Low-cycle fatigue studies on commercial aluminium in combined bending and torsion

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Abstract

A strain-controlled low-cycle combined bending and torsional fatigue testing machine was designed and fabricated. It has two independent 4-bar mechanism with stepless control of both input crank lengths thus giving an independent precise control on the maximum bending deflection and maximum angle of twist.

98·9 per cent pure aluminium specimens of the ASTM hour glass type were tested in pure bending, pure torsion and combined bending and torsional fatigue loading.

The machine performed satisfactorily throughout the range of bending strain and shear strain for which it was designed. The results showed that, in the pure bending and pure torsional fatigue tests, they resembled the test results of previous investigators. The combined bending and torsion low-cycle fatigue results show resemblance to high cycle fatigue results of other investigators quoted. The plot of test results can be used for design of components subject to low-cycle combined bending and torsional fatigue loading.

Key words : Metal fatigue, low-cycle fatigue, life curves.

1. Introduction

Majority of the failures in practice can be attributed to fatigue. In fact, very few structures in service life are subjected to purely static loading.

In the past few decades, a new dimension has been added to the studies of fatigue under the heading 'Low-Cycle Fatigue'. Here the working stresses are deliberately allowed to approach as close to the strength limits as it is feasible in modern designs, where strength to weight ratio is an important consideration.

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In practice, fatigue failures are not only due to uniaxial fatigue loads, but also due to multiaxial fatigue loads. Moreover, the latter is the most commonly observed phenomenon. In earlier days, uniaxial fatigue tests were carried out on various metals and the information obtained from such tests was utilized for design of components or structures where the fatigue loading was not uniaxial, by providing suitable high 'factor of safety'. However, it is desirable that this factor of safety should not be a guess, but a realistic value based on facts. In order to get the realistic information, practical tests carried out as close to the real conditions as possible will be useful and for this multiaxial fatigue tests will be ideal.

2. Literature review

There is a lot of literature on multiaxial fatigue testing in low-cycle region for various combinations of stresses, but there is one combination namely combined bending and torsion on which very little literature is available. In 1974, an attempt was made in this direction[1], but no results as such have been reported. In high-cycle region, Gough and Pollard[2] tested many specimens under combined bending and torsion and reported some firm results. According to them when fatigue limits are plotted for various combinations of stresses, the experimental points lie very nearly on ellipses having the equations

$$\frac{\sigma^2}{b^2} + \frac{\tau^2}{t^2} = 1 \quad \text{(for ductile materials)}$$

where

b = fatigue limit in bending, kg/cm^2

t = fatigue limit in torsion, kg/cm^2

σ = bending stress, kg/cm^2

τ = torsional stress, kg/cm^2.

Therefore, a machine was designed and fabricated for low-cycle combined bending and torsion fatigue testing and tested to see whether the above given theory was valid for low-cycle fatigue or not.

3. The machine

Fig. 1 (Also see Fig. 1*a*) shows the schematic diagram of the fabricated machine. It consists of two V-belt drives, a single stage reduction gear box and two 4-bar mechanisms. From the electric motor a V-belt drive is given to the reduction gear box whose output is transmitted through a V-belt drive to the input crank-1 for torsion. At the other end of the shaft of this crank-1, another input crank-2 for bending is fitted. By adjusting the lengths of these cranks, any desired bending deflection and angle of twist can be obtained. Angle of twist is measured by means of a protractor

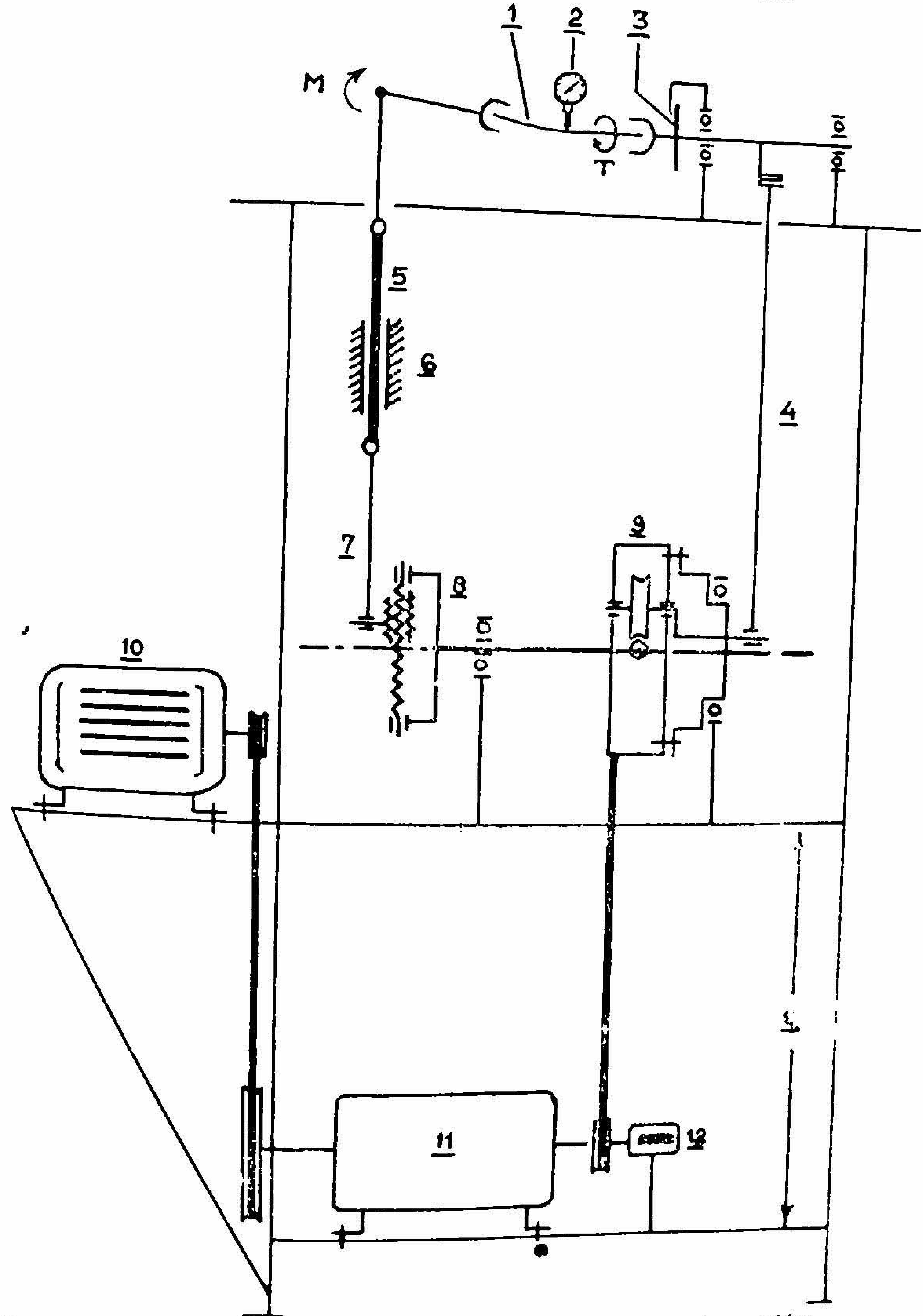

FIG. 1. Schematic diagram of combined bending and torsion fatigue testing machine.

1. Specimen
2. Dial Gauge
3. Protractor
4. Connecting rod (torsion)
5. Slider
6. Guide
7. Connecting rod (bending)
8. Crank (bending)
9. Crank (torsion)
10. Motor
11. Gear box
12. Counter
13. Supporting structure

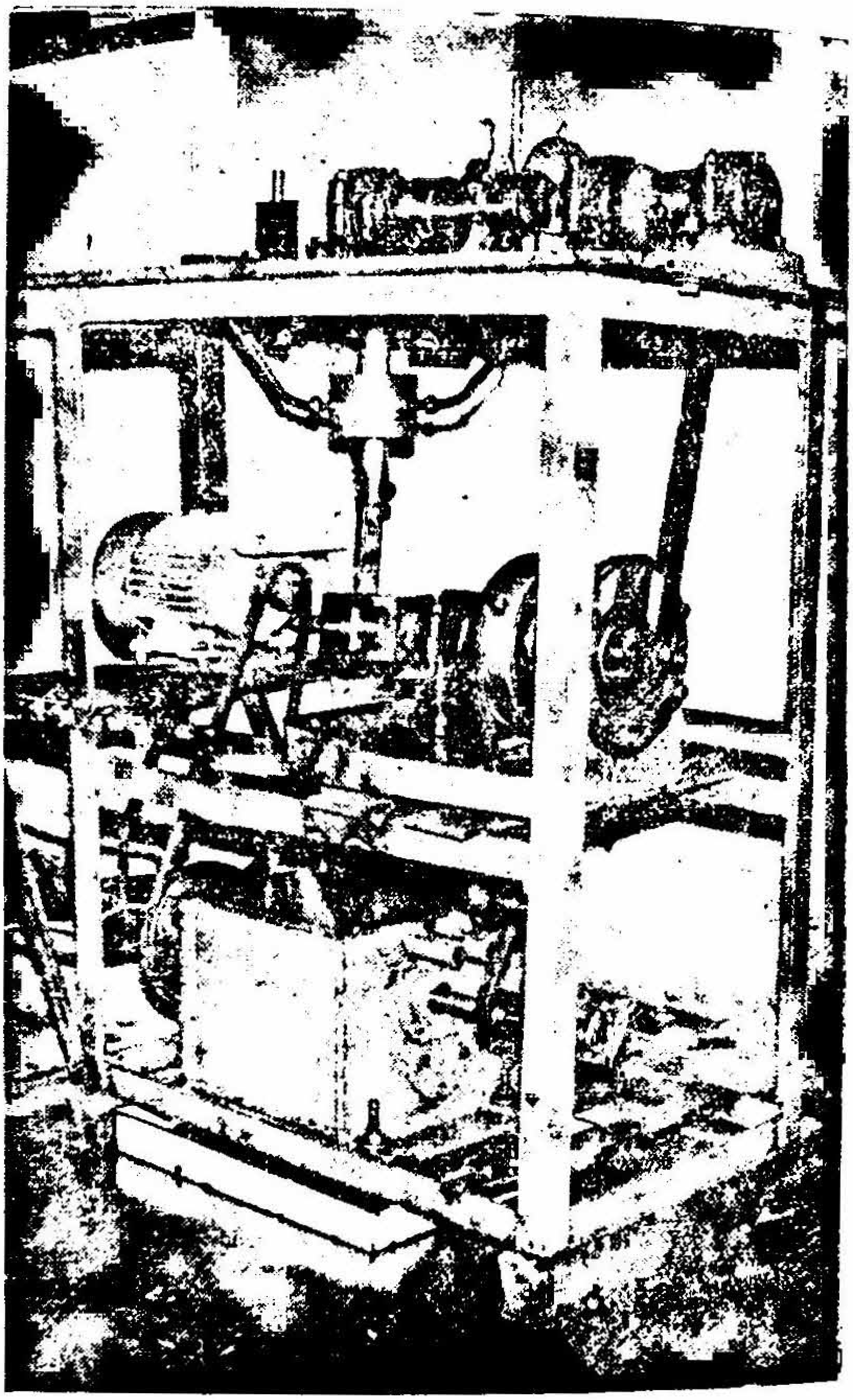

FIG. 1 *a*. General view of the combined bending and torsion low-cycle fatigue testing machine.

and bending deflection is measured by means of a dial gauge. A revolution counter measures the number of cycles executed. This machine was entirely designed and fabricated in the machine design section of the Mechanical Department, I.I.T., Bombay.

4. Experimentation and experimental results

Three different types of fatigue tests carried out on the fabricated machine are described below. The material used for investigation was 98·9% pure aluminium in as received condition. A standard hour glass type ASTM specimens were used in all the tests. The material properties of aluminium tested are: $\sigma_{ultimate} = 12$ kg/mm^2; reduction of area = 70%.

(a) *Pure bending fatigue tests*

Pure bending fatigue tests were carried out at four strain levels. At each strain level five specimens were tested until failure (rupture of specimen) occurred. From the test results bending strain amplitude 'ε_T' *versus* number of cycles to failure 'N' curve was plotted as shown in Fig. 2. Respective confidence intervals are also marked. The scatter in results for any particular strain level was less as compared to high-cycle fatigue tests. High strain applied might have eliminated the effects of scratches and residual machining stresses produced on the specimen surface.

(b) *Pure torsion fatigue tests*

Pure torsion fatigue tests were carried out at four strain levels, five specimens being tested at each strain level. Torsional shear strain amplitude 'γ_s' was plotted against number of cycles to failure 'N' as shown in Fig. 3.

(c) *Combined bending and torsion fatigue tests*

Combined bending and torsion fatigue tests were carried out at nine strain ratios, five specimens were tested at each ratio. Shear strain 'γ_s' was plotted against number

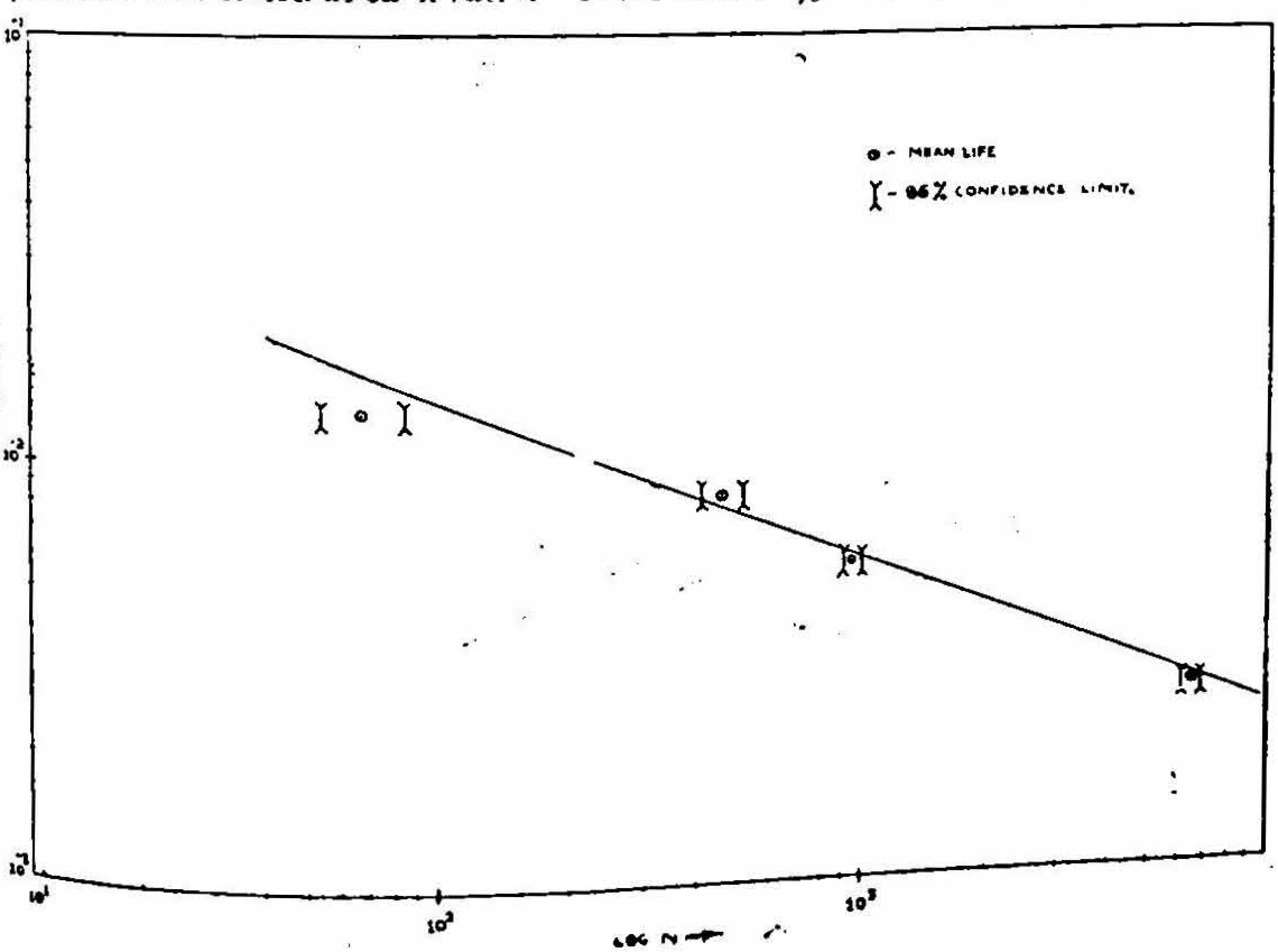

FIG. 2. $\mathrm{Log}_{10}\varepsilon_T$ *vs* Log_{10}N curve under pure bending.

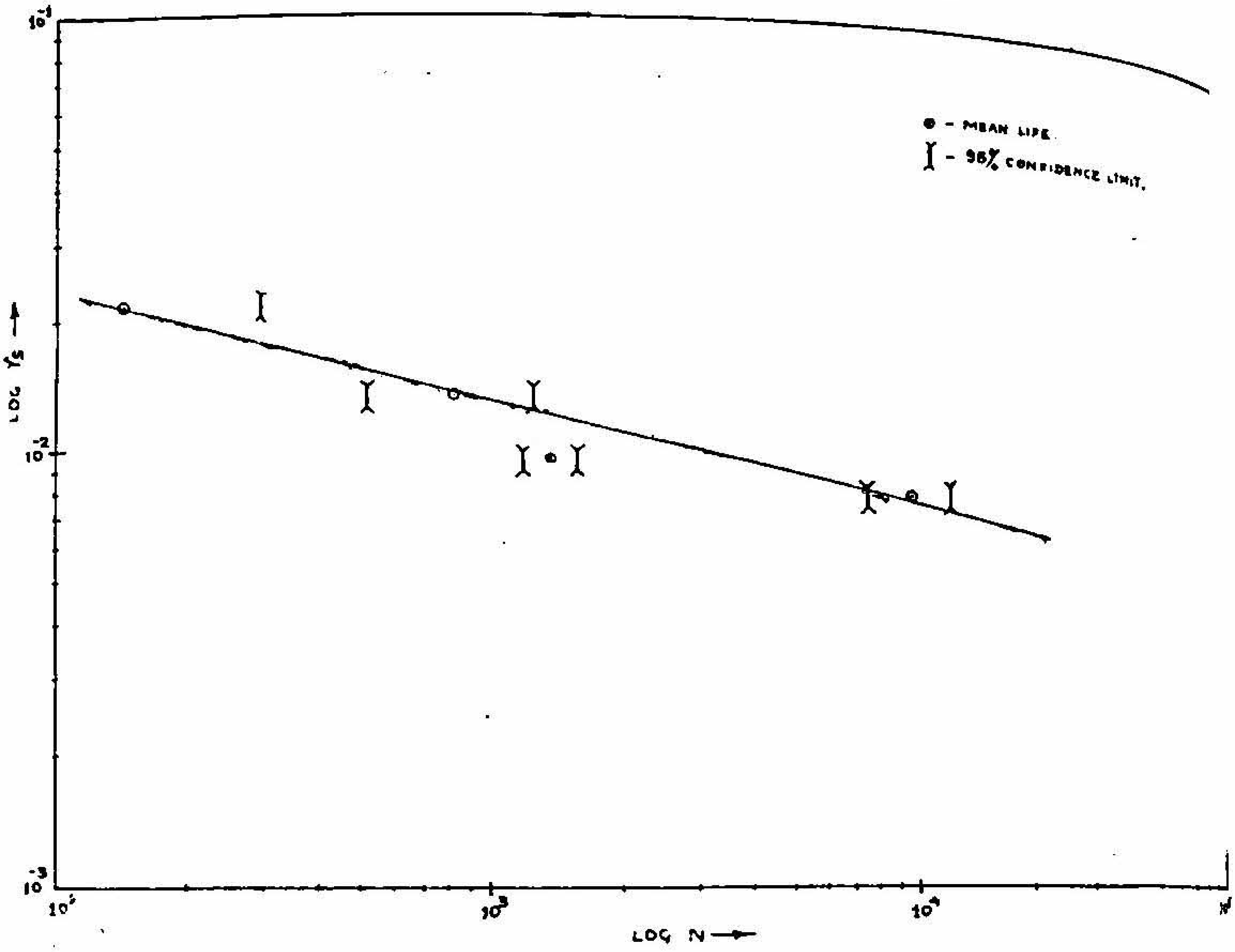

FIG. 3. $\mathrm{Log}_{10}\gamma_s$ *vs* Log_{10}N curve under pure torsion.

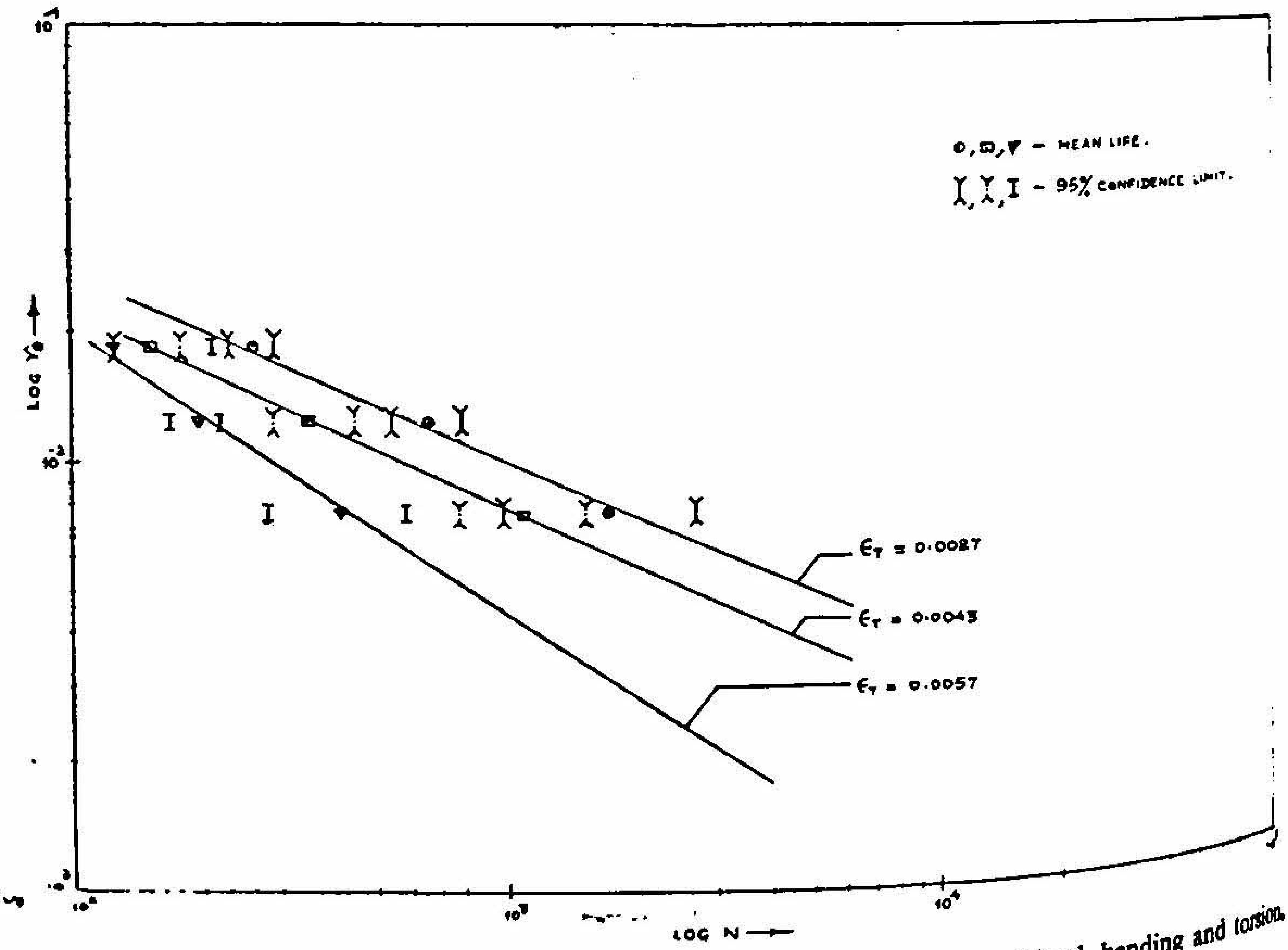

FIG. 4. $\mathrm{Log}_{10}\gamma_s$ *vs* Log_{10}N curves for different values of ε_T under combined bending and torsion.

of cycles to failure 'N' for different values of bending strain 'ε_T' as shown in Fig. 4. Similarly as shown in Fig. 5, bending strain 'ε_T' was plotted against number of cycles to failure 'N' for different values of 'γ_s'.

(d) Different design curves for specified number of cycles to failure

With the help of the plots in Figs. 2 and 3, fatigue limits based on 10^4 cycles and 10^7 cycles for pure bending (ε_{T-1}) and pure torsion (γ_{s-1}) were determined. Then the dimensionless ratio ($\varepsilon_T/\varepsilon_{T-1}$) was plotted against the dimensionless ratio (γ_s/γ_{s-1}) for

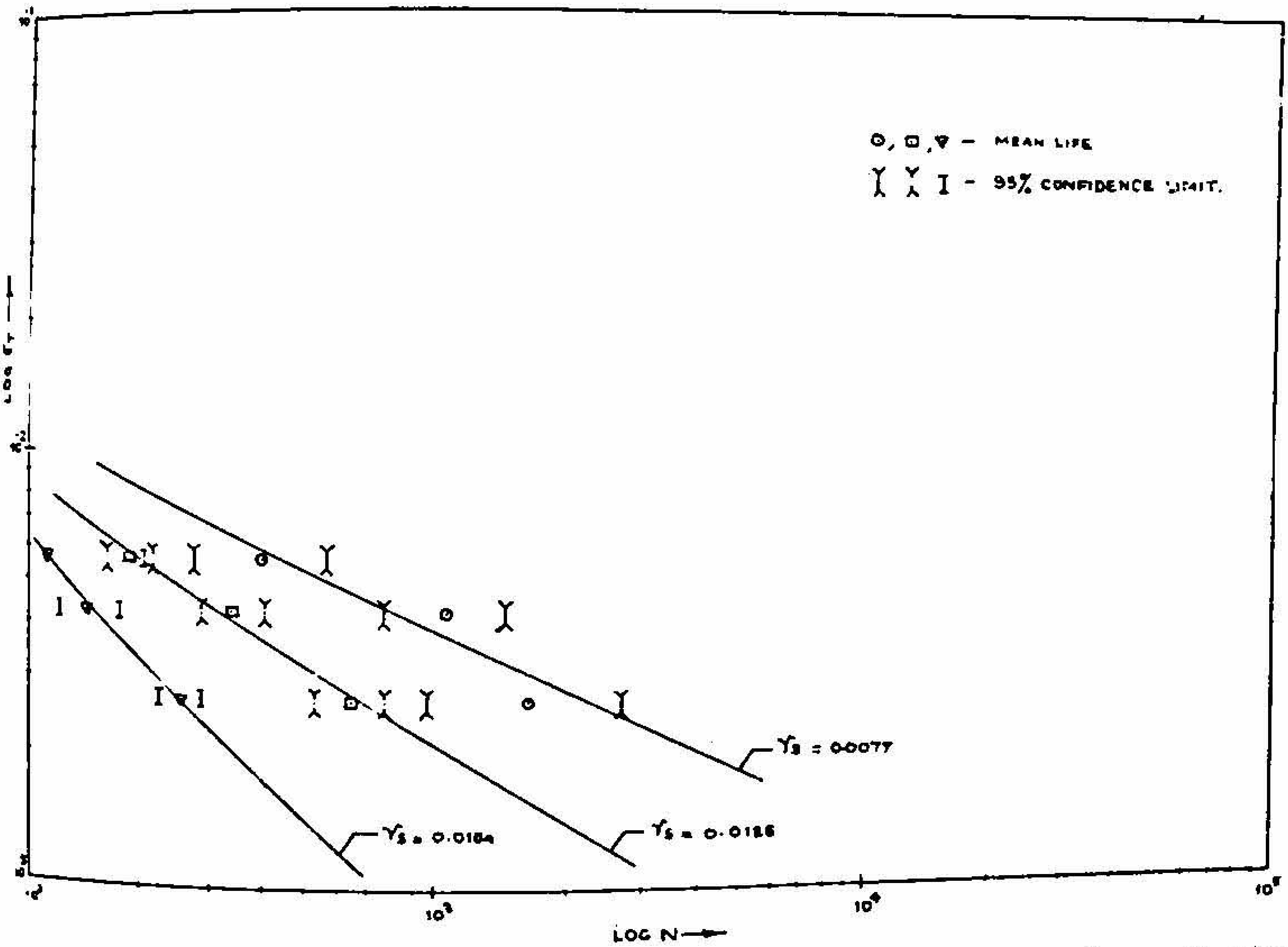

FIG. 5. $\text{Log}_{10}\varepsilon_T$-*vs.*-$\text{Log}_{10}$N curves for different values of γ_s under combined bending and torsion.

different number of cycles to failure, *viz.*, 500, 1,000, 1,500 cycles to failure. Fig. 6 shows such curves for endurance limit based on 10^4 cycles while Fig. 7 shows such curves for endurance limit based on 10^7 cycles.

5. Discussion

The plots in Figs. 2 and 3 have revealed that, they resemble the test results investigated by Manson[3], Coffin[4] and Martin[5] uniaxial tests.

The shape of the curves in Fig. 4 for combined fatigue tests show that as ε_T increases the slope of the line also increases which is obvious because as ε_T increases, the

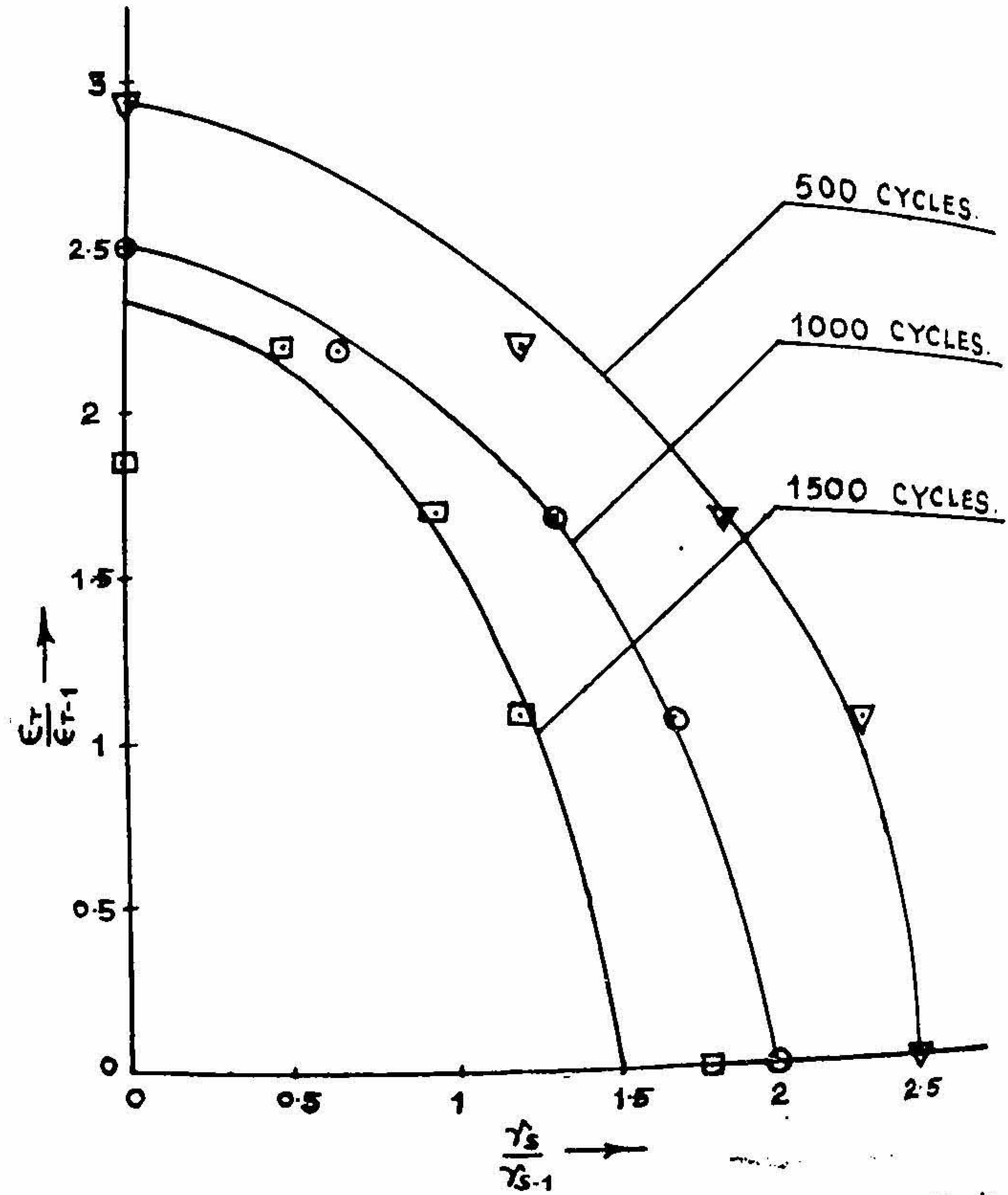

FIG. 6. Relation between $(\varepsilon_T/\varepsilon_{T-1})$ and (γ_s/γ_{s-1}) for ε_{T-1} and γ_{s-1} based on 10^4 cycles.

equivalent strain also increases and life decreases. Similar reasoning is valid for the curves in Fig. 5.

From the shape of the curves in Figs. 6 and 7, it is clear that they are quadrants of ellipses with $\varepsilon_T/\varepsilon_{T-1}$ as major axis and γ_s/γ_{s-1} as minor axis. This is exactly similar to the results of high-cycle fatigue tests under combined bending and torsion as investigated by Gough and Pollard[2].

6. Conclusions and suggestions

From the above analysis and discussions following conclusions may be drawn:

(i) Designed and fabricated machine is suitable for carrying out low-cycle pure bending, pure torsion and combined bending and torsion fatigue tests.

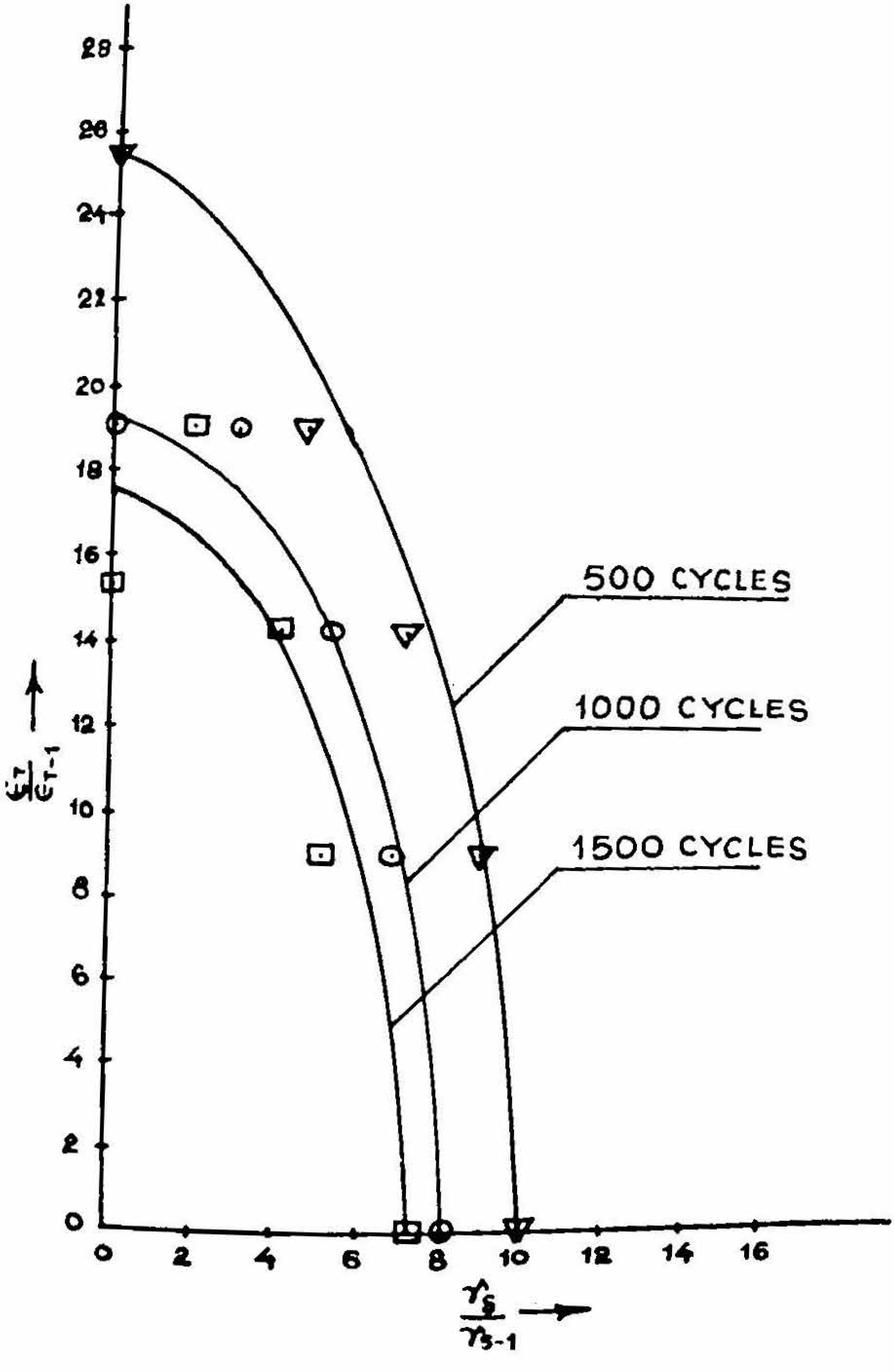

FIG. 7. Relation between $(\varepsilon_T/\varepsilon_{T-1})$ and (γ_s/γ_{s-1}) for ε_{T-1} and γ_{s-1} based on 10^7 cycles.

(ii) Results of uniaxial fatigue tests are in fair agreement with the published results.

(iii) Results of combined fatigue tests resemble with those for high-cycle combined bending and torsion fatigue tests[2].

However more experiments are needed on a variety of materials to confirm these results.

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