranks are adjustable in throw and phase relation. The vector sum of the two crank throws produces the bending moment and mode I crack, and vector difference produces the twisting moment and mode III crack propagation on round or flat specimen. The constants which convert the vectors to actual bending and twisting deflections and stresses depend on the size of the specimen and on the length of the cross beam.

2.2 Frame and Driving Mechanism

The fatigue machine consists of a frame, a motor, two eccentric disks, a phase plate assembly, two connecting rods, a main shaft, grips and load cells. Fig. 3 shows the layout drawing of the fatigue machine designed. The eccentric crank produces alternating bending deflections up to 140 mm on the specimen. The eccentric crank was designed to be adjustable continuously to form the fluctuating component of stress. The connecting rods were designed to produce static stress on the specimen by adjusting their length. The connecting rod assembly can be extended or contracted by twisting the rod because the ends of the connecting rod have opposite threads. The phase plate assembly connects the two sections of the main shaft which was split to allow relative motion between the eccentrics for phase adjustment. The drive plate and driven plate were designed for continuous adjustment. The

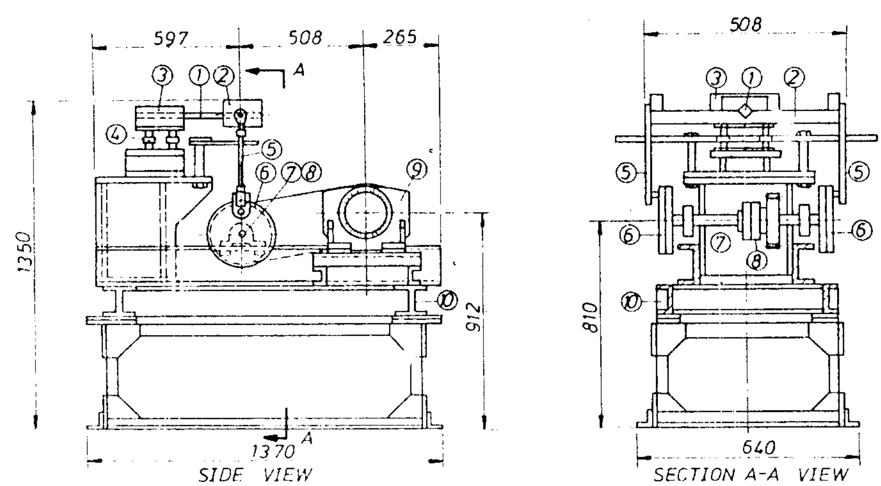

Fig. 3 A layout drawing of the multiaxial fatigue testing machine. Dimensions in mm. (1. Specimen; 2. Cross beam, Moving grip; 3. Fixed grip; 4. Load cells; 5. Connecting rods; 6. Eccentric disks; 7. Main shaft; 8. Phase plate; 9. Motor; 10. Test frame.)

specimen is part of the frame, and the moments on the specimen are transmitted to the fixed grip and to the three load cells. The fixed grips, connecting rods, the main shaft, and the test frame were designed so that high stresses and fatigue stresses occur at the specimen and not any of the machine components.

Variable speed (150~1500 rpm) AC motor was determined for power source of the fatigue machine. Motor capacity of 3 Hp was determined to produce 500 MPa bending stress and 300 MPa torsional stress on the round specimen of 10 mm in diameter and 300 mm in length. A timing belt transmitted power smoothly to the main shafts.

2.3 Kinematic Analysis of the Machine

The machine produces various combinations of bending moments and twisting moments with very simple mechanisms. The kinematic analysis of the machine includes the instantaneous vector components of the machine mechanism as shownin Fig. 4 and their trigonometric calculation. The vector sum of crank throws of right eccentric disk, $\boldsymbol{R}$ and left eccentric disk, $\boldsymbol{L}$ yields bending deflection $\boldsymbol{B}$, while the vector difference produces torsional deflection $\boldsymbol{T}$. The angle ϕ is the phase difference between bending and torsional moments. The angle A is the phase plate adjustments between two eccentric disks.

One must set the machine with parameters of R, L, and A to produce the desired deflections of bending (B) and torsion (T) with phase angle ϕ. The machine setting parameters R, L, A can be obtained as following analysis. The stroke of left eccentric disk L, is derived with given B, T, and ϕ in ΔOPQ as the following equation,

$$L=\frac{1}{2}(B^2+T^2-2B\ T\ \cos\phi)^{1/2} \tag{1}$$

and in ΔOPN and ΔOPQ the stroke of right eccentric disk R is derived as

$$R=\left(\frac{1}{2}B^2+\frac{1}{2}T^2-L^2\right)^{1/2} \tag{2}$$

The phase plate adjustment angle A can be obtained in ΔOPN as

$$A=\cos^{-1}\frac{R^2+L^2-B^2}{2\ R\ L} \tag{3}$$

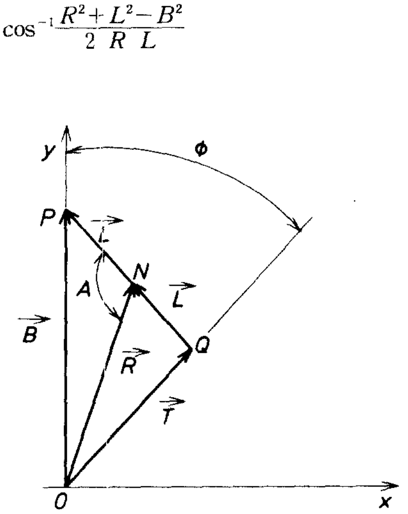

Fig. 4 The instantaneous vector components of the mechanism of the multiaxial fatigue testing machine.

The mechanism is simple, but the kinematic analysis involves lengthy calculations. However such trigonometric calculation was performed easily to make a machine setting table for various values of B, T, and ϕ with a simple FORTRAN program.

2.4 Measurement of Moments

Three 500 kg tension-compression load cells, U2M1 500K, were arranged under fixed grip to monitor loads on the specimen. Three load cells work as the sensor of cracks. The signal of load cells are amplified and connected to the control devices described in the later section. Fig. 5 shows the arrangement of three load cells under fixed grip. Bending and twisting moments can be obtained with the three load cell readings, F_A, F_B, and F_C. The bending moments, M_x, at the location x is given as

$$M_X=[F_C-(F_A+F_B)]\ x+100\ F_C \tag{4}$$

and the twisting moment, T_m, is given as

$$T_m=50\ |F_A-F_B| \tag{5}$$

The constants which convert the moments to actual stresses at a point in the specimen depend on the geometry of the specimen.

2.5 Control Devices

During a fatigue testing, it is necessary to detect the specimen failure. When it fails the test should be discontinued so that the specimen will not be destroyed and the accurate cycles to failure can be counted. For this purpose, an automatic power cut-off device was made. It consists of three main stages; sensing, signal processing, and activating relay.

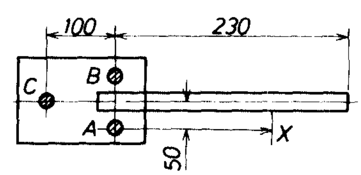

Fig. 5 The arrangement of three load cells under fixed grip. Dimensions in mm.

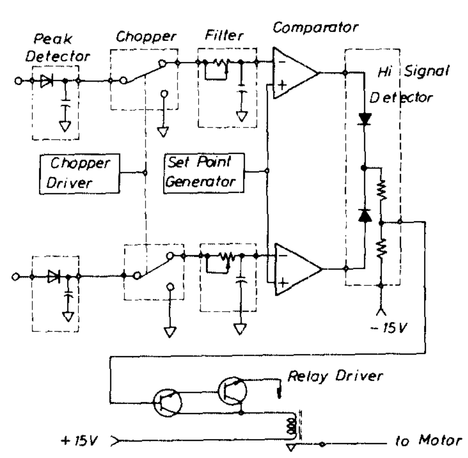

Fig. 6 A schematic diagram of the control circuit for the multiaxial fatigue testing machine.

This control system monitors the load level and activates a relay to turn off the motor when the maximum load is less than a specified level (normally 90% of the original one). Fig. 6 shows the schematic diagram of the control circuit.

Several other control devices such as optical methods cycle counter, timer, load indicator, and testing speed controller were used for accurate testing.

3. EVALUATION AND APPLICATION OF THE MACHINE

The multiaxial fatigue testing machine was evaluated by comparing its test data against the data by a commonly used fatigue testing machine, and against the prediction of the well proved theory suggested by Lee (1985) for combined bending and out-of-phase torsion. The applicability of the multiaxial fatigue testing machine was shown in a discriminating specimen test and fatigue test of a golf shaft.

3.1 Evaluation 1 : Comparing with a Conventional Machine

Constant amplitude fatigue tests were performed under cyclic bending, and under cyclic torsion separately with the multiaxial fatigue testing machine, and also with a Schenck fatigue testing machine which can apply bending or torsion separately. The material tested was SM45C structural steel. Fig. 7 shows the fatigue test results under bending stress and torsional stress. Open circles and open squares in Fig. 7 indicate data obtained with the multiaxial fatigue testing machine, and solid circles and squares indicate the data obtained with the conventional Schenck fatigue tester. Data produced by the multiaxial fatigue testing machine were in good agreement with data by the well proved conventional fatigue testing machine. The multiaxial fatigue testing machine produces reliable data and is safely considered to be suitable for multiaxial fatigue testing.

3.2 Evaluation 2 : Comparing Test Data against Theory Prediction

If the test data are confirmed with the prediction of a well proved multiaxial fatigue theory under out-of-phase bending and torsion, then it can be evaluated as an acceptable multiaxial fatigue testing machine. A multiaxial fatigue criterion proposed by Lee (1985) was selected as the reference criterion because it shows the equivalent life explicitly in terms of applied bending and torsion and their phase angle. The equivalent stress SLEE according the the criterion, which we repeat here for convenience, can be expressed as

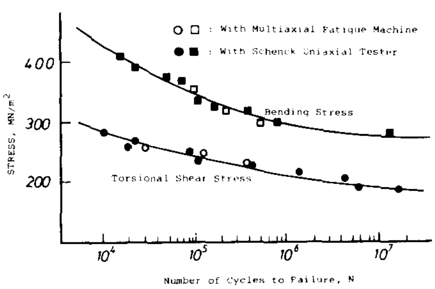

Fig. 7 Fatigue test results of SM45C steel under bending stress and torsional stress.

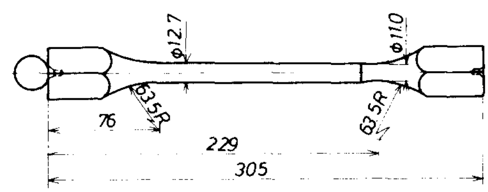

Fig. 8 The specimen used for the bending and torsion fatigue testing. Dimensions in mm.

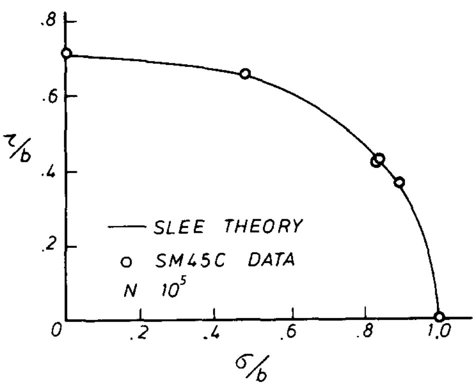

Fig. 9 Fatigue data of various combinations of 90 degree out-of-phase bending and torsion loadings and the constant life curve according to the multiaxial fatigue theory *SLEE*.

$$SLEE=\sigma\left[1+\left(\frac{b}{2t}K\right)^{\alpha}\right]^{1/\alpha} \tag{6}$$

$$\alpha=2\,(1+\beta\sin\phi) \tag{7}$$

where σ is an applied bending stress amplitude and $K=\frac{2\tau}{\sigma}$; τ is an applied torsional shear stress ampltude ; β is an empirical constant and 0.15 for SM45C steel ; ϕ is the phase angle between bending and torsion ; ϕ is a bending fatigue strength for a given life N ; t is the torsional fatigue strength for the same life N.

To verify the multiaxial fatigue testing machine, fatigue tests were performed under 90 degree out-of-phase bending and torsion with SM45C structural steel using the multiaxial fatigue testing machine developed. Fig. 8 shows the specimen used for the bending and torsion fatigue testing. Fig. 9 shows the fatigue data of various combinations of out-of-phase bending and torsion loadings and the constant life curve according to the multiaxial fatigue theory *SLEE*. The fatigue test results with the multiaxial fatigue testing machine were in good agreement with the prediction of the well proved multiaxial fatigue theory.

3.3 Application 1 : Tests with Discriminating Specimens

The possibility of special application of the testing machine was explored in evaluating multiaxial fatigue theories by using a discriminating specimen.

A specimen is called "discriminating" if it can compare the predictive power of several fatigue theories by the location of failure on the specimen. If we design a specimen such that according to theory Ⅰ, the damage accumulates faster near the front end and according to theory Ⅱ it accumulates faster near the rear end, then failure at the front end implies that

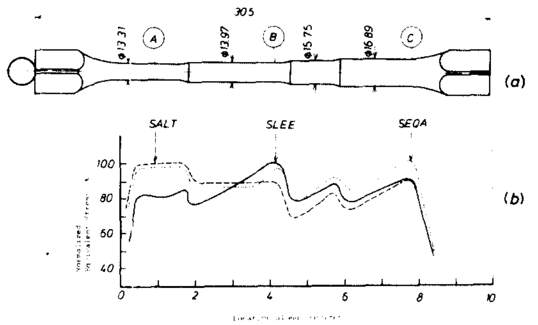

Fig. 10 Geometry of a discriminating specimen with three test sections : A, B, and C. The section C is near the fixed grip. Dimensions in mm.

theory Ⅰ is superior to theory Ⅱ and conversely. Fuchs (1979) used the discriminating specimen in fatigue research for in-phase bending and torsion. In this paper, a discriminating specimen was desgned to show the applicability of the multiaxial fatigue testing machine in fatigue research for out-of-phase bending and torsion.

(1) Plausible theories on complex multiaxial fatigue

There are many multiaxial fatigue theories but none is generally accepted for complex loadings. Among many theories, three plausible theories suggested by Lee(1989) were chosen to compare for fully-reversed out-of-phase torsion and bending loadings. Those are *SALT*, *SLEE*, and *SEQA*. *SALT* is the equivalent stress derived by Lee(1980) from ASME Boiler and Pressure Vessel Code(1974) procedures suggested by Langer(1971). *SEQA* is the equivalent stress derived by Lee(1980) from Code Case(1978) procedures. *SALT* reduces to Tresca criterion and *SEQA* to von Mises criterion when the applied load is in-phase bending and torsion, i.e. $\phi=0$.

(2) Discriminating specimen and loading

Figure 10 shows the geometry of the discriminating specimen which has three test sections : A, B, and C. The section C is near the fixed grip. The developed multiaxial fatigue testing machine applied 90 degree out-of-phase torsion and bending loadings on the specimen so that maximum torsional stress occurs at section A, maximum bending stress occurs at section C. Then *SALT* predicts failure at A, *SLEE* at B, and *SEQA* at C on the specimen.

(3) Results of discriminating specimen tests

Failure was defined as 10% drop in specimen stiffness, which corresponded to visible fatigue cracks. Three specimens of 304 stainless steel were tested under stepwise loadings. All three of the discriminating specimens failed at test section B where *SLEE* predicted the failure. This results indicated that the conventional Tresca and von Mises type criterion might underestimate the out-of-phase multiaxial fatigue damage. A similar trend was also reported by Lee (1989) but with different shape of discriminating specimen, which confirmed that the multiaxial fatigue testing machine can be successfully used in discriminating multiaxial fatigue theories.

3.4 Application 2 : Bending Fatigue Test on Golf Shafts

To show the versatility of the multiaxial fatigue testing machine, a shaft shaped structural component was tested with the developed multiaxial fatigue testing machine. A golf shaft was chosen as the specimen because it is subject to repeated bending and torsion loadings. Practically fatigue tests were required in developing golf shafts with composite material such as carbon fiber reinforced plastic(*CFRP*) as shown in Jun et al.(1984).

It was known that the weak spot in the golf club is around 102 mm from the end ; the joining area between the golf shaft and the head. The area in the shaft was fixed and cantilever bending load was given with bending arm of 183 mm from the fixed point. To avoid the stress concentration, grip end was rounded. Fig. 11 shows grip arrangement for the bending fatigue test of the golf shaft with the multiaxial fatigue testing machine. Fig. 12(a) shows the load versus deflection lines for the steel shaft and the *CFRP* shaft. Fatigue test

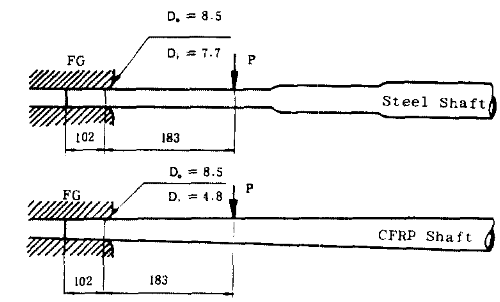

Fig. 11 Grip arrangement for the bending fatigue test of golf shafts with the multiaxial fatigue testing machine. D_o, D_i are outer and inner diameters of the hollow golf shaft. Dimensions in mm. FG : Fixed Grip ; P : Load exerted by the moving grip.

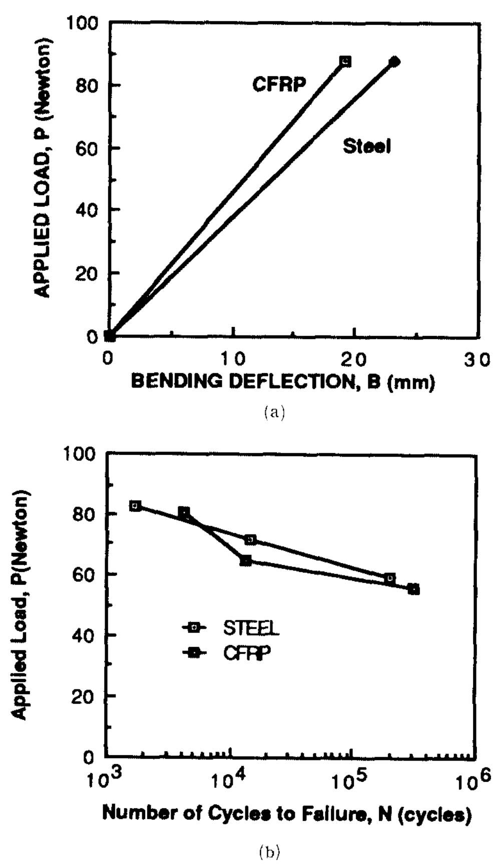

Fig. 12 (a) Load versus deflection lines for steel shaft and *CFRP* shaft. (b) Fatigue test results of golf shafts with the multiaxial fatigue testing machine.

results of golf shafts with the multiaxial fatigue testing machine are shown in Fig. 12(b). The *CFRP* shaft and the steel shaft showed the similar fatigue strength. Failure occurred at the tensile loading side for the steel shaft, while at the compressive side for the *CFRP* shaft. This failure location implies that the carbon fiber in the *CFRP* shaft is strong in tension but weak in compression.

4. DISCUSSIONS

The basic concept of the multiaxial fatigue testing machine described here came from the first machine designed and built by a group of students as a student project at Stanford University (Herandez et al., 1977). This first machine was then modified and improved by Lee (1980) for the complex multiaxial fatigue research. The improved machine by Lee (1980) was good enough for discriminating specimen tests but restricted to a constant test speed of 3 Hz and its machine setting was still very difficult. To overcome such limitations the multiaxial fatigue testing machine was redesigned. This multiaxial fatigue testing machine now can produce multiaxial cyclic loadings with variable test speed and with more precise control and measurement of applied loads.

The multiaxial fatigue machine developed can apply bending moments and twisting moments at the same frequency but adjustable difference in phase angle, difference in amplitudes, and difference in mean values. The multiaxial faigue testing machine achieved the objective of producing various loadings with very simple mechanisms, at the expense of more computation in setting the desired parameters. However the computation can be done very cheaply by electronic means. This is the significant difference to the prior art in which setting of the parameters was fairly obvious; but at the expense of rather complex mechanisms or closed loop servo-hydraulic systems.

The testing machine can be used in the investigation of the mean and normal stress effect on multiaxial fatigue study and fatigue crack propagation study under mode Ⅰ, and mode Ⅲ and combination of both. The mean stress can be obtained by adjusting the two connecting rods since the deviation from the neutral length of the rods produces the static stress on the cantilever type specimen. Since the mean stress effect on fatigue is known to be significantly reduced when the maximum stress on the specimen is above the yield strength of the specimen, it is noteworthy that high strength of material should be used in the investigation of mean stress effect. The rate and direction of crack propagation under multiaxial loading can be obtained with the replica on a flat specimen loaded by the multiaxial fatigue testing machine. The continuous movement of crack propagation can be recorded with proper accessories such as microscopic video camera and screen.

5. CONCLUSION

A deflection controlled multiaxial fatigue testing machine was developed to produce multiaxial cyclic loadings with variable speed on a cantilever type specimen. The multiaxial cyclic loadings were achieved with the multiaxial fatigue testing machine by applying bending moments and twisting moments at the same frequency but with adjustable phase angle, amplitudes, and mean values.

The bending fatigue data and torsion fatigue data produced by the multiaxial fatigue testing machine were in good agreement with the data produced by the well proved commercial fatigue testing machine which can apply bending or torsion separately. Multiaxial fatigue test data produced by the multiaxial fatigue testing machine were in good agreement with the prediction of the well proved multiaxial fatigue theory.

The multiaxial fatigue testing machine was shown to be useful in evaluating multiaxial fatigue theories by discriminating specimen tests. The multiaxial fatigue testing machine was proved to be applicable for the testing of actual components such as golf shafts.

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