THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE FATIGUE PROPERTIES OF A UNIDIRECTIONAL CARBON FIBRE REINFORCED PLASTIC MATERIAL SUITABLE FOR LEAF SPRINGS

by

L.F. Reynolds, M.Sc.Tech.,M.I.M.

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SUMMARY AND CONCLUSIONS

A method of fatigue testing fibre reinforced composites on an Avery 7303 bending fatigue machine has been developed, using reduction in flexural modulus of the sample as a criterion of failure.

Subsequent fatigue tests carried out on samples of pultruded Type A carbon fibre reinforced plastic have shown that the composite has a fatigue performance at 10^6 cycles equal to that of strain peened spring steel. The specific fatigue properties of the composite, which take into account the relative densities of the composite and steel, however, are at least four times greater than those of the strain peened spring steel.

This Type A C.F.R.P. is likely to prove a satisfactory technical alternative to spring steel for leaf spring applications, as a simple exercise in cost/benefit analysis has shown that replacement of the steel spring unit by the C.F.R.P. material in a typical 8 tonne (unladen weight) commercial vehicle should result in an increased pay load to the value of over £2000 during the normal operating life of the vehicle.

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1. INTRODUCTION

Carbon fibre reinforced plastics (C.F.R.P.) have been recognised as high strength materials for some time, although the serious consideration of the composite as a material suitable for structural engineering purposes is a relatively recent innovation.

The manufacture and potential of C.F.R.P. in the context of the spring industry has been the subject of a recent SRAMA report(1).

Carbon fibre composites can be categorised as low density materials exhibiting high strengths in elastic deformation. This latter point should be clearly understood, since the fact that C.F.R.P. behaves elastically up to the onset of failure requires that careful attention be given to the detailed stressing of the component at the design stage of manufacture. This prerequisite is necessary to prevent the introduction of high localised stresses which could induce premature failure, rendering it impossible to obtain the best combination of strength and reliability from the component.

The strength of the resin matrix and the interlaminar shear strength of the resin/fibre bond should be approximately one fifth of the matrix (resin) strength(2). In theory, values of the interlaminar shear strength greater than (Matrix strength/5) would lead to higher elastic strengths, but in practice would lead to brittle fracture and catastrophic failure at high stress levels.

In terms of spring design, it is also important to appreciate that unidirectional composite materials develop their highest strengths when stressed in tension in a direction parallel to the fibre direction. In this context, it has been pointed out that long, shallow beams develop the full flexural strength of the composite(3) and hence the highly anisotropic properties of unidirectional lay-ups have particular significance for C.F.R.P. intended as leaf spring materials.

Studies at Rolls Royce have shown that, except in situations where weight savings are particularly important, composites formed of Type A carbon fibre are likely to be the most cost effective materials for general engineering applications(4). This Type A material also has modulus (E) and elastic properties which are similar to those of spring steel. The Type A composite was therefore chosen for study in the present work.

2. EXPERIMENTAL PROCEDURE

2.1 Material

Pultruded Type A unidirectionally aligned carbon fibre reinforced strip was obtained from the Materials Development Division of Harwell, A.E.R.E. The composite contained 65% w/w of Type A carbon fibre in a matrix of MY753/HY956 epoxide resin, having been pultruded at 8 cm per min., and cured at 150°C.

The strip had a nominal cross-section of 15 mm width x 2 mm thickness, and was obtained as specimens which varied from 80 to 200 mm in length.

2.2 Static Mechanical Properties

2.2.1 Tensile testing

Tensile specimens were prepared from 200 mm lengths of the pultruded strip, to the design shown in Fig. 1A.

The tensile tests were carried out on a Hounsfield Tensometer capable of testing up to loads of 20 kN., the tensile strengths being calculated from the maximum load at failure.

2.2.2 Flexural strength testing

Flexural strength tests in both 3-point and 4-point bending were carried out on a Hounsfield Tensometer with suitable jig attachments.

Specimens of plain rectangular cross-section were used for the 3-point test, whilst shaped samples of the design shown in Fig. 1B were used for the 4-point tests.

In each case, the supports through which the loads were applied were radiused to reduce the possibility of damage at the surface of the composite.

The maximum stress at fracture was then calculated from the following relationships:

3-point bending:

$$\sigma f = \frac{3}{2} \cdot \frac{WL}{BD^2} \qquad \ldots\ldots \quad 1$$

4-point bending:

$$\sigma f = \frac{6\,Wa}{BD^2} \qquad \ldots\ldots \quad 2$$

where

σf = maximum stress at fracture, N/mm^2

W = applied load, N

L = distance between outer supports, mm.

a = distance between inner and outer supports, mm. (4-point test only)

B = specimen width at centre, mm

D = specimen thickness, mm

2.2.3 Determination of flexural modulus

A coates 'Comaco' cantilever type spring load testing machine was modified for this test, by incorporating three radiused triangular supports. The strip specimen, of nominal dimensions 80 x 15 x 2 mm, was supported horizontally on two of the supports which were mounted on a steel block, the complete arrangement being attached to the bottom plate of the load tester. The third radiused edge was attached to the top plate of the tester, and thus varying loads were applied to the centre of the specimen across a known gauge length (63.5 mm), the midspan deflection being noted on a "Baty" dial gauge.

The deflections for given incremental increases in load were recorded. Further readings were than taken with the loads decreasing by the same increments, the deflection at a given load being taken as the mean value of those observed with increasing and decreasing loads.

The flexural modulus was then calculated from the relationship:

$$E = \frac{WL^3}{48Iy} \qquad \ldots\ldots \quad 3$$

where

E = flexural modulus, N/mm^2

W = applied load, N

L = distance across horizontal supports, mm

I = 2nd moment of inertia = $\frac{BD^3}{12}$, mm^4

y = central deflection of specimen at loads W, mm

Measurements were made of the deflection, y, at various loads, W, of up to 490 N, and a mean value of E was calculated from the results.

2.3 Fatigue Testing

2.3.1 Failure criterion

Fatigue failure of metals is almost always initiated at the surface by slip processes which ultimately lead to the formation of a propagating crack. Under most circumstances, only one such crack propagates to produce the final failure, and the crack initiation process can be considered to have a negligible effect on the other mechanical properties of the specimen. Since considerable scatter is encountered in the results, and also due to the practice of plotting lives logarithmically, it is considered acceptable to define such failures in terms of either visual cracking or total separation of the specimen.

In fibre reinforced plastics, however, fatigue failures are progressive and extend throughout the stressed region of the material(5).

Essentially, under fatigue conditions, debonding occurs between the fibres and the matrix, accompanied by the formation and progressive intensification of cracks in the resin matrix. The first signs of damage can occur at relatively small fractions of the ultimate fracture stress, and if this stress is exceeded in a fatigue test permanent damage is present from the first cycle of stress.

As damage progresses, hysteresis increases, and the strength and modulus properties decrease concurrently. The criterion of failure selected must therefore take into consideration the progressive nature of the change in the mechanical properties of the composite during the course of fatigue testing. This is especially true in the case of machines operating with a fixed deflection, where progressive reduction of the applied stress would tend to make actual fracture and separation of the sample unlikely.

Smith and Owen have shown that it is possible to produce S-N curves which define the onset of particular states of damage(6). Their work involved the measurement of the tensile modulus, E, followed by careful microscopical examination of cross-sections taken from glass fibre reinforced composites which had been subjected to a single tensile loading at progressively increasing values of tensile stress. The authors concluded that the two main contributors to the change in mechanical properties, namely fibre/resin debonding and resin cracking, could be correlated with the loss in modulus exhibited by the stressed samples which they examined (Fig. 2).

Although the quantitative aspects of their work were necessarily approximate, it can be seen from Fig. 2 that a loss of modulus of 2-4% was considered indicative of fibre/resin debonding, whilst a loss of modulus of 11-14% corresponded to the onset of resin cracking.

Similar conclusions should apply to the carbon fibre reinforced plastics, although the stress levels for the appropriate failure mechanism should be higher than those obtained in the glass fibre reinforced plastic, due to two main factors:

1. The reduced interfacial free energy of the carbon (graphite)/organic resin bond in the C.F.R.P., leading to an interlaminar shear strength of about 70 N/mm^2 in the C.F.R.P., as compared to 25 N/mm^2 in the G.F.R.P.

2. The higher stresses necessary to produce the strain required for resin cracking in the C.F.R.P., due to the higher modulus of the pure carbon fibre (2 x 10^5 N/mm^2) when compared to that of the pure glass fibre (7 x 10^4 N/mm^2).

In later work, Bevan and Sturgeon investigated the flexural fatigue properties of both Type I and Type II C.F.R.P.(7). All their tests were carried out at a frequency of 16.6 Hz using constant sign loading, i.e. bending one side of zero, the minimum stress being 5% of the maximum stress. Each specimen was removed at intervals from the fatigue jig and the residual flexural modulus was determined. Tests were discontinued when the modulii had fallen to 87.5% of their original value.

Based on this previous work, it was considered appropriate in the present instance to define flexural fatigue failure in terms of a pre-determined loss of modulus after the appropriate number of cycles at a specified level of initial stress.

Whilst the levels of residual modulus chosen may appear to be rather arbritrary, the work of Smith and Owen (Fig. 2) suggests that a residual modulus of about 96% corresponds to fibre/resin debonding, whilst the outset of resin cracking would be represented by a residual modulus of about 87%.

These two values of residual modulus were therefore adopted in the present work to define the onset of the two types of failure. Further careful and detailed examination of the type A C.F.R.P., of a nature similar to that carried out by Smith and Owen, would however be necessary to verify or discount this conclusion.

In terms of the spring industry, it should be pointed out that the lower value of 87% residual modulus is likely to prove of greater importance in practice, since it is indicative of a catastrophic decrease in the measured flexural modulus of the composite. By contrast, a 4% loss of modulus would lead to an equal reduction in the spring rate, which would probably be acceptable in most leaf spring designs.

2.3.2 Fatigue testing procedure

Type A composite specimens of the design shown in Fig. 1C were fatigue tested using an Avery 7303 machine which was capable of applying a maximum bending moment of 2.83×10^4 N.mm.

The maximum stress in pure bending was calculated from the relationship

$$\sigma\ \text{max} = \frac{6M}{BD^2} \qquad \ldots\ldots \quad 4$$

where

σ max = maximum stress, N/mm^2

M = maximum bending moment, N.mm

B = specimen width at centre, mm

D = specimen thickness, mm

The bending moment was measured using a spring dynamometer which was connected to two dial gauges by a measuring arm. The dynamometer spring was calibrated using a system of standard weights and free running pulleys, the calibration being carried out in the direction of bending to be used in the fatigue tests.

In all cases, fatigue testing was carried out from zero bending stress to the maximum initial bending stress.

At an early stage of the work, it became apparent that the sharp edges of the relatively hard steel grips used were causing considerable damage to the gripped compression faces of the C.F.R.P. test specimens, although no such damage was in evidence on the tension faces of the samples. This damage was eliminated entirely by using suitably radiused C.F.R.P. shims interposed between the steel grips and the gripped compression faces of the samples.

The edges of all the specimens tested were carefully smoothed off using fine, dry 800 grade emery paper, prior to dimensional measurement and fatigue testing.

After the specimen had been set up for fatigue testing at the relevant maximum test stress, measurements were made of the vertical throw of the eccentric applying the bending moment, and of the deflection at the end of the dynamometer arm, by means of appropriately placed dial gauges.

From these measurements, and by consideration of the machine/sample geometry, it was possible to calculate the radius of curvature, R, of the arc through which the specimen was bent by the applied moment. By further calculation involving the known specimen gauge length, the central deflection of the specimen could then be estimated, measured with respect to the centre of the chord of the circle, radius R, which intersected the ends of the specimen over the fixed gauge length.

The initial flexural modulus of the composite could then be estimated from the relationship

$$E = \frac{ML^2}{8yI} \qquad \ldots\ldots \quad 5$$

where

M = applied moment, N.mm

L = gauge length = 25.4 mm

y = central deflection of specimen, mm

I = second moment of inertia = $\frac{BD^3}{12}$

Since, as already stated, the 7303 machine used an eccentric of constant throw to apply a particular bending moment, the measurement of this vertical deflection required to be taken only at the beginning of the test, although the reading was checked after the test was completed to ensure that this parameter had not altered during the course of a particular test.

During the course of the test, however, the deflection of the dynamometer by the specimen decreased as the stiffness (modulus) of the specimen decreased. The change in the central deflection of the specimen could be derived as previously stated, together with the change in the applied moment, M, via the calibration curve which had been previously determined experimentally. From these two new measurements of 'y' and 'M', the new modulus of the sample could be estimated at intervals throughout the test by the simple expedient of stopping the machine and measuring the deflection of the spring dynamometer, via the two dial gauges attached to the moment arm. This was particularly convenient in that it was not necessary to remove the specimen from the machine for the measurement of 'E', a procedure which could have led to considerable difficulties in respect of specimen re-alignment and re-stressing to the required level.

It is appreciated that certain geometrical assumptions were made with respect to the calculation of the flexural modulus using the Avery 7303 fatigue machine. The assumptions concerning the deflection geometry of the specimen under the applied moment, for instance, were not strictly valid and would lead to a systematic error in the estimated value of 'E', the magnitude of which would increase with increasing specimen deflection. However, the important characteristic was considered to be the change in modulus, rather than the absolute value of this parameter. Consequently, it is considered unlikely that serious errors would be introduced into the conclusions drawn from the fatigue work which was carried out using this technique.

3. EXPERIMENTAL RESULTS

The results of the tensile tests carried out on the composite are shown in Table 1, whilst the flexural strength results are shown in Tables 2 and 3.

The flexural modulus results, which were obtained in three point bending, are given in Table 4.

The initial flexural modulii of the fatigue specimens, calculated from the geometry of the stressing technique employed by the Avery 7303 fatigue machine, are shown in Table 5.

In each case, the estimated values of the Most Probable Errors associated with the individual measurements are given in the Tables (The definition of M.P.E. is given in the Appendix to the report).

The reductions in flexural modulus, exhibited by the composite during fatigue testing at varying levels of initial stress, are shown in Figs. 3-9, whilst the S/N data derived from these curves and corresponding to 96% and 87% residual modulus are shown plotted in Figs. 10 and 11 respectively.

4. DISCUSSION

4.1 Static Properties

The composite had a mean tensile strength of 1225 N/mm^2, which was in reasonable agreement with the value of 1400 N/mm^2 quoted for a similar composite material in a previous report published by SRAMA(1).

Considerable scatter has been reported in the literature for the tensile strength of unidirectional C.F.R.P. (8). The scatter encountered in the present work, however, was not unreasonable ($s = 70$ N/mm^2), so that the value of tensile strength obtained in the present work is probably a realistic estimate of this parameter.

The flexural strengths previously reported for this composite were very similar in value to the reported tensile strengths(1). In the present instance, the flexural strength in 3 point bending, 1345 N/mm^2, was also very similar to the tensile strength of the material. It has been pointed out, however, that the flexural strength in 3 point bending is not likely to give a representative estimate of the true strength of the material, due to the considerable risk of surface damage resulting from the very high local stresses generated at the central compressive region of the material where the load is applied(9). This parameter should therefore be treated with extreme caution.

Determination of the flexural strength in 4 point bending gave a mean flexural breaking stress of 3000 N/mm^2. This was considered to be a more realistic interpretation of the flexural strength, bearing in mind that leaf springs designed for this material would almost certainly operate largely under this mode of stressing.

However, the large reduction in flexural strength brought about by the highly lecalized stresses resulting from 3 point bending serves to illustrate the care which must be taken at the design state if the high strength of this material is to be fully realized.

The flexural modulus of the material was estimated at 1.12×10^5 N/mm^2, which is in good agreement with both the reported value of 10^5 N/mm^2 (1) and the theoretical value of 1.36×10^5 N/mm^2. The latter value can be estimated from the general relationship

$$E_{composite} = E_f V_f + E_R (1 - V_f) \quad \ldots\ldots \quad 6$$

where

E_f = modulus of carbon fibre, = 2.08×10^5 N/mm^2 for Type A fibre

V_f = volume fraction of fibre in composite,
= c. 0.65

E_R = modulus of thermosetting resin matrix, c. 3×10^3 N/mm^2 (5)

The values of the initial modulus, estimated for the fatigue samples by consideration of the fatigue machine/specimen geometry, varied between 1.26×10^5 and 1.40×10^5 N/mm^2, indicating that this method of interpreting the specimen deflection data could be used with some degree of assurance.

4.2 Dynamic Properties

The results of the fatigue tests carried out on the C.F.R.P. are shown in Figs. 9 and 10, which suggest that the fatigue strength at 10^6 cycles in bending one side of zero from zero initial stress can be considered as 1200 N/mm^2 for a 4% loss of modulus, and 1475 N/mm^2 for a 13% loss of modulus, as a conservative estimate. Very little information appears to be available concerning the fatigue strength of the Type A C.F.R.P. Bader and Johnson, however, suggested that a realistic value for the fatigue strength at 10^6 cycles of C.F.R.P. stressed in unidirectional bending would be 65% of the static flexural strength. Their criterion of failure involved complete fracture and/or delamination of their pre-preg lay ups. Fatigue failures using reduction of modulus as a criterion, however, may have occurred at lower fractions of of the static bending strength.

In the present instance, and employing both 4% and 13% reduction in modulus as failure criteria, the fatigue strength at 10^6 cycles of the Type A material was assessed at 40% and 49% respectively of the static flexural strength in 4 point bending (which is 3000 N/mm^2).

It is interesting to note that the fatigue strength in pure bending at 10^6 cycles, employing 4% loss of modulus as a criterion, can be interpreted as 89% of the flexural strength in 3-point bending. This emphasises a particular characteristic of all unidirectional fibre reinforced materials which contain a high proportion of the fibre constituent (e.g. C.F.R.P., G.F.R.P., wood), namely, that the composites usually display their highest strengths in tension, but fail more readily in compression. The compression failures, involving buckling of the fibres, occur most readily at areas of localized high stress, hence the caution which must be exercised in the interpretation of 3 point flexural data and in the design of components using these materials, where inadequate attention to the detailed stressing can lead to locally high stresses, resulting in failure at nominally low stresses.

4.3 Comparison of Type A C.F.R.P. and Spring Steel Strip

4.3.1 Static Properties

A revealing comparison (Table A) can be made between the appropriate mechanical properties of the composite and a typical spring steel strip material by reference to previous investigations carried out at SRAMA on the properties of CS80 steel strip (11,12).

TABLE A

Material	Material condition	R_m N/mm^2	$R_p0.1$ N/mm^2	Modulus E, N/mm^2	Flexural elastic strength in 4-point bending, σ_f, N/mm^2
CS80 (11)	Hardened and tempered strip, 2.5 mm	1620	1385	2.08×10^5	-
CS80 (12)	Pre-hardened and tempered strip, 0.25 mm	1660	1100	2.08×10^5	1560
Type A C.F.R.P.	Pultruded strip, 2 mm	1225	-	1.12×10^5	3000

Although it would appear that the spring steel possesses a higher uniaxial tensile strength than the C.F.R.P., it must be remembered that the composite behaves in a completely elastic manner almost to the point of failure.

The spring steel, by contrast, is strained well beyond its elastic limit and has undergone a considerable amount of plastic deformation, when the tensile strength is considered. It would therefore be more appropriate to consider a defined "elastic" property, such as a proof stress, when comparing the properties of the steel strip with those of the composite. In this context, it can be seen that the composite compares very favourably with both examples of spring steel, whilst the superiority of the composite in 4-point bending is also clearly indicated.

The specific gravities of steel and the C.F.R.P. composite are 7.7 and 1.7 respetively, however. The effect of the specific gravity, ρ, in terms of the relative strength/weight ratios of the two materials is shown below (Table B), together with the specific stored energy coefficient, $\sigma_f^2/6E\rho$.

This latter parameter represents the strain energy per unit weight stored in a beam element of specific gravity, ρ, and elastic modulus, E, when subjected to a bending moment which produces a maximum flexural stress, σf, in the material.

TABLE B

Material	$R_p 0.1/\rho$ N/mm^2	σ_f/ρ N/mm^2	E/ρ N/mm^2	Flexural stored energy coefficient, $\sigma_f^2/6E\rho$ N/m^2
CS80(11)	180	-	$2.7\mathrm{x}10^4$	-
CS80(12)	143	203	$2.7\mathrm{x}10^4$	0.25
Type A C.F.R.P.	721*	1765	$6.6\mathrm{x}10^4$	7.88

* Tensile strength, approximately equal to elastic strength for C.F.R.P.

The superiority of the C.F.R.P. over CS80 material, in terms of its strength/weight ratios, specific stiffness and its ability to store strain energy in bending can plainly be seen from this comparison, suggesting that considerable savings in weight should be possible if a spring component is designed to exploit the strength and weight advantages of the composite.

4.3.2 Dynamic properties

Work carried out at SRAMA on the fatigue properties in bending, one side of zero, of free peened and strain peened CS80 strip yields an interesting comparison with the results of the present work on C.F.R.P.(11) (Table C).

TABLE C

Material	Condition	Flexural fatigue limit, σ_L at 10^6 cycles, N/mm^2
CS80(11)	Hardened and tempered, 2.5 mm shot peened	600
CS80(11)	Hardened and tempered, 2.5 mm strain peened	1340
C.F.R.P. Type A	Pultruded, 2 mm	1200* 1475**

* σ_L for 4% reduction in modulus

**σ_L for 13% reduction in modulus

When the appropriate specific gravities of the materials are considered, the difference in the fatigue performance of the steel and the C.F.R.P. is more readily apparent, as shown below (Table D).

TABLE D

Material	Condition	Specific Fatigue Limit, σ_L/ρ N/mm^2	Specific stored energy coefficient $\sigma^2_L/6E\rho$ N/mm^2
CS80(11)	Hardened and tempered, 2.5 mm shot peened	78	0.037
CS80(11)	Hardened and tempered, 2.5 mm strain peened	174	0.187
C.F.R.P. Type A	Pultruded, 2mm	706* 868**	1.261* 1.904**

* σ_L for 4% reduction in modulus

** σ_L for 13% reduction in modulus

The advantages of the composite with respect to the specific fatigue strength and the specific stored energy coefficient can again be easily seen, indicating that large savings in weight should be possible for C.F.R.P. components such as leaf springs, with no reduction in fatigue performance compared to the more usual spring steel components.

In terms of the specific fatigue properties, for example, the work suggests that it should be possible to design a C.F.R.P. leaf spring of the Type A composite which should exhibit fatigue properties at least equal to the strain peened steel component, but which would only be 15-25% of the weight of the steel spring. In terms of the specific stored energy coefficient, however, the C.F.R.P. component would be only 10% of the weight of the strain peened steel spring it would replace.

4.4 Cost Analysis

A direct cost comparison between leaf springs of equivalent rate manufactured from C.F.R.P. and the more conventional spring steel material is obviously fraught with difficulties.

If it is assumed, however, that composite leaf springs would be manufactured by a pre-preg technique, so as to allow the end attachment points to be built into the spring design, then some information can be obtained from the literature, since the cost of pre-preg and the pure carbon fibre filaments are roughly comparable(13).

The price of carbon fibre filament suitable for leaf springs has been dropping continuously since 1971, i.e. £130/Kg in 1971, £65/Kg in 1974 and £39/Kg in 1977.

The actual composite cost will, of course, be markedly affected by the volume of fibre used, and the most recent estimates of such costs would suggest that production runs involving 100 tonne of material could reduce the cost to approximately £15/Kg(14), as shown in Fig. 12.

Since the cost of an equivalent steel leaf spring would be of the order of 26P/Kg, this would appear to confirm a recent U.S. estimate suggesting that C.F.R.P. materials will have to be reduced in price by more than a factor of ten over their present price in order to become competitive on the general market(15).

It is possible to carry out a simple costing exercise and cost/benefit analysis, however, based on the most recent estimates of the operating costs of a typical commercial vehicle. In such a case, a reduction in the unladen weight of the vehicle would lead to an increase in the potential pay-load carried by the vehicle.

Consider the following values:-
Weight of unladen vehicle = 8 tonnes
Pay load carried by vehicle = 16 tonnes
Total weight of laden vehicle = 24 tonnes
Weight of 2 rear springs, at 127 Kg each = 254 Kg
Weight of 2 front springs, at 118 Kg each = 236 Kg
Total weight of steel springs = 490 Kg = 0.49 tonne

The individual steel leaves of a milti leaf spring would normally be free peened prior to construction of the complete spring unit.

In terms of the specific stored energy coefficient, it has been shown that, under dynamic conditions, this parameter has a value of 0.037 N/mm^2 for free peened spring steel, and 1.904 N/mm^2 for the C.F.R.P. composite investigated. Hence if C.F.R.P. was used in this application, about 10Kg of material would be required, which would result in a weight saving of 480Kg, or 0.48 tonne.

A simple price comparison, therefore, shows that the material cost for the steel spring units would be £128, whilst that for the C.F.R.P. spring units would be approximately £390 at present day (1977) prices. This latter figure could be reduced to about £150 for long production runs.

In the operating life of the vehicle, 300,000 Km, the pay load could therefore be increased by 144,000 tonne Km. The most recent estimates give the operating cost of the vehicle as 1.69 P/tonne Km., hence the increased pay load would yield £2,400 (without the profit factor) over the 4-5 year operational life of the vehicle. It can be seen, therefore, that a case can be made for suggesting that the C.F.R.P. material may shortly provide a viable alternative to the peened steel spring units which are used at present.

Furthermore, the savings accruing from reduced fuel consumption (due to the reduction in the unladen weight) and the reduction in the damping requirements for adequate road holding (resulting from the high damping capacity of C.F.R.P.) may both seem to make the composite more attractive than spring steels in the context considered.

The results of the present work therefore suggest that the C.F.R.P. composite could prove to be a viable alternative to spring steel for the manufacture of leaf springs, in the not too distant future.

5. CONCLUSIONS

1. The uniaxial elastic properties of the carbon fibre reinforced polymer are very similar to those of a typical spring steel.

2. The flexural elastic properties of the composite in pure bending are superior to those of the spring steel material.

3. When the specific gravities of the composite and the steel are considered, the composite possesses specific elastic properties and strain energy storage capabilities which are superior to those of a spring steel both in uniaxial tension and in flexure.

4. The fatigue strength at 10^6 cycles of the composite, in bending one side of zero, is superior to that of spring steel tested in the free peened condition. The fatigue strength is equal to that of strain peened spring steel.

5. The specific flexural fatigue properties of the composite, which allow for the low specific gravity of the material, are superior to those of the strain peened spring steel.

6. Carbon fibre composites show considerable promise as a potential leaf spring material, provided that suitable lay-ups are chosen to avoid damaging stress concentrations.

7. In the case of commercial vehicles, a simple cost analysis suggests that replacement of the spring steel leaf springs by suitably designed carbon fibre composite units should result in substantial cost benefits over the operating life of the vehicle.

6. RECOMMENDATIONS

1. Further work would be desirable to clarify the failure mechanisms of Type A C.F.R.P. under both tension and compression conditions.

2. The work may be sufficiently encouraging to warrant the design, manufacture and fatigue testing of full size leaf springs using suitable lay-ups. Such a design would probably be based initially on a single leaf spring exhibiting a substantially constant stress across its length in order to utilize the strength and weight properties of the composite most efficiently.

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8. APPENDIX

Assessment of Experimental Errors

Only a small number of samples were used for the static tests, and it was therefore considered imperative to quantitatively assess the errors involved in the estimation of the various composite properties measured. These errors would lead to cumulative errors in the final test result.

Since a realistic estimate of the total error was required, the statistic chosen for this purpose was the Most Probable Error (M.P.E.), which is defined as follows[(17)]:

If Q is a function of quantities x,y,z, such that

$$Q = f\left(\frac{xy}{z}\right)$$

then the most probable error in Q, SQ, can be found from the relationship

$$(\delta Q)^2 = \left(\frac{\partial Q}{\partial x} \times e_y\right)^2 + \left(\frac{\partial Q}{\partial y} \times e_y\right)^2 + \left(\frac{\partial Q}{\partial z} \times e_z\right)^2$$

where e_x, e_y and e_z are the estimated errors inherent in the techniques of measurement employed for the relevant test.

The last partial differential would be a negative quantity of course, but this would become positive upon squaring the result. Thus SQ is the square root of the sum of the squares of the greatest errors in Q, due to an error in each variable separately. This leads to a more pessimistic, and therefore a more realistic, estimate of the total error than would be obtained by the more usual technique leading to the summation of the positive and negative components of the errors.
i.e.

$$Q = f\left(\frac{xy}{z}\right)$$

$$\therefore \text{Log } Q = \text{Log } x + \text{Log } y - \text{Log } z$$

$$\therefore \frac{dQ}{Q} = \frac{dx}{x} + \frac{dy}{y} - \frac{dz}{z}$$

$$\text{and } dQ = Q\left(\frac{dx}{x} + \frac{dy}{y} - \frac{dz}{z}\right)$$

ACKNOWLEDGEMENTS

The assistance of A.E.R.E., Hanwell in their provision of the material necessary for this work is gratefully acknowledged.

TABLE I TENSILE STRENGTH OF PULTRUDED TYPE A C.F.R.P.

SAMPLE NO.	TENSILE STRENGTH, σ_T, N/mm^2	MOST PROBABLE ERROR $\delta\sigma_T$, N/mm^2
1	1305	19
2	1255	18
3	1180	17
4	1150	17
Mean value	1225	20 (rounded)

TABLE II FLEXURAL STRENGTH OF PULTRUDED TYPE A C.F.R.P. DETERMINED IN 3 POINT BENDING

SAMPLE NO.	FLEXURAL STRENGTH, σ_F N/mm^2	MOST PROBABLE ERROR $\delta\sigma_T$, N/mm^2
1	1350	21
2	1345	19.5
3	1340	19.4
Mean value	1345	20 (rounded)

TABLE III FLEXURAL STRENGTH OF PULTRUDED TYPE A C.F.R.P. DETERMINED IN 4 POINT BENDING

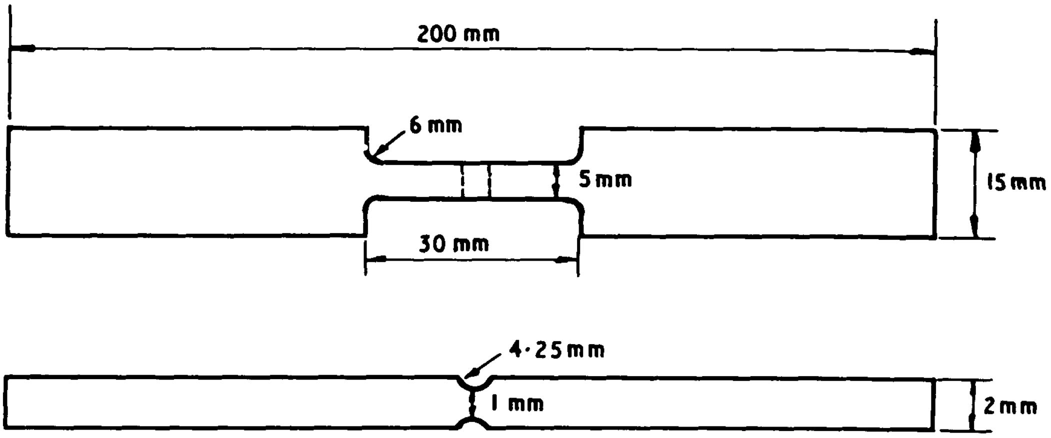
SAMPLE NO.	FLEXURAL STRENGTH σ_F, N/mm^2	MOST PROBABLE ERROR, $\delta\sigma_F$, N/mm^2
1	3050	61
2	2970	60
3	2980	60
Mean value	3000	60 (rounded)

TABLE IV FLEXURAL MODULUS OF PULTRUDED TYPE A C.F.R.P. DETERMINED IN 3 POINT BENDING

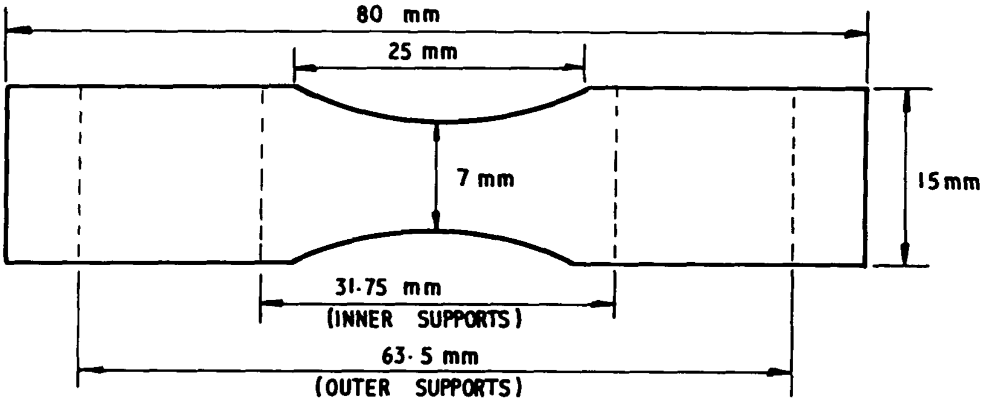
SAMPLE NO.	FLEXURAL STRESS N/mm^2	FLEXURAL MODULUS E, N/mm^2	MOST PROBABLE ERROR, δE, N/mm^2
1	413	1.07×10^5	5.6×10^3
	496	1.08×10^5	5.5×10^3
	579	1.10×10^5	5.5×10^3
	661	1.11×10^5	5.6×10^3
	744	1.11×10^5	5.5×10^3
	827	1.13×10^5	5.6×10^3
2	402	1.13×10^5	5.9×10^3
	483	1.14×10^5	5.8×10^3
	563	1.14×10^5	5.7×10^3
	643	1.15×10^5	5.7×10^3
	724	1.15×10^5	5.7×10^3
	804	1.15×10^5	5.6×10^3
Mean value		1.12×10^5	6×10^3 rounded

TABLE V CALCULATED VALUES OF INITIAL FLEXURAL MODULUS IN 4 POINT BENDING FOR PULTRUDED TYPE A C.F.R.P.

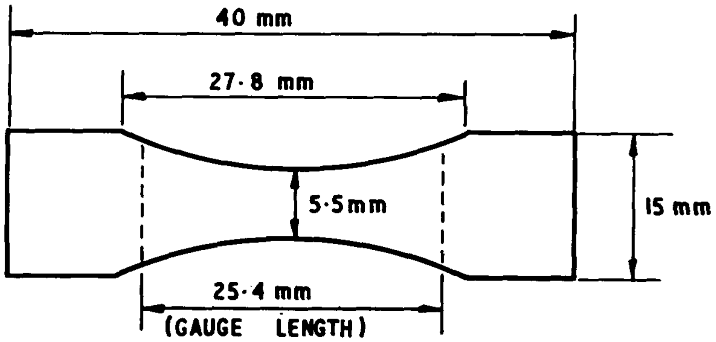
SAMPLE NO.	INITIAL FLEXURAL STRESS N/mm^2	INITIAL FLEXURAL MODULUS, E, N/mm^2	MOST PROBABLE ERROR, δE, N/mm^2
1A	1210	1.26×10^5	2.2×10^4
2A	1315	1.29×10^5	2.2×10^4
3A	1535	1.37×10^5	2.3×10^4
4A	1450	1.40×10^5	2.4×10^4
5A	1455	1.43×10^5	2.5×10^4
6A	1500	1.40×10^5	2.4×10^4
7A	1475	1.40×10^5	2.4×10^4



A TENSILE SPECIMENS.



B FOUR-POINT FLEXURAL STRENGTH SPECIMENS.



C FATIGUE SPECIMENS.

FIG. 1 TEST SPECIMENS OF TYPE A PULTRUDED CARBON FIBRE REINFORCED PLASTIC. (NOT TO SCALE)

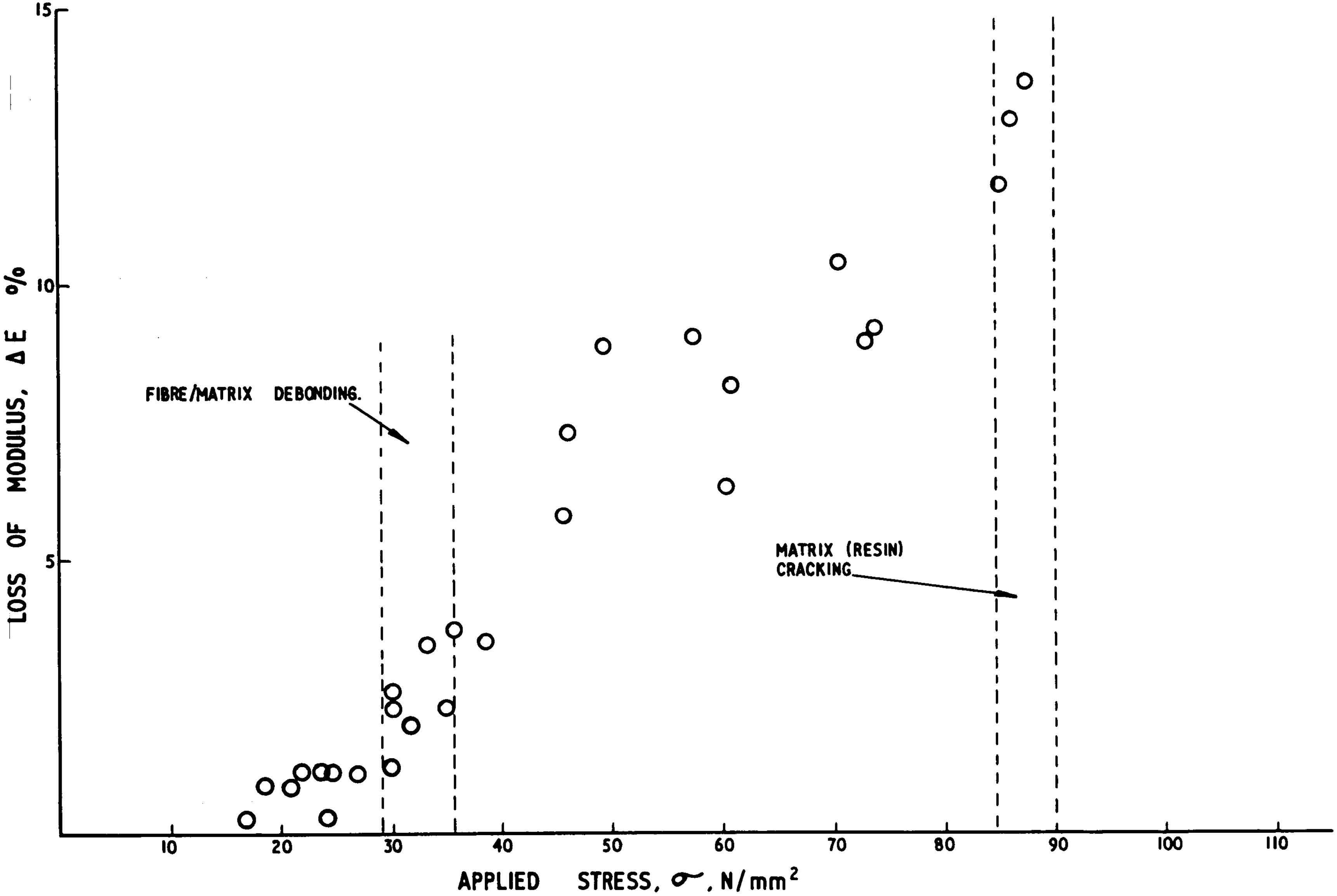


FIG. 2. PROGRESSIVE DAMAGE IN CHOPPED STRAND MAT POLYESTER LAMINATE (FROM REF. 6)

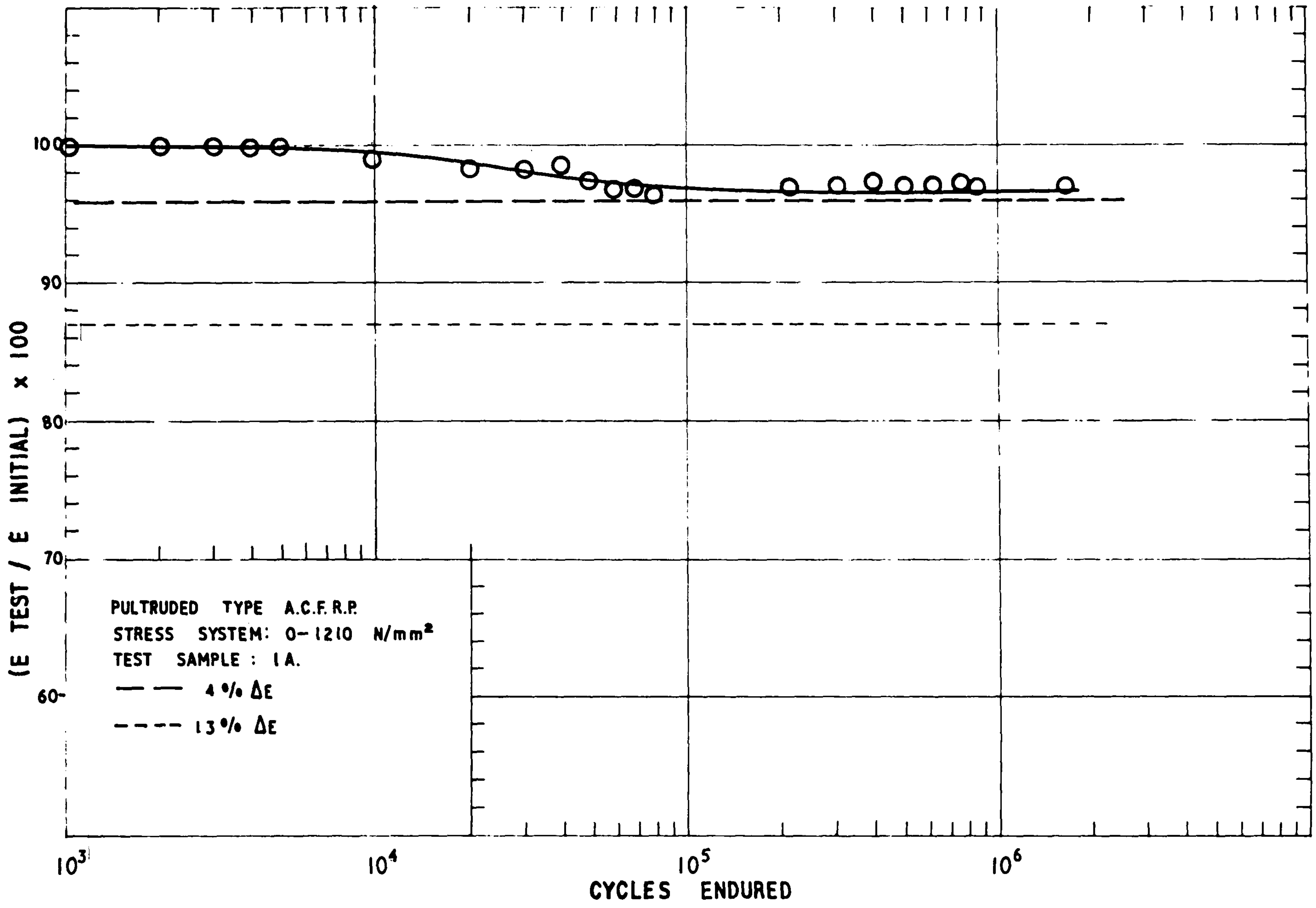


FIG. 3 PROGRESSIVE CHANGE IN MODULUS OF TYPE A.C.F.R.P. DURING FATIGUE TEST.

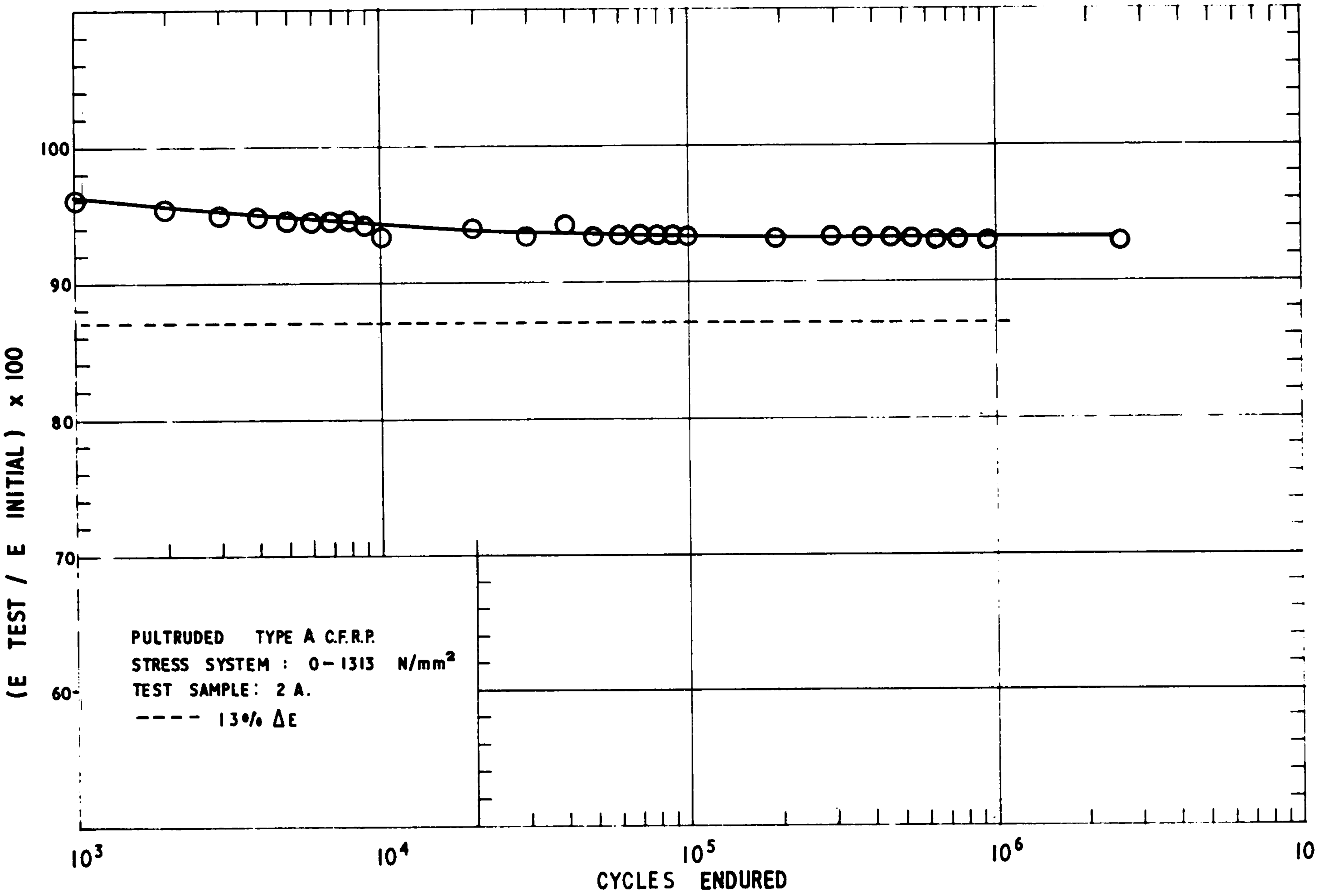


FIG. 4 PROGRESSIVE CHANGE IN MODULUS OF TYPE A.C.F.R.P. DURING FATIGUE TEST.

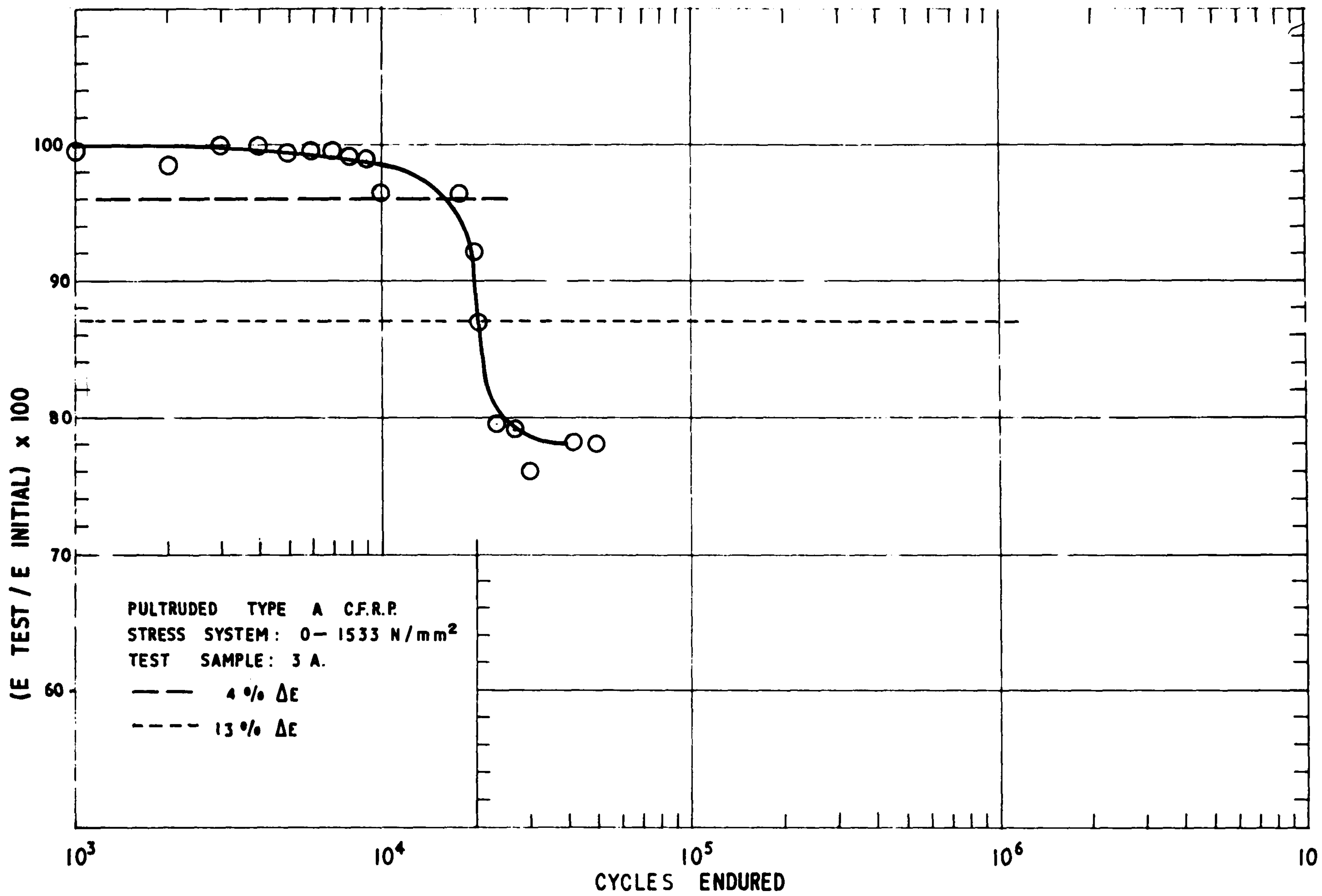


FIG. 5 PROGRESSIVE CHANGE IN MODULUS OF TYPE A C.F.R.P. DURING FATIGUE TEST.

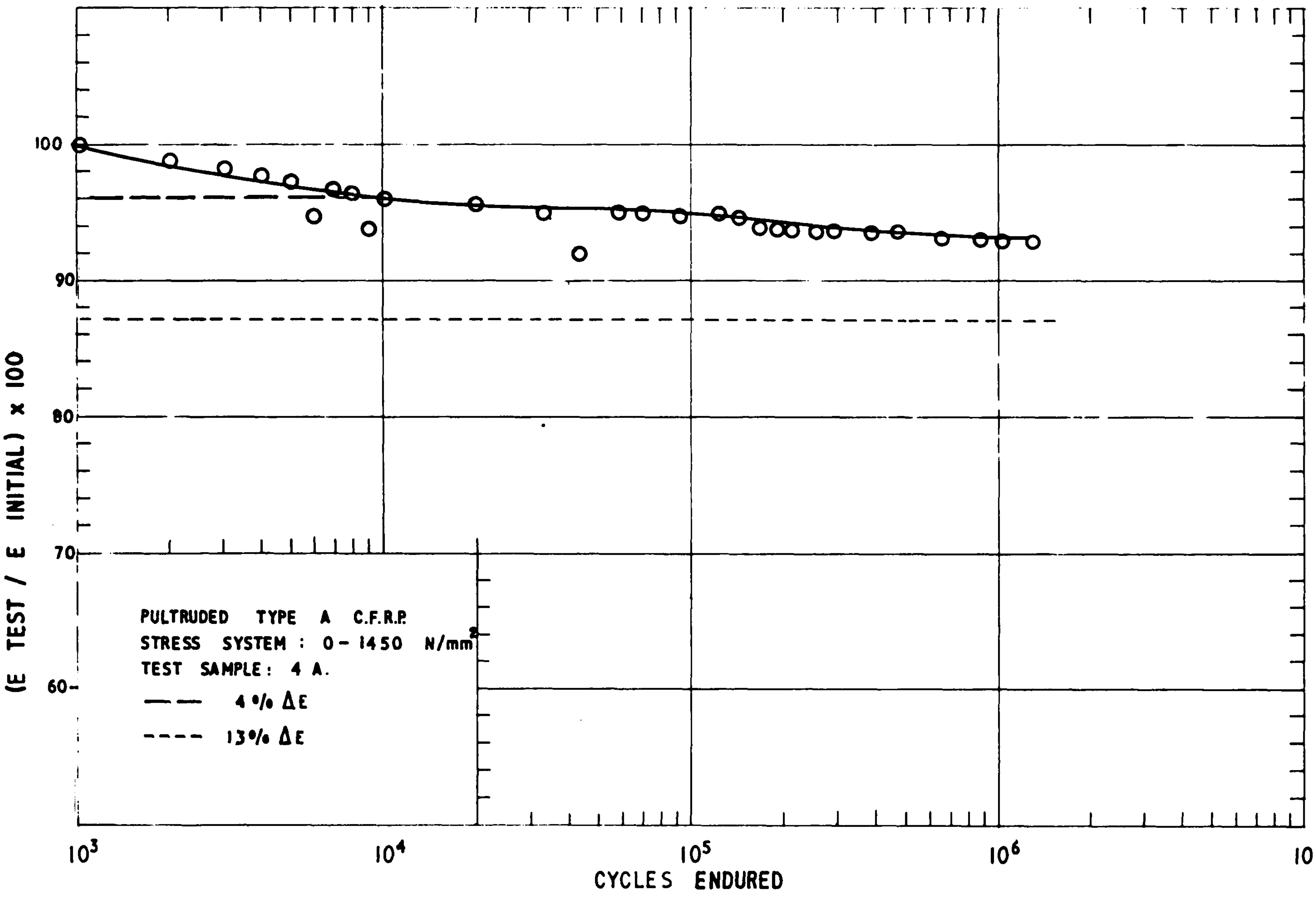


FIG. 6 PROGRESSIVE CHANGE IN MODULUS OF TYPE A C.F.R.P. DURING FATIGUE TEST

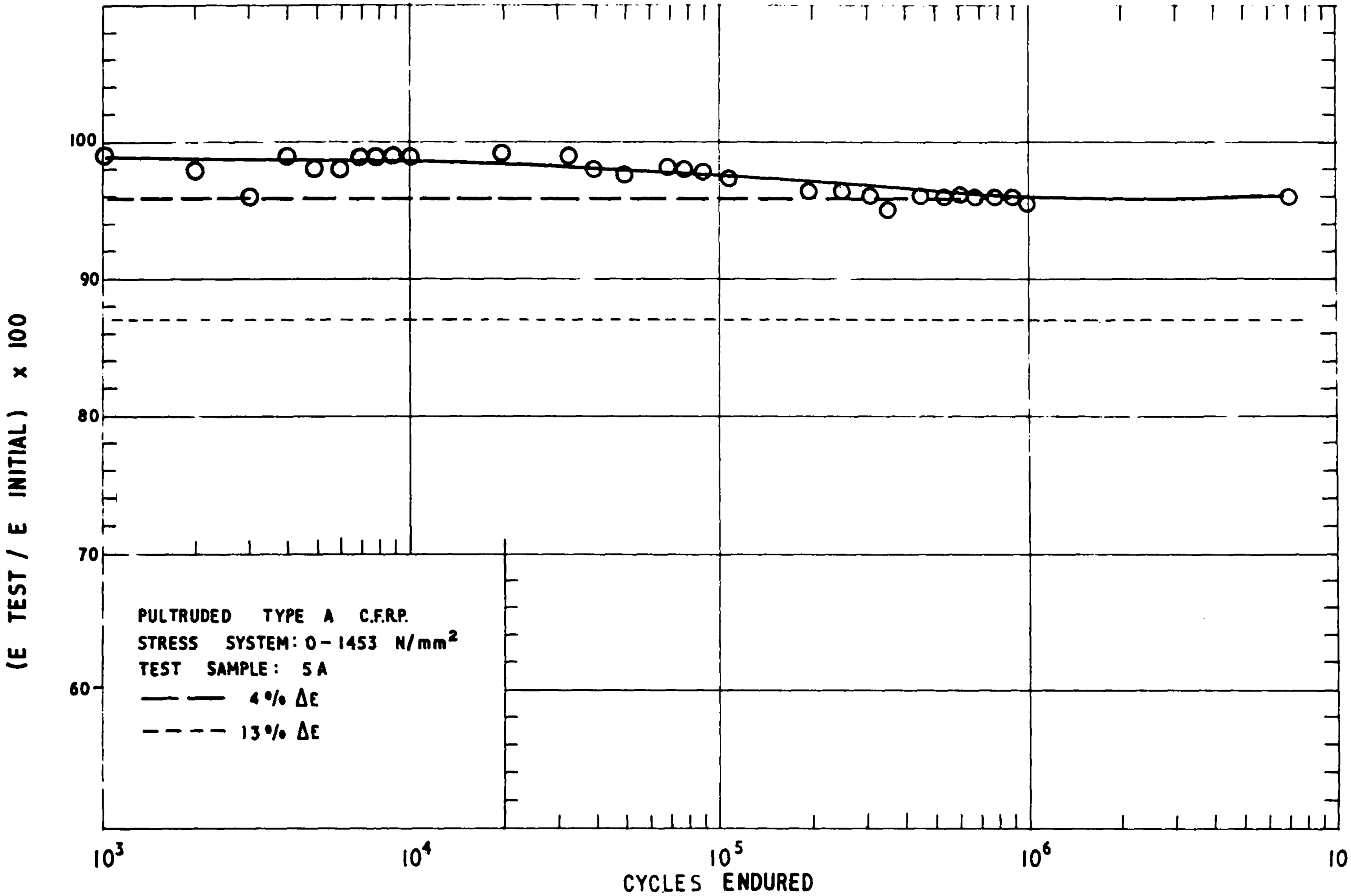


FIG. 7 PROGRESSIVE CHANGE IN MODULUS OF TYPE A C.F.R.P. DURING FATIGUE TEST

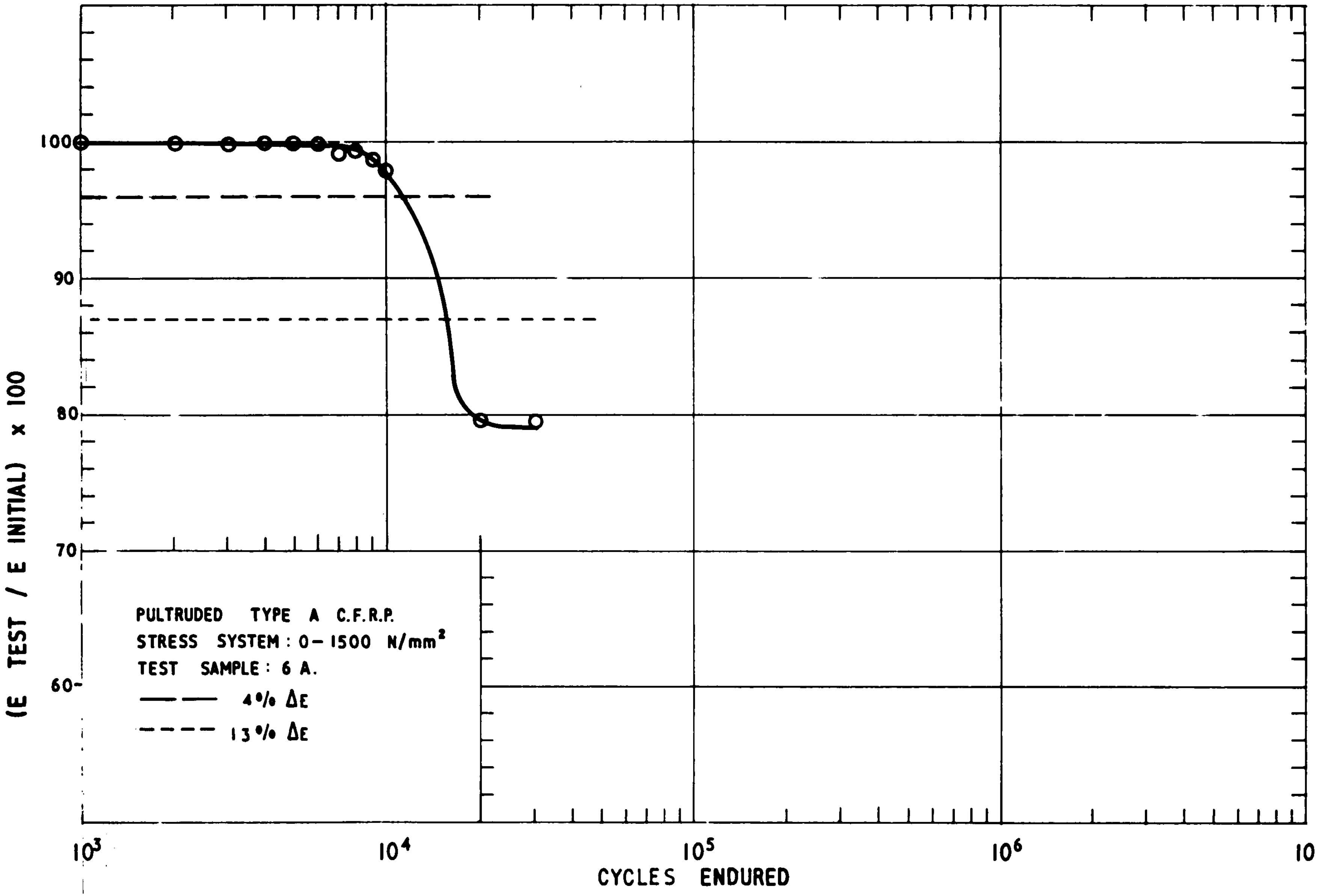


FIG. 8 PROGRESSIVE CHANGE IN MODULUS OF TYPE A C.F.R.P. DURING FATIGUE TEST.

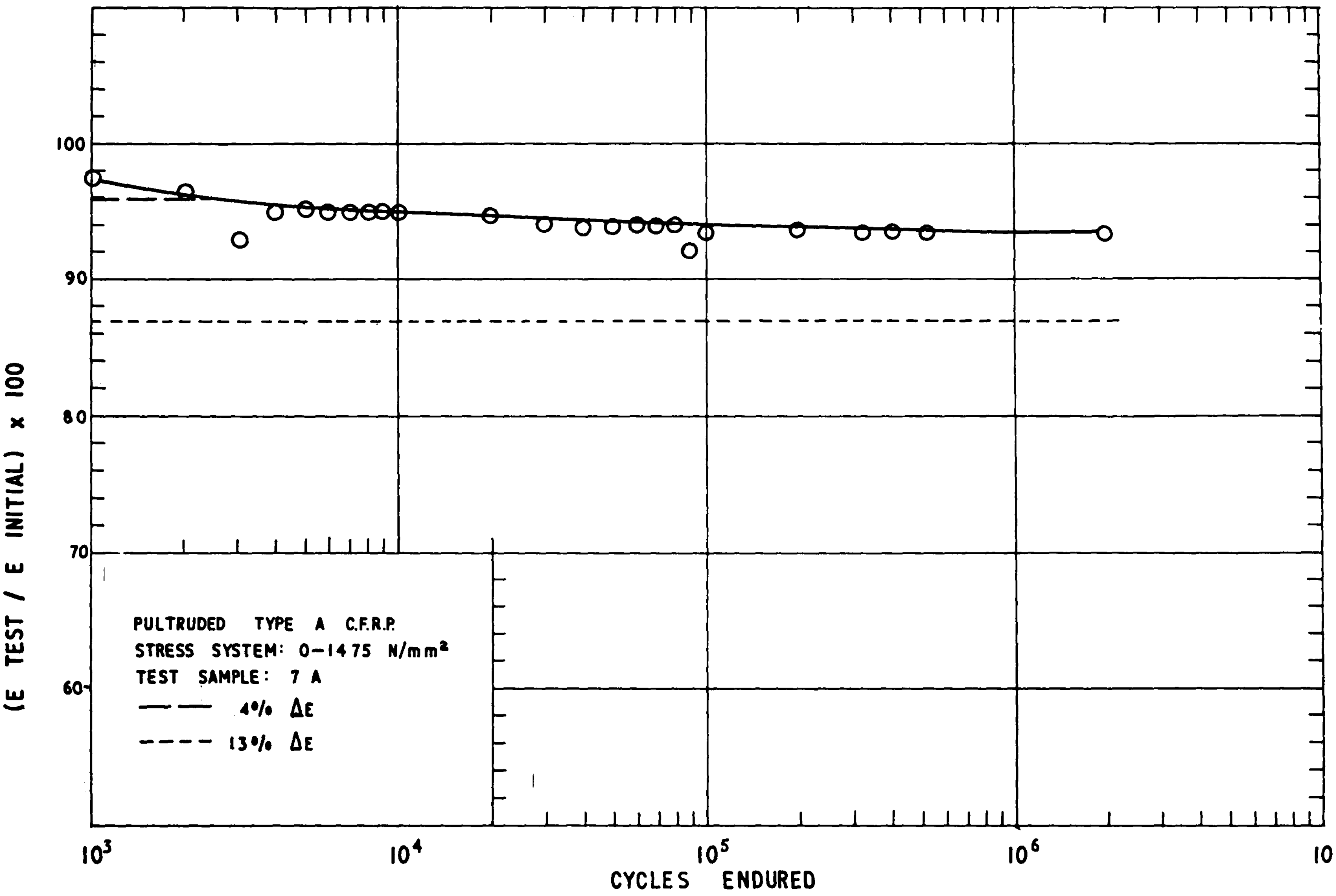


FIG. 9 PROGRESSIVE CHANGE IN MODULUS OF TYPE A C.F.R.P. DURING FATIGUE TEST.

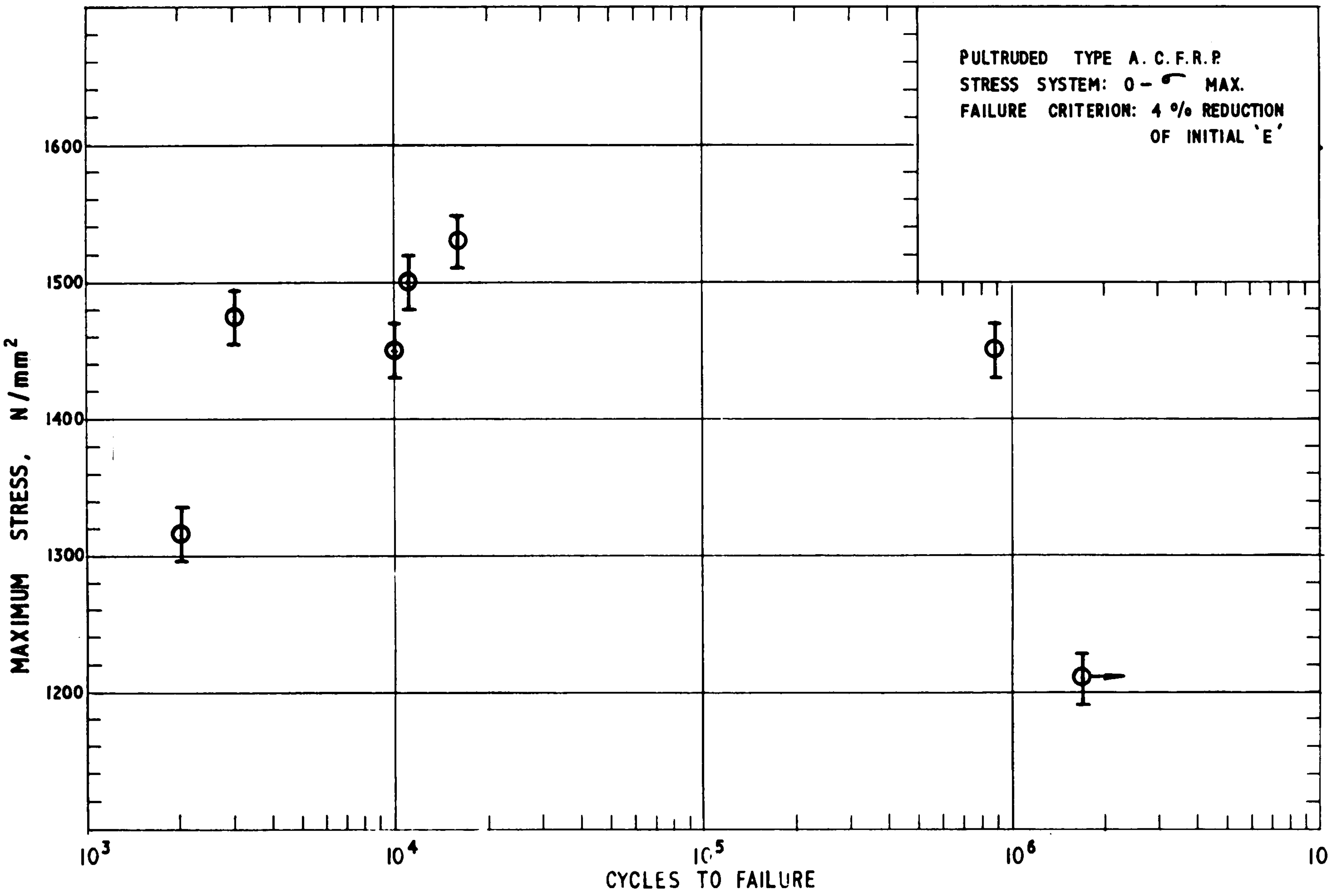


FIG. 10 FATIGUE DATA FOR TYPE A C.F.R.P. IN BENDING ONE SIDE OF ZERO.

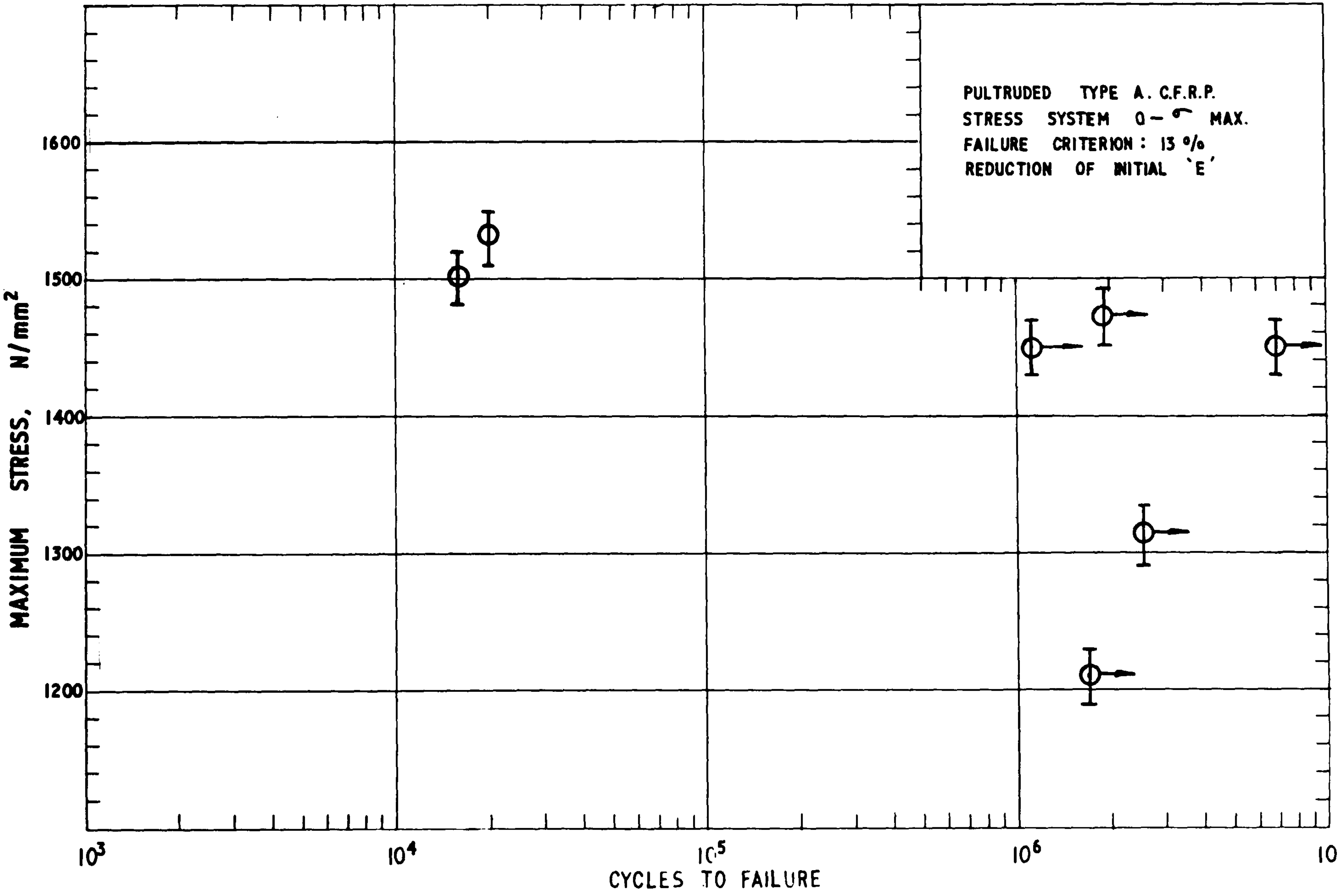


FIG. 11 FATIGUE DATA FOR TYPE A C.F.R.P IN BENDING ONE SIDE OF ZERO.

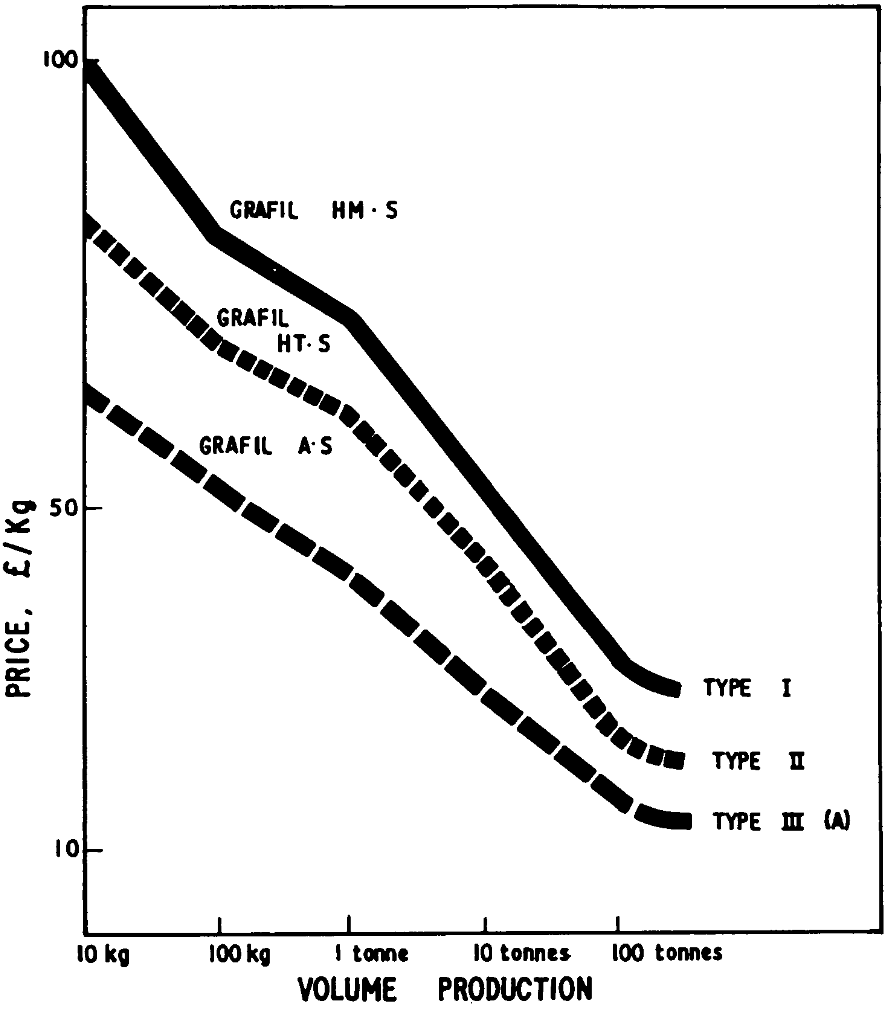


FIG. 12. INDICATION OF PRICE / VOLUME RELATIONSHIP FOR CONTINUOUS CARBON FIBRE / PRE-PREG. ORDERS. (REF 14).