JAERI-M
84-130

BOWING TEST OF HTGR GRAPHITE SLEEVE

—OUT OF PILE HEAT-UP EXPERIMENT AND BENDING TEST—

July 1984

Motokuni ETO, Katsuo FUJISAKI, Shinichi YODA
and Tatsuo OKU

日本原子力研究所
Japan Atomic Energy Research Institute

JAERI-M レポートは，日本原子力研究所が不定期に公刊している研究報告書です。
入手の問合わせは，日本原子力研究所技術情報部情報資料課（〒319-11 茨城県那珂郡東海村）あて，お申しこしください。なお，このほかに財団法人原子力弘済会資料センター（〒319-11 茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.
Inquiries about availability of the reports should be addressed to Information Section, Division of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

編集兼発行　日本原子力研究所
印　　刷　いばらき印刷(株)

BOWING TEST OF HTGR GRAPHITE SLEEVE
--OUT OF PILE HEAT-UP EXPERIMENT AND BENDING TEST--

Motokuni ETO, Katsuo FUJISAKI, Shinichi YODA
and Tatsuo OKU

Department of High Temperature Engineering,
Tokai Research Establishment, JAERI

(Received June 27, 1984)

Bowing characteristics were examined for IG-11 and H451 graphite sleeve specimens to which temperature gradients were given in the circumferential direction using a specially prepared rig. Measurements were also carried out on load or bending moment which was caused in the sleeve specimens under constraint as a result of temperature gradients. Experimental data were well analyzed on the basis of the elastic theory on the deflection of beams. Bending tests of the sleeve specimens indicated that the bending moment generated in the sleeve specimens under constraint was less than one-third of that at fracture even when the maximum temperature difference along the circumferential direction was more than 200°C.

Keywords : HTGR, Graphite, Graphite Sleeve, Fracture, Strength
Bending Test, Temperature Gradients

JAERI－M 84－130

高温ガス炉用黒鉛スリーブの湾曲試験
－炉外加熱実験と曲げ試験の結果－

日本原子力研究所東海研究所高温工学部
衛藤基邦・藤崎勝男・依田真一
奥　達雄

（1984年6月27日受理）

高温ガス実験炉炉心部用黒鉛IG－11及びH451製スリーブの円周方向に温度差を与える装置を試作し，温度差とスリーブの湾曲量との関係を調べた。また，スリーブ試験体に拘束下で温度差を与え，発生応力あるいは曲げモーメントを測定した。実験データを，はりの曲りの弾性論によって解析した。スリーブ試験体の曲げ試験の結果，拘束下で発生する曲げモーメントは，試験体破断時のモーメントよりはるかに小さく，円周方向温度差200度の場合でも破断モーメントの1／3程度であることが明らかになった。

CONTENTS

目　　次

1. INTRODUCTION

It is believed that the fuel sleeve of the experimental VHTR (VHTRex), which is now at the research and development stage at Japan Atomic Energy Research Institute (JAERI), would possibly have a temperature difference in its circumferential direction, because of the eccentricity of fuel rod, inhomogeneity of heat generation or heat flow, etc. A calculation indicated that during operation of the reactor this temperature difference could be more than 200 degrees at its maximum.[1)] It is very probable that the thermal strain caused by the temperature difference, together with the dimensional changes of graphite due to neutron-irradiation, would lead to the bowing of sleeve. In fact, the bowing of fuel element or reflector graphite has been reported and analyzed in the Dragon Project.[2)]

The ultimate purpose of the bowing test of sleeve is to establish a method for the precise estimation of its bowing behavior, based on a model demonstrated experimentally, which is to be applicable to the design and safety analysis of VHTRex.

Purpose of this report is firstly, as the first step to the ultimate, to obtain out-of-pile experimental data on the bowing of sleeve specimen as a function of temperature difference in its circumferential direction and to evaluate them by comparing with calculation.

Secondly,this report gives the data on thermal stresses generated in sleeve specimen when it is subjected to a circumferential tempereture difference under constraint, i.e., the specimen is forced to keep its original shape. Moreover, the result of bending tests of sleeve specimens is summarized here to evaluate the integrity of graphite sleeve under thermal stresses. Ring compressive tests have also been carried out to analyze the data on the fracture of sleeve specimens.

2. EXPERIMENTAL

2.1 Specimens

Graphites used in the present experiment were Grades IG-11 and H451. The latter is an extruded graphite manufactured by Great Lakes Carbon Corp., and the former, an isotropic nuclear graphite manufactured by Toyo Tanso Co., Ltd. Some properties of these graphites are listed in Table 1. Three types of specimens were machined from blocks of each graphite :(I) specimens with 50mm outer diameter(OD) x 40mm inner diameter(ID) x 555mm length, (II)46mm OD x 36.3mmID x 600mm length without ribs, and (III)specimens with almost the same size as that of the second type, but, with ribs. Detailed dimensions of Type I specimen are shown in Fig. 1, and those for Types II and III, in Figs. 2 and 3, respectively. Fig. 4 shows the dimensions of bending specimen with ribs.

The outer and inner diameters of specimens were changed to the smaller ones corresponding to a change in the design of VHTRex. However, all types of specimens are believed to simulate well enough the actual fuel sleeve of VHTRex. in terms of the evaluation of the bowing caused by temperature differences and the bending fracture of graphite sleeves.

2.2 Rig for the measurement of bowing

A schematic of the main part of the rig used in the heat-up experiment is shown in Fig. 5. As is seen in the figure, the rig is equipped with two actuators located near the upper and middle regions of a sleeve specimen, respectively. At the lower position, it has a micrometer by which the displacement of the bottom region of sleeve specimen was measured. The displacement of the upper and middle positions of sleeve specimen was measured by transmitting it to two actuators in use of graphite rods 15mm in diameter. Not only the displacement but also the load which is caused by the temperature difference in the circumferential direction can be measured using these actuators when they are controlled under constant displacement conditions, i.e., specimens under constraint.

The eccentric heating was done using a graphite heater which was so placed as to heat up only one side of a sleeve specimen along the whole longitudinal axis. The experiment was carried out mainly in vacuo,although the rig can be used either in vacuo or in any inert atmospheres.

The temperature distribution within a sleeve specimen was measured using chromel- alumel thermocouples which were glued to the specimen with carbon cement. They were placed at five or six points along the longitudinal axis, with four or eight thermocouples at each longitudinal point so that they form the right angle or 45 degrees from the neighboring themocouples. The total number of thermocouples was 24 at the maximum. Fig. 6 shows an overview of the heating experiment. The interior of the rig is shown in Fig. 7.

Electromotive force of the thermocouples and the outputs of the two actuators which indicated both displacements and loads of sleeve specimen through the graphite rods were transmitted to a Hewlett Packard scanner, Model 3495A and then to a digital voltmeter, Model 3455A. Data were processed using a Hewlett Packard microcomputer, Model 9835A. The program for this process is shown in Appendix. A 9876A printer and 9885M flexible disk drive were also used.

2.3 Bending test of sleeve specimens

Bending tests were carried out using an Instron-type test machine on the three types of specimens mentioned above after the heat-up experiments. Some of the bending specimens were simple hollow tubes with or without ribs, as is shown in Figs. 2 and 4 for the specimens witn ribs and without ribs, respectively.

Fig. 8 shows the set-up of the bending test. To measure the deflection near the center edge which was connected to the cross-head of the test machine, an electrical dial gage was used. Strains were measured during bending tests using 5 strain gages for one specimen, three of which were glued to the tensile side of specimen, and the other two on the compressive side.

Spans between the edges for bending tests were 400mm and 458mm for specimens without ribs and those with ribs, respectively. Cross-head speed was 0.5mm/min.

2.4 Ring compressive tests

Ring compressive test specimens were machined from the end parts of sleeve specimens for bending tests, to which no bending load was applied. They measured 46mm O.D. x 36.3mm I.D. x 18mm length. Ring compressive tests were carried out at a cross-head speed of 0.5mm/min. Strain gages were glued to each of the lateral outer surfaces, one of the lateral inner surfaces, and the upper and lower inner surfaces, as is shown in Fig. 9. The numbers in the figure indicated the locations of these strain gages.

3. RESULTS AND DISCUSSION

3.1 Heat-up experiment

Some examples of the results of the heat-up experiment are shown in Figs. 10(a) to (d) for IG-11 graphite Type I specimens. Figs. 11(a) and (b) show examples of the results obtained for IG-11 graphite Types II and III specimens, respectively. In these figures, the right-hand abscissa represents the temperatures of various points of specimen. The displacement respectively.

Fig. 8 shows the set-up of the bending test. To measure the deflection near the center edge which was connected to the cross-head of the test machine, an electrical dial gage was used. Strains were measured during bending tests using 5 strain gages for one specimen, three of which were glued to the tensile side of specimen, and the other two on the compressive side.

Spans between the edges for bending tests were 400mm and 458mm for specimens without ribs and those with ribs, respectively. Cross-head speed was 0.5mm/min.

2.4 Ring compressive tests

Ring compressive test specimens were machined from the end parts of sleeve specimens for bending tests, to which no bending load was applied. They measured 46mm O.D. x 36.3mm I.D. x 18mm length. Ring compressive tests were carried out at a cross-head speed of 0.5mm/min. Strain gages were glued to each of the lateral outer surfaces, one of the lateral inner surfaces, and the upper and lower inner surfaces, as is shown in Fig. 9. The numbers in the figure indicated the locations of these strain gages.

3. RESULTS AND DISCUSSION

3.1 Heat-up experiment

Some examples of the results of the heat-up experiment are shown in Figs. 10(a) to (d) for IG-11 graphite Type I specimens. Figs. 11(a) and (b) show examples of the results obtained for IG-11 graphite Types II and III specimens, respectively. In these figures, the right-hand abscissa represents the temperatures of various points of specimen. The displacement observed at the upper and middle portions of sleeve specimen are plotted on the left-hand abscissa. In most cases, negligible amounts of displacements were observed at the lowest position. The ordinate of the figures represents the location of the thermocouples and actuators along the longitudinal axis. The rectangle at the center of each figure is drawn to give an approximate idea regarding the size of sleeve specimen.

The displacement observed at the upper portion versus the temperature difference generated in the circumferential direction is plotted in Fig. 12 for various types of sleeve specimens. Here,the difference was taken as the mean value of the temperatute differences obtained along the longitudinal axis, since, as was shown in Figs. 10 and 11, the temperature and its difference in the circumferential direction differed from one point to another along the longitudinal axis.

It is apparent, from the results shown in Fig. 12, that ribs have almost no influence on the amount of bowing caused by the temperature differences in the circumferential direction of sleeve specimens.
It is also seen that there is almost no difference in the amount between IG-11 and H451 graphites. In the heat-up experiment the bowing is believed to result from the difference in the thermal expansion due to the temperature difference. Since the thermal expansion coefficient is about 4×10^{-6} /°C for both IG-11 and H451 graphites,[3] it is reasonable that the amount of bowing does not differ much from each other in the cases of these graphites.

3.2 Analysis of the amount of bowing

Fig. 13 shows a model expressing the relationship between the amount of bowing, i.e., the displacement at the upper portion of sleeve specimen, x, and the radius of curvature, R. From this model, we obtain

$$x = R + r_2 - \sqrt{(R + r_2)^2 - l^2} \,. \qquad (1)$$

Here, r_2 and l are the outer radius of specimen and the distance between the fixed end of specimen and the position of the upper actuator.

Let the longitudinal stress and strain generated by the temperature difference be σ_{zz} and ε_{zz}. The schematic of the cross-section of sleeve specimen is shown in Fig. 14 with appropriate cordinates to be chosen. Let the following characters represent as:

E : Young's modulus

M : Bending moment

A : Cross-sectional area

I : Moment of inertia of area

α : Coefficient of thermal expansion

T : Mean temperature difference in the circumferential direction.

We obtain,

$$\sigma_{zz} = E\,\varepsilon_{zz} = \frac{E}{R}\,y \tag{2}$$

$$M \equiv \int_A \sigma_{zz}\, y\, dA = \frac{E}{R}\int_A y^2\, dA = \frac{E}{R}\, I \tag{3}$$

$$\begin{aligned} M &= 2\int_{-\pi/2}^{\pi/2}\int_{r_1}^{r_2} \sigma_{zz}\, r\cos\theta\, r\, d\theta\, dr \\ &= 2\int_{-\pi/2}^{\pi/2} d\theta \int_{r_1}^{r_2} \sigma_{zz}\, r^2\cos\theta\, dr \end{aligned} \tag{4}$$

$$R = \frac{EI}{M} = \frac{E\,I}{2\int_{-\pi/2}^{\pi/2} d\theta \int_{r_I}^{r_2} \sigma_{zz}\, r^2\cos\theta\, dr} \tag{5}$$

$$I = \frac{\pi}{4}\left(r_2^4 - r_1^4 \right) \tag{6}$$

with the consideration of the temperature distribution in the circumferential direction, an example of which is shown in Fig. 15, σ_{zz} may be approximated in the equation,

$$\sigma_{zz} = \frac{1}{2} E\alpha \Delta T \cos\theta . \tag{7}$$

Substitution of Eq.(7) into Eq.(8) gives the bending moment as

$$M = \frac{\pi}{6} E\alpha \Delta T (r_2^3 - r_1^3) \tag{8}$$

From Eqs.(5),(6) and (8), we obtain

$$R = \frac{3}{2} \frac{r_2^4 - r_1^4}{\alpha \Delta T (r_2^3 - r_1^3)} \tag{9}$$

Eliminating R in Eq.(1) using Eq.(9), we can calculate the displacement, x.

The solid line in Fig. 12 was obtained from the calculation, which indicates that the bowing of sleeve specimens observed in the present heat-up experiment is well expressed by Eqs.(1) and (9).

3.3 Heat-up of sleeve specimens under constraint

Fig. 16 shows the load generated during the heat-up experiment at the upper portion of sleeve spenimen under constraint as a function of temperature difference in the circumferential direction. These data were obtained for the specimens without ribs. It is found that the load generated in the H451 graphite specimens is larger than that in IG-11 graphite specimens. Since the Young's modulus of H451 graphite is 10—15% larger than that of IG-11 graphite and, as was shown in Eq.(9), the amount of bowing depends only on thermal expansion coefficient, which is almost the same for both graphites, it is reasonable that the generated load or bending moment is larger for H451 graphite than for IG-11 graphite.

3.4 Bending test of sleeve specimens

Figs. 17(a), (b), (c) and (d) show the results of bending tests of IG-11 graphite sleeve specimens without ribs. In the upper half of each figure, the strains at fracture measured at three positions on the tensile side are shown, whereas the applied load-deflection at beam center curve is shown in the lower half. The locations of the strain gages used in the tests are schematically shown in Fig. 17(a). The right ordinate of each of the lower figures represents the bending moment.

Figs. 18(a) and (b) show similar results obtained for IG-11 graphite sleeve specimens with ribs. Similar results of bending tests are shown in Figs. 19(a),(b), and 20 for H451 graphite sleeve specimens.

It is found, from the results shown in these figures, that there is no pronounced difference in load or strain between the specimens with ribs and without ribs. In the case of IG-11 graphite the load is at most 10% larger for the specimens with ribs than for those without ribs. It is to be noted that the strain at fracture measured at the center is almost equal to the fracture strain in the uniaxial tensile test.[3] This indicates that the flexural fracture of sleeve specimen is to occur when the maximum strain on the tensile side reaches the tensile fracture strain.

3.5 Ring compressive tests

Ring compressive tests were carried out for both IG-11 and H451 graphite specimens. The method as well as the locations of strain gages glued to a specimen is schematically shown in Fig. 9. As was the case for the bending tests, the fracture strains on the tensile sides,i.e., those indicated by the gages #3 and #4 are almost equal to the mean fracture strain observed during uniaxial tensile tests. The results of these tests are summarized in Table 2.

Results of several types of bending tests including ring compressive tests are summarized in Table 3. No clear difference in strength was observed between the three-point bending strength and that of small rods, which suggests that the volume effect on strength did not appear in the present case. This is probably because sleeve specimens flattened at the center region when the load was relatively high. In fact, as is shown in the table, the ring compressive tests where specimens fracture as they flatten gave the larger values of strength with any results of bending tests.

3.6 Comparison of the results of the heat-up experiment with the bending test data

To evaluate the possibility of the fracture of graphite sleeve caused by the thermal stress, which is generated from the temperature difference in the circumferential direction, it is believed that the data on sleeve specimens under constraint can be compared with the results of bending test. In Fig. 15, we see that the bending moment acting on sleeve specimen is about 60 N-m and 100 N-m for IG-11 and H451 graphites, respectively, provided that the temperature difference is 200 degrees. These values are much lower than the bending moment at fracture for both graphites, as is shown in Figs. 16 to 19. This indicates that the fracture of sleeve due to the thermal stress is very unlikely for these graphites. It is to be noted that the margin is larger for IG-11 than for H451 graphite.

4. SUMMARY

The heat-up experiment and bending tests have been carried out for IG-11 and H451 graphite sleeve specimens with or without ribs. Conclusions derived from the results of these experiment and tests are :

tests are summarized in Table 3. No clear difference in strength was observed between the three-point bending strength and that of small rods, which suggests that the volume effect on strength did not appear in the present case. This is probably because sleeve specimens flattened at the center region when the load was relatively high. In fact, as is shown in the table, the ring compressive tests where specimens fracture as they flatten gave the larger values of strength with any results of bending tests.

3.6 Comparison of the results of the heat-up experiment with the bending test data

To evaluate the possibility of the fracture of graphite sleeve caused by the thermal stress,which is generated from the temperature difference in the circumferential direction, it is believed that the data on sleeve specimens under constraint can be compared with the results of bending test. In Fig. 15, we see that the bending moment acting on sleeve specimen is about 60 N-m and 100 N-m for IG-11 and H451 graphites, respectively, provided that the temperature difference is 200 degrees. These values are much lower than the bending moment at fracture for both graphites, as is shown in Figs. 16 to 19. This indicates that the fracture of sleeve due to the thermal stress is very unlikely for these graphites. It is to be noted that the margin is larger for IG-11 than for H451 graphite.

4. SUMMARY

The heat-up experiment and bending tests have been carried out for IG-11 and H451 graphite sleeve specimens with or without ribs. Conclusions derived from the results of these experiment and tests are :

1) The amount of bowing measured as the displacement at the upper portion of sleeve specimen is approximately expressed as a function of outer and inner specimen radii, thermal expansion coefficient, and the temperature difference in the cicumferential direction, giving rise to a value of about 2mm, for example, when the difference is 200 degrees.
2) The bending moment generated in the IG-11 or H451 graphite which is heated up under constraint is much lower than that at fracture obtained during bending tests. This indicates that the fuel sleeve used for JAERI's VHTR is most unlikely to fracture, even if it is constrained with a temperature difference of 200 degrees under some circumstances.

Acknowledgements

The authors would like to thank Drs. T. Aochi and Y. Okamoto for their continual encouragement throughout the course of this work. Thanks are also due to Messrs. T. Kikuyama and H. Kakui for making the rig and Mr. Y. Honda for the help in carrying out the experiment.

REFERENCES

1) Unpublished report on the fuel element of the VHTR, Check & Review Working Group #12, JAERI, December 1976 (in Japanese).

2) For example, Nuclear Engineering International, 19(1974) 667.

3) Unpublished report on the screening test of the graphites for the VHTRex., September 1981 (in Japanese).

1) The amount of bowing measured as the displacement at the upper portion of sleeve specimen is approximately expressed as a function of outer and inner specimen radii, thermal expansion coefficient, and the temperature difference in the cicumferential direction, giving rise to a value of about 2mm, for example, when the difference is 200 degrees.
2) The bending moment generated in the IG-11 or H451 graphite which is heated up under constraint is much lower than that at fracture obtained during bending tests. This indicates that the fuel sleeve used for JAERI's VHTR is most unlikely to fracture, even if it is constrained with a temperature difference of 200 degrees under some circumstances.

Acknowledgements

The authors would like to thank Drs. T. Aochi and Y. Okamoto for their continual encouragement throughout the course of this work. Thanks are also due to Messrs. T. Kikuyama and H. Kakui for making the rig and Mr. Y. Honda for the help in carrying out the experiment.

REFERENCES

1) Unpublished report on the fuel element of the VHTR, Check & Review Working Group #12, JAERI, December 1976 (in Japanese).

2) For example, Nuclear Engineering International, 19(1974) 667.

3) Unpublished report on the screening test of the graphites for the VHTRex., September 1981 (in Japanese).

1) The amount of bowing measured as the displacement at the upper portion of sleeve specimen is approximately expressed as a function of outer and inner specimen radii, thermal expansion coefficient, and the temperature difference in the cicumferential direction, giving rise to a value of about 2mm, for example, when the difference is 200 degrees.
2) The bending moment generated in the IG-11 or H451 graphite which is heated up under constraint is much lower than that at fracture obtained during bending tests. This indicates that the fuel sleeve used for JAERI's VHTR is most unlikely to fracture, even if it is constrained with a temperature difference of 200 degrees under some circumstances.

Acknowledgements

The authors would like to thank Drs. T. Aochi and Y. Okamoto for their continual encouragement throughout the course of this work. Thanks are also due to Messrs. T. Kikuyama and H. Kakui for making the rig and Mr. Y. Honda for the help in carrying out the experiment.

REFERENCES

1) Unpublished report on the fuel element of the VHTR, Check & Review Working Group #12, JAERI, December 1976 (in Japanese).

2) For example, Nuclear Engineering International, 19(1974) 667.

3) Unpublished report on the screening test of the graphites for the VHTRex., September 1981 (in Japanese).

Table 1 Some properties of IG-11 and H451 graphites parallel to the longitudinal axis of each graphite block

	Apparent density (g/cm^3)	CTE ($10^{-6}/°C$)	Young's modulus (GPa)	Tensile strength (MPa)	Bending strength (MPa)	Compressive strength (MPa)
IG-11	1.75	3.6	9.4	24.9	34.7	73.4
H451	1.74	3.3	10.6	14.2	24.0	46.2

Table 2 Results of ring compressive tests of IG-11 and H451 graphite specimens

IG-11 No. 1

P kg	N	# 1 (%)	# 2 (%)	# 3 (%)	# 4 (%)	# 5 (%)
10	98	0.044	0.043	0.108	0.095	-0.056
20	196	0.093	0.093	0.234	0.224	-0.124
30	294	0.147	0.148	0.376	0.372	-0.202
35	343	0.177	0.176	0.451	0.447	-0.244
40	392	0.208	0.207	0.532	0.532	-0.286
44.5	436	0.238	0.238	0.607	0.613	-0.326

IG-11 No. 2

P kg	N	# 1 (%)	# 2 (%)	# 3 (%)	# 4 (%)	# 5 (%)
15	147	0.064	0.068	0.147	0.144	-0.094
25	245	0.114	0.123	0.266	0.265	-0.167
35	343	0.170	0.184	0.399	0.400	-0.248
40	392	0.200	0.216	0.468	0.472	-0.291
45	441	0.230	0.250	0.542	0.548	-0.336
47.9	469	0.250	0.270	0.586	0.568	-0.349

IG-11 No. 3

P kg	N	# 1 (%)	# 2 (%)	# 3 (%)	# 4 (%)	# 5 (%)
10	98	0.041	0.039	0.093	0.088	-0.081
20	196	0.087	0.088	0.217	0.205	-0.125
30	254	0.141	0.144	0.358	0.336	-0.174
35	343	0.168	0.172	0.435	0.404	-0.226
40	392	0.199	0.202	0.515	0.478	-0.283
42.8	419	0.216	0.220	0.562	0.522	-0.331

Table 2 Results of ring compressive tests of IG-11 and H451 graphite specimens (continued)

H 451 No. 1

P kg	P N	# 1 (%)	# 2 (%)	# 3 (%)	# 4 (%)	# 5 (%)
10	98	0.055	0.052	0.058	0.118	-0.081
15	147	0.085	0.083	0.116	0.195	-0.125
20	196	0.120	0.116	0.181	0.277	-0.174
25	245	0.156	0.150	0.260	0.373	-0.226
30	294	0.197	0.190	0.347	0.477	-0.282
34.1	334	0.234	0.224	0.544	0.589	-0.331

H 451 No. 2

P kg	P N	# 1 (%)	# 2 (%)	# 3 (%)	# 4 (%)	# 5 (%)
10	98	0.051	0.048	0.113	0.106	-0.067
15	147	0.081	0.076	0.183	0.176	-0.113
20	196	0.114	0.105	0.264	0.253	-0.159
25	245	0.150	0.140	0.353	0.342	-0.212
30	294	0.190	0.179	0.452	0.447	-0.266
38.9	381	0.215	0.202	0.515	0.533	-0.303

H 451 No. 3

P kg	P N	# 1 (%)	# 2 (%)	# 3 (%)	# 4 (%)	# 5 (%)
10	98	0.051	0.051	0.103	0.096	-0.072
20	196	0.114	0.114	0.230	0.226	-0.165
25	245	0.150	0.150	0.306	0.303	-0.215
30	294	0.189	0.189	0.389	0.388	-0.268
35	343	0.231	0.231	0.480	0.482	-0.327
38.9	381	0.269	0.269	0.556	0.516	-0.376

Table 3 Summary of the results of bending tests of various types of specimens and ring compressive tests

Grade	IG-11	H-451	Note
Sleeve	39.8	31.2	No Rib
3-point bending	40.7	30.0	
strength/ MPa	39.8	-	
	40.1 ± 0.5	30.1 ± 0.1	Mean
	33.8	30.1	With Rib
	39.1	-	
Small rod (6^{ϕ} x 60)			
3-point bending	40.6 ± 2.4	26.8 ± 1.5*	* □ 6.5x55
strength/ MPa	(25)	(12)	
Small rod (6^{ϕ} x 60)			
4-point bending	37.1 ± 2.6	24.0 ± 4.4	-
strength/ MPa	(25)	(56)	
Ring compressive	44.2	33.3	
strength/ MPa	45.5	37.5	-
$(46-36.3)^{\phi}$ x 18	41.6	32.3	
	43.8 ± 1.5	34.4 ± 2.3	Mean

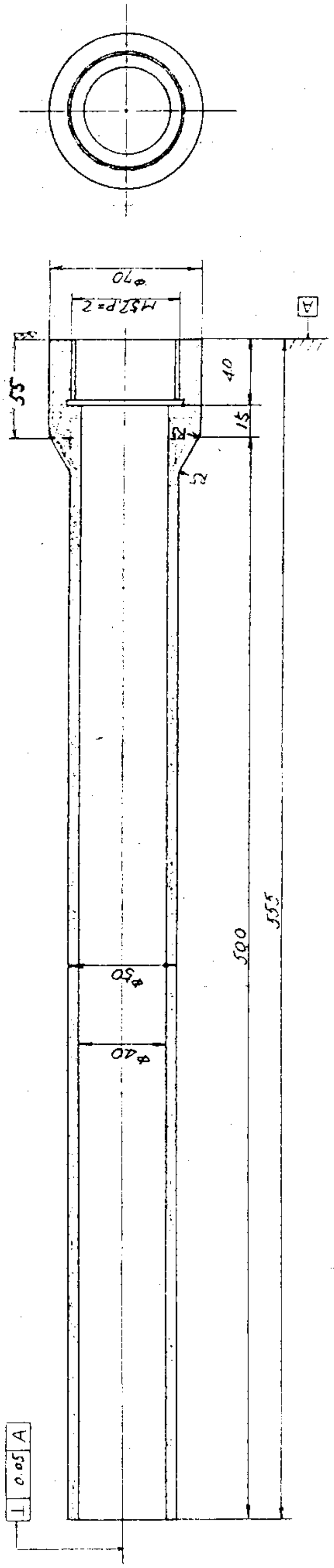


Fig. 1 Dimensions of Type I specimen for the heat-up experiment.

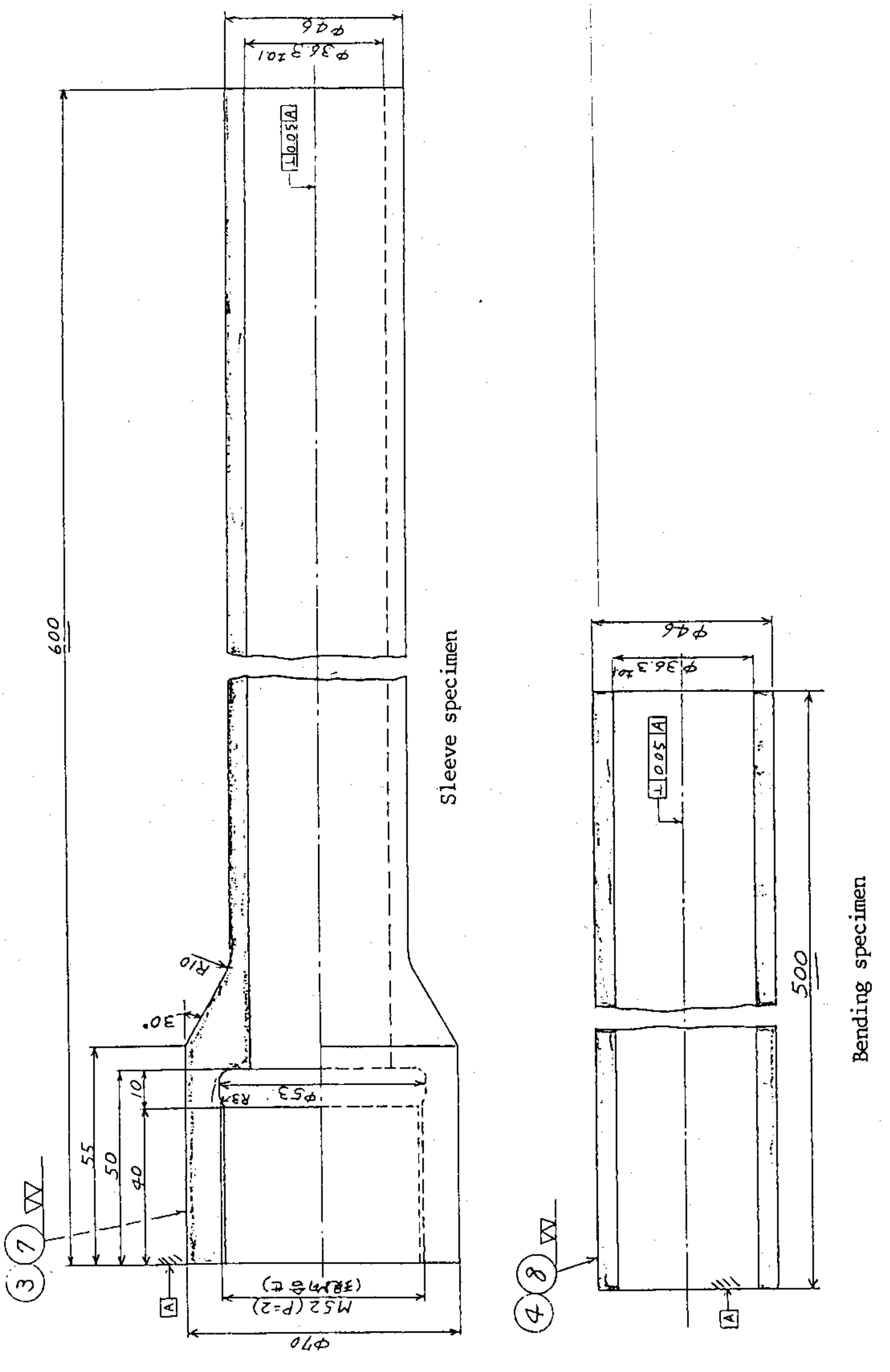


Fig. 2 Dimensions of Type II specimen and the hollow tube specimen for bending test.

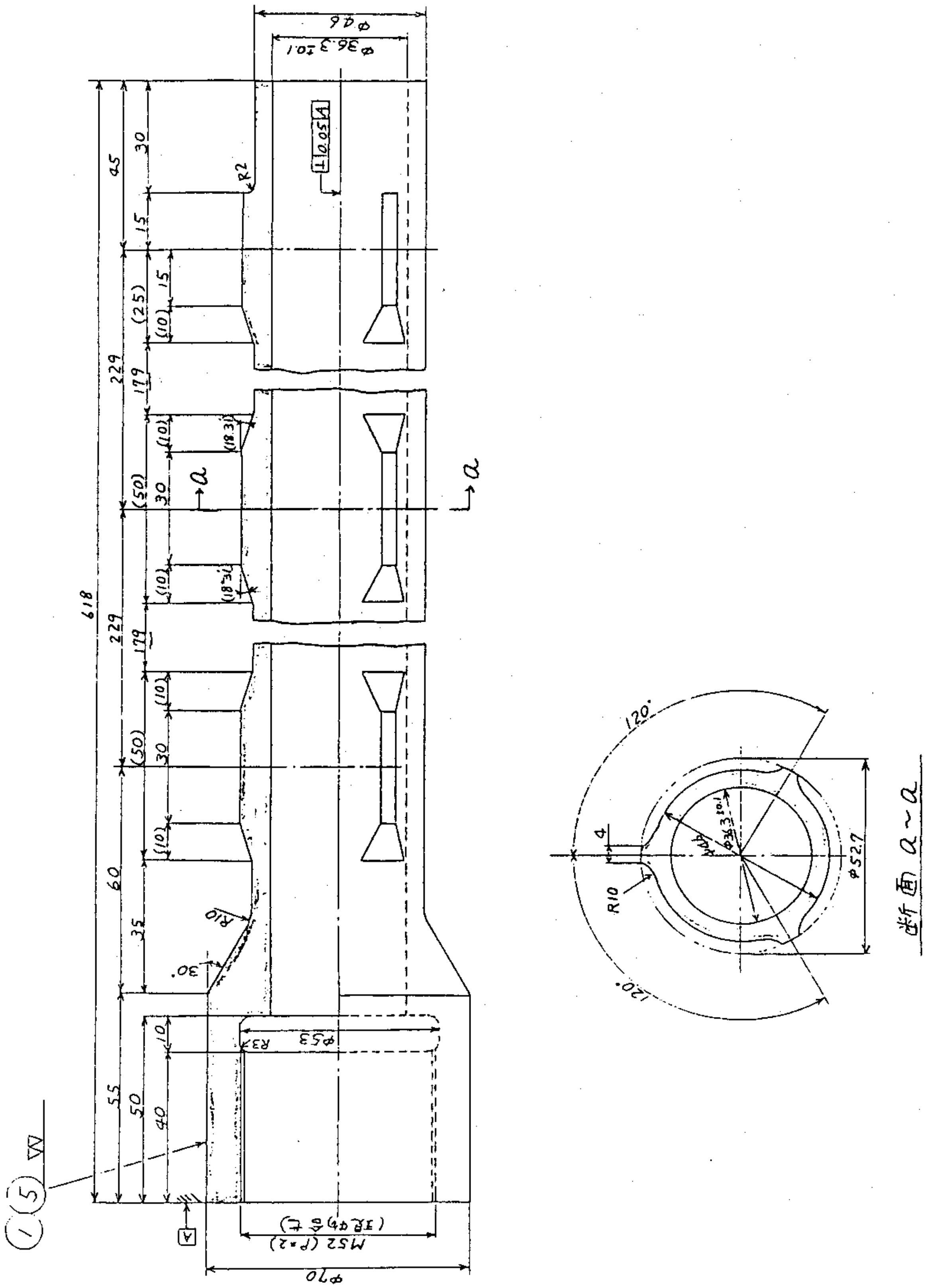


Fig. 3 Dimensions of Type III specimen.

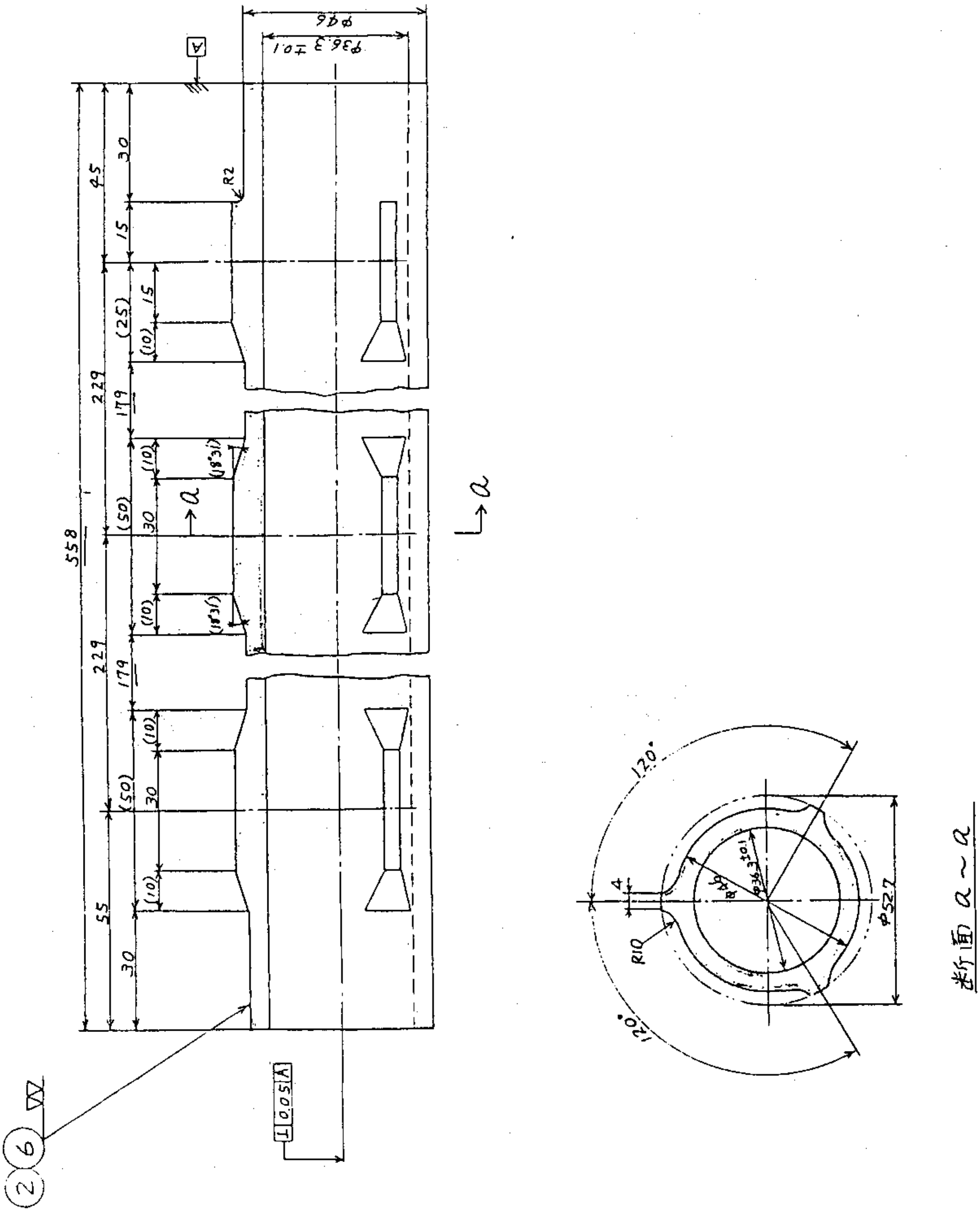


Fig. 4 Dimensions of the bending specimen with ribs.

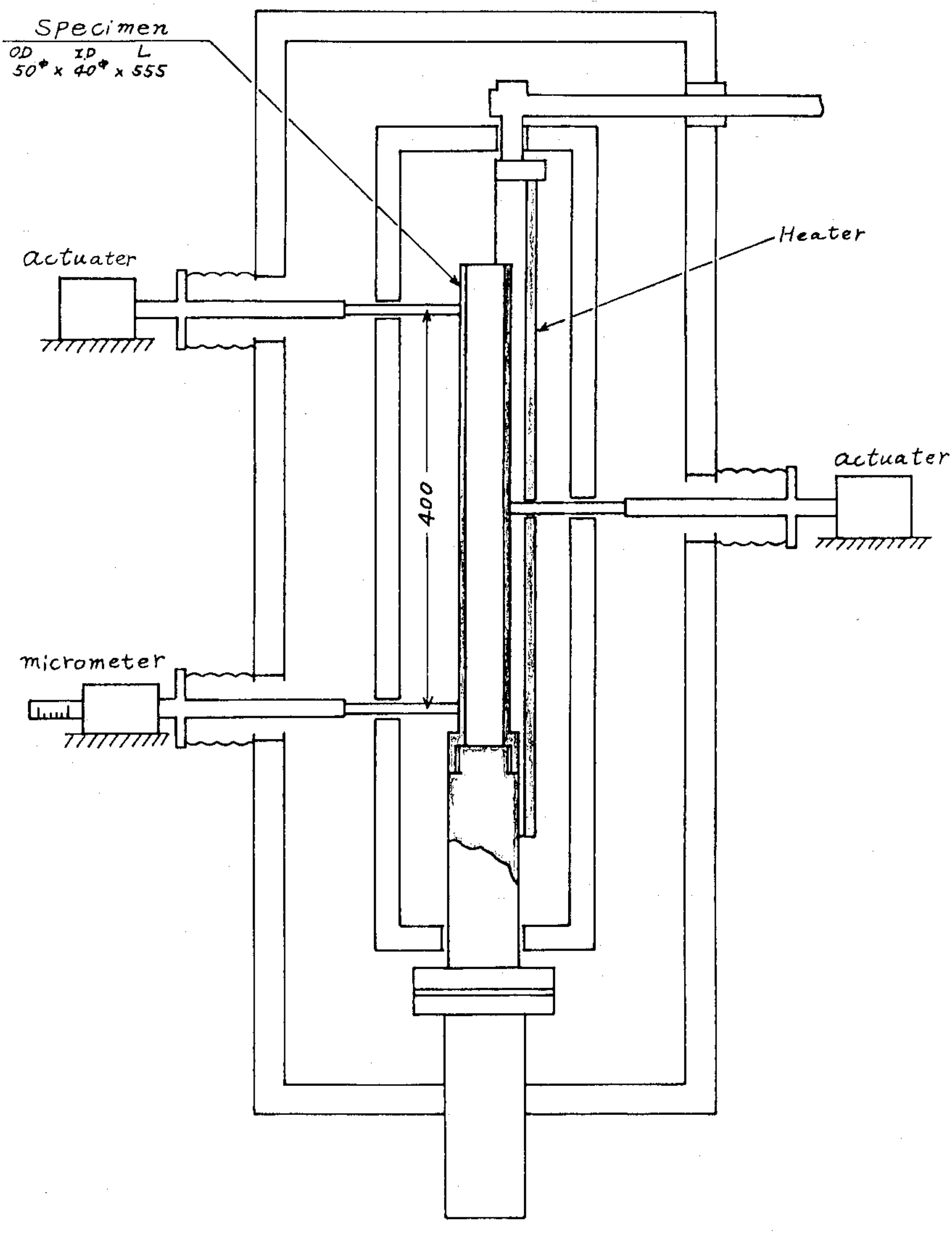


Fig. 5 Schematic of the main part of the rig used in the heat-up experiment.

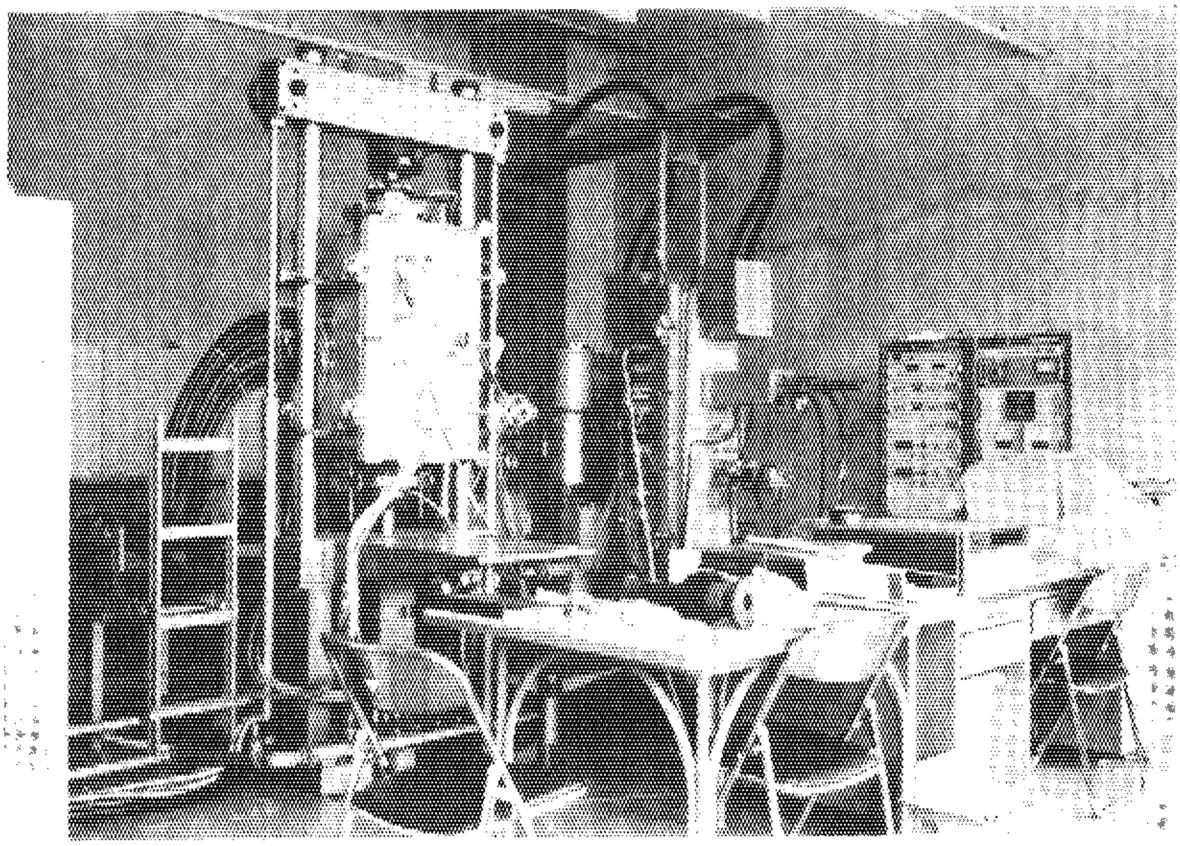


Fig. 6 Overview of the whole system of the heat-up experiment.

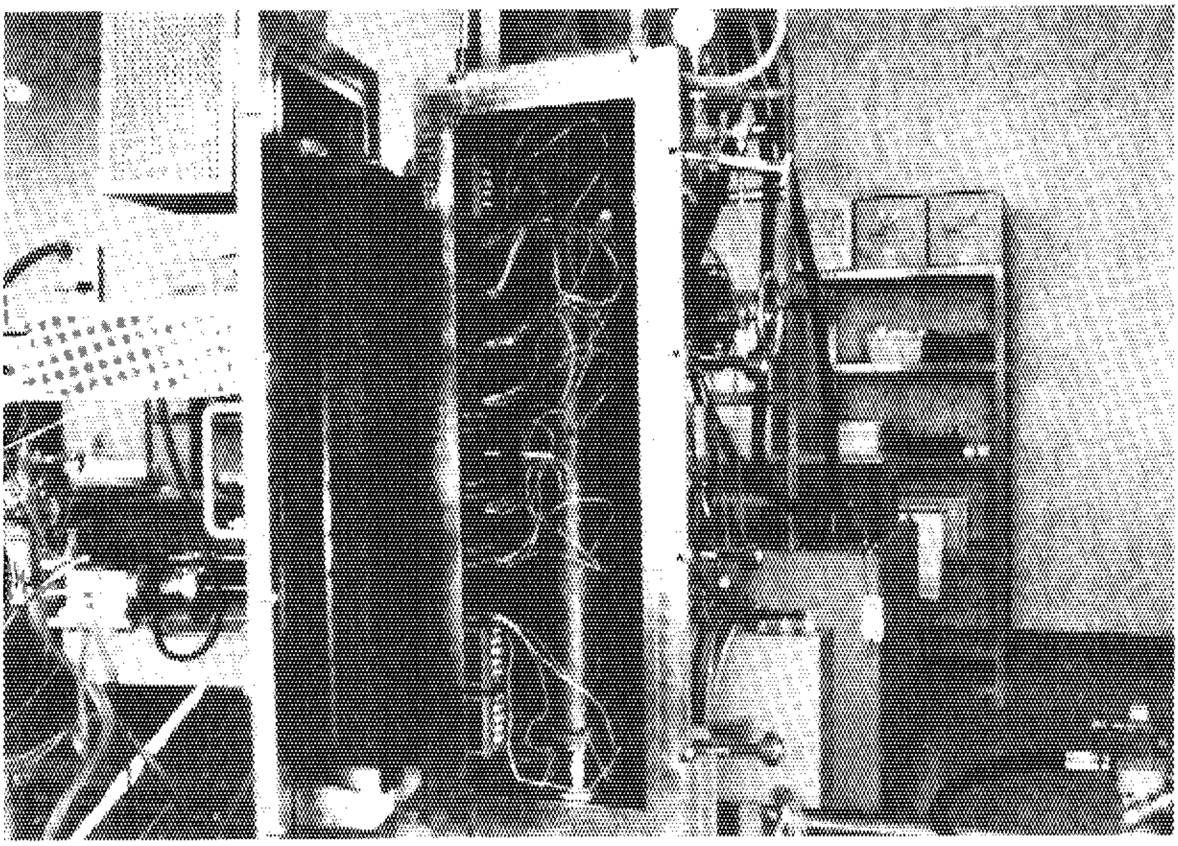


Fig. 7 Interior of the rig for the heat-up experiment.

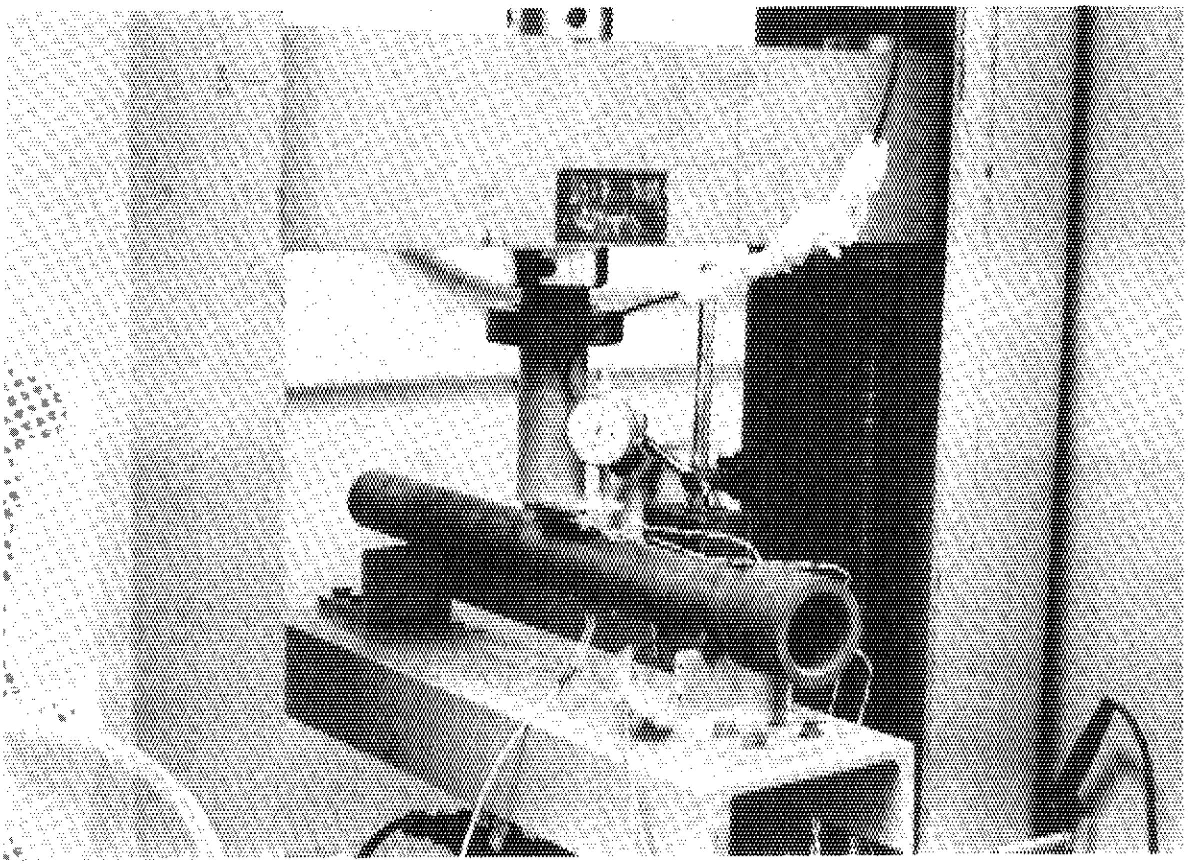


Fig. 8 Overview of the bending test of sleeve specimen.

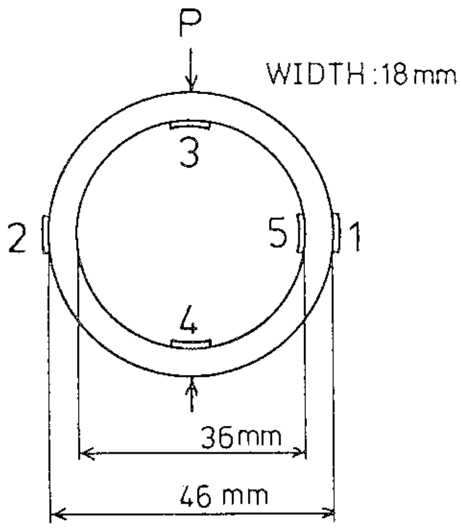
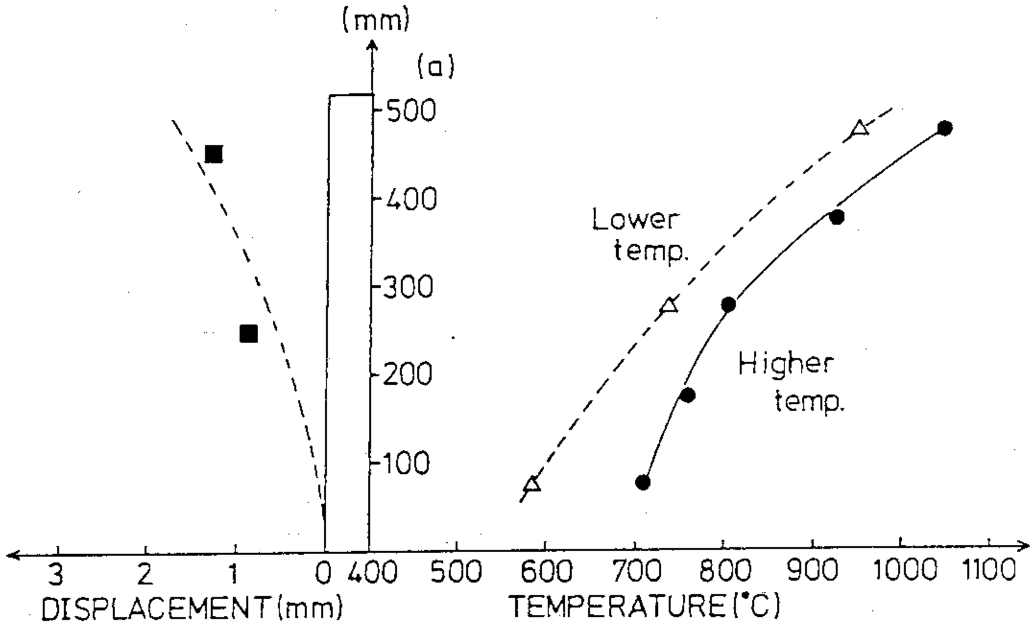


Fig. 9 Ring compressive test specimen and the locations of strain gages glued to it.



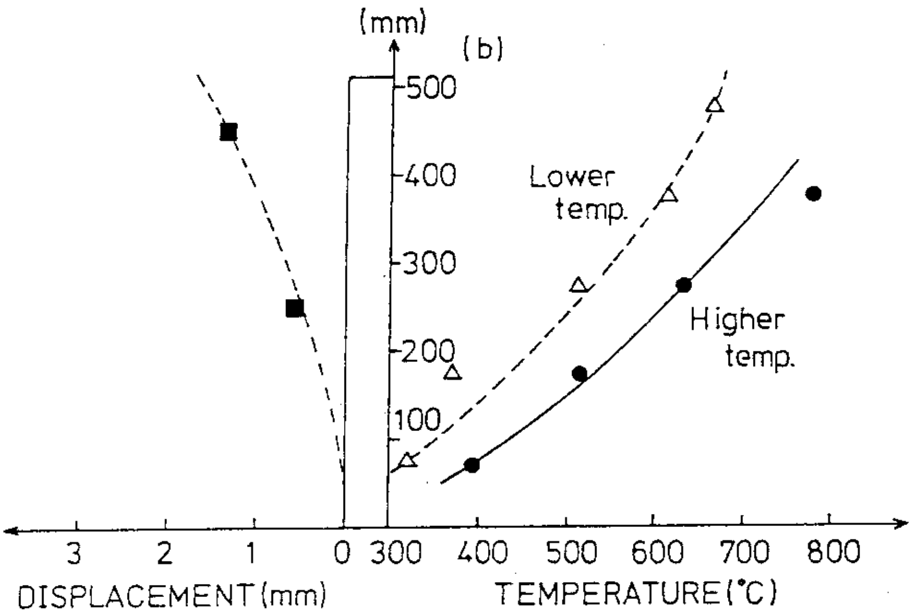
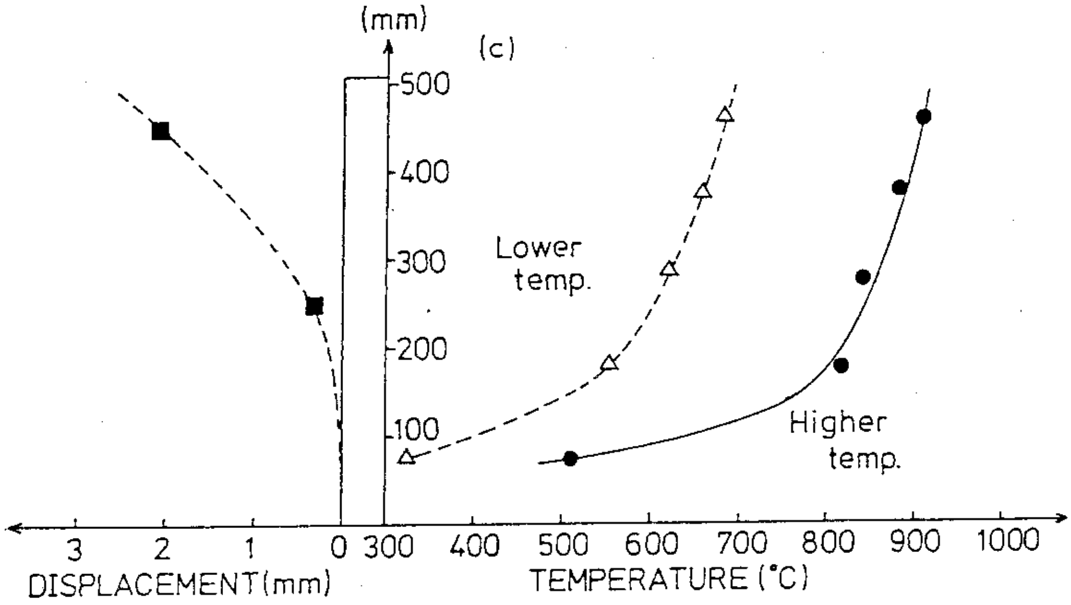


Fig. 10 Examples of the results of the heat-up experiment on IG-11 graphite Type I specimens.



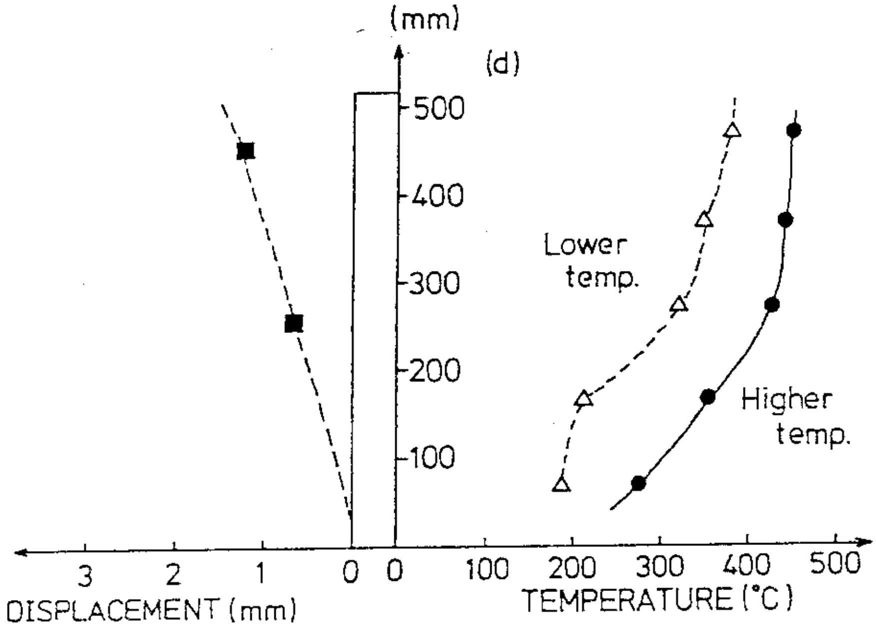


Fig. 10 Examples of the results of the heat-up experiment on IG-11 graphite Type I specimens. (continued)

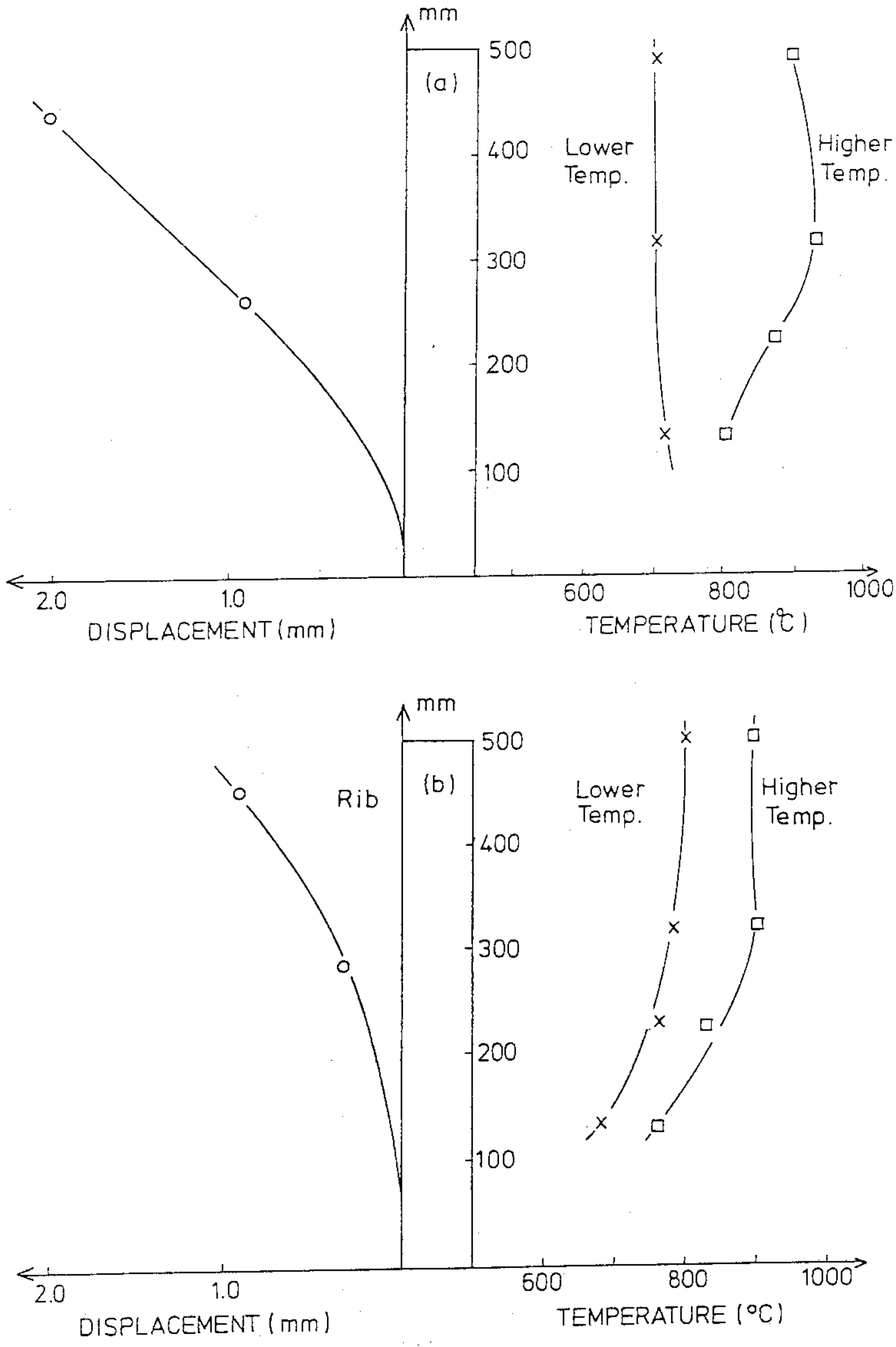


Fig. 11 Examples of the results of the heat-up experiment on IG-11 graphite Type II(a) and III(b) specimens.

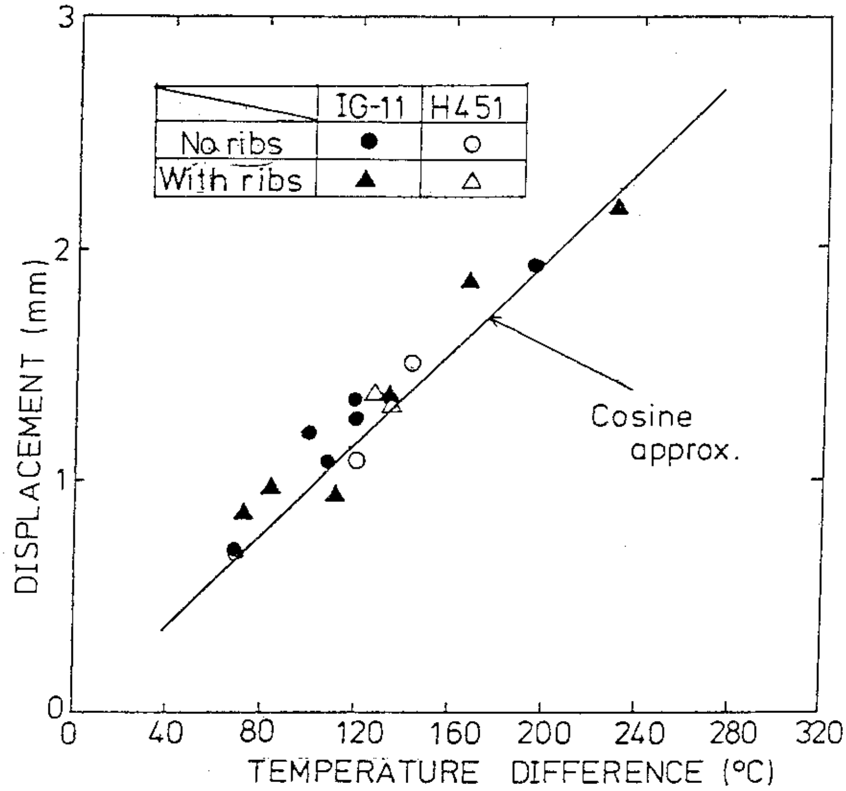


Fig. 12 Displacement of the upper portion of sleeve specimens as a function of the temperature difference along the circumferential direction.

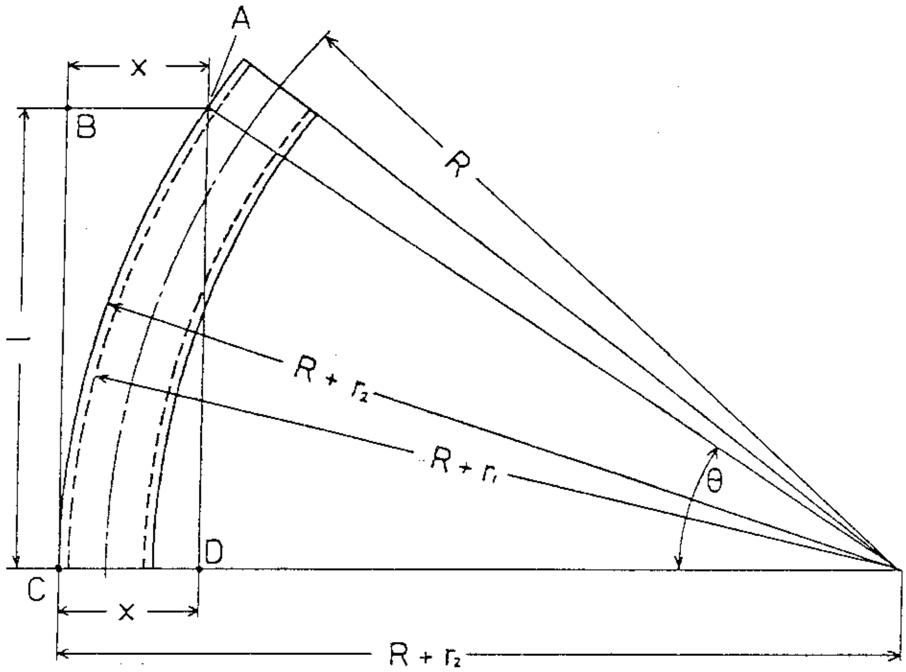


Fig. 13 Model for the calculation of the amount of bowing from the radius of curvature.

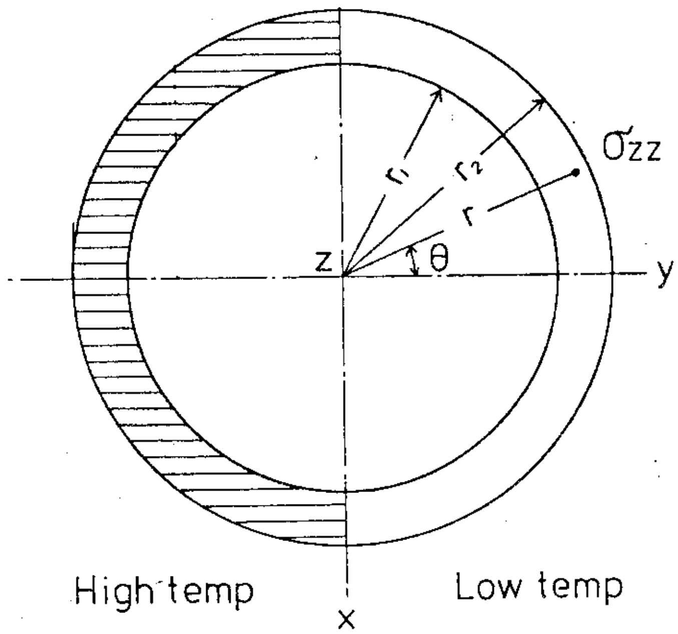


Fig. 14 Schematic of the cross-section of a sleeve specimen.

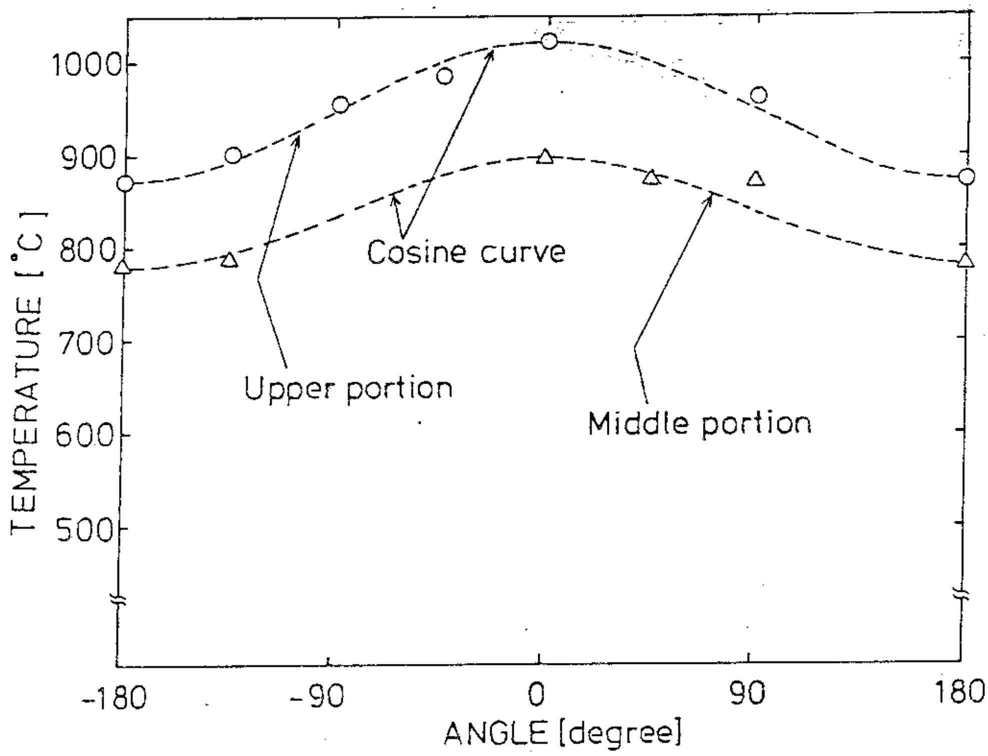


Fig. 15 An example of the temperature distribution along the circumferential direction of IG-11 graphite specimen.

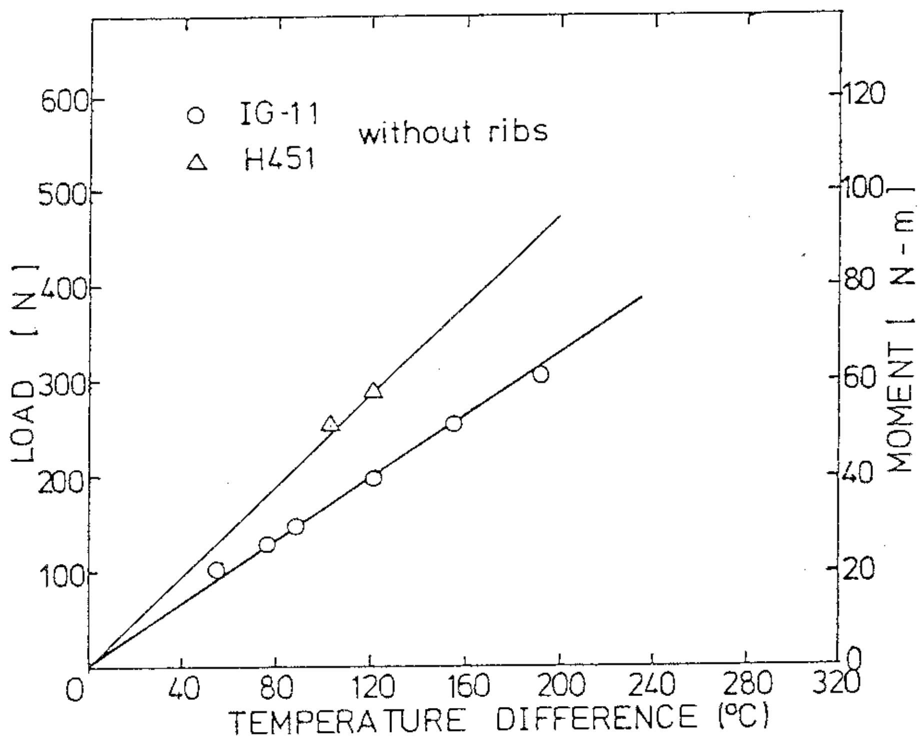


Fig. 16 Load generated at the upper portion of sleeve specimens as a function of temperature difference.

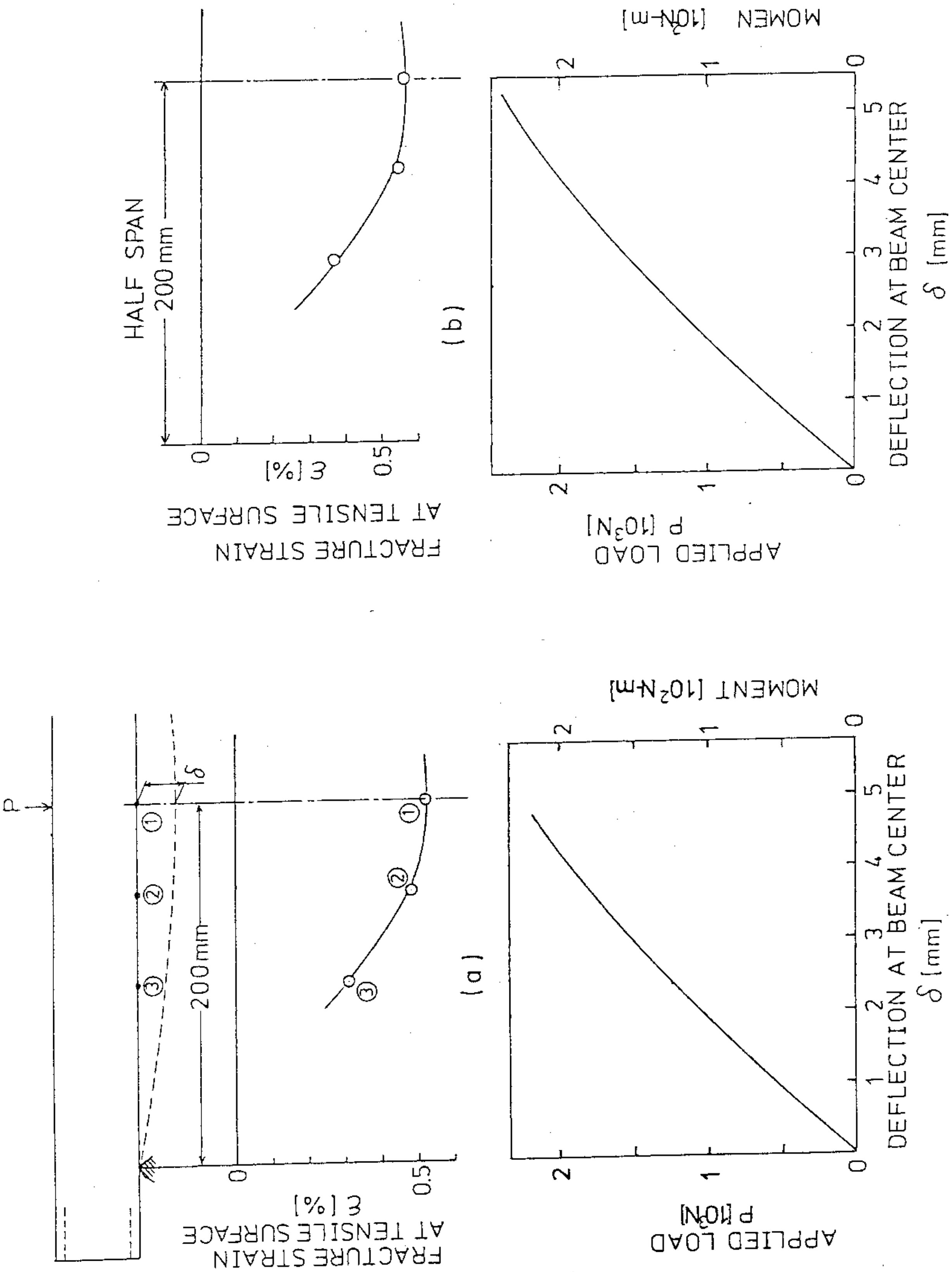


Fig. 17 Results of bending tests of IG-11 graphite specimens without ribs.

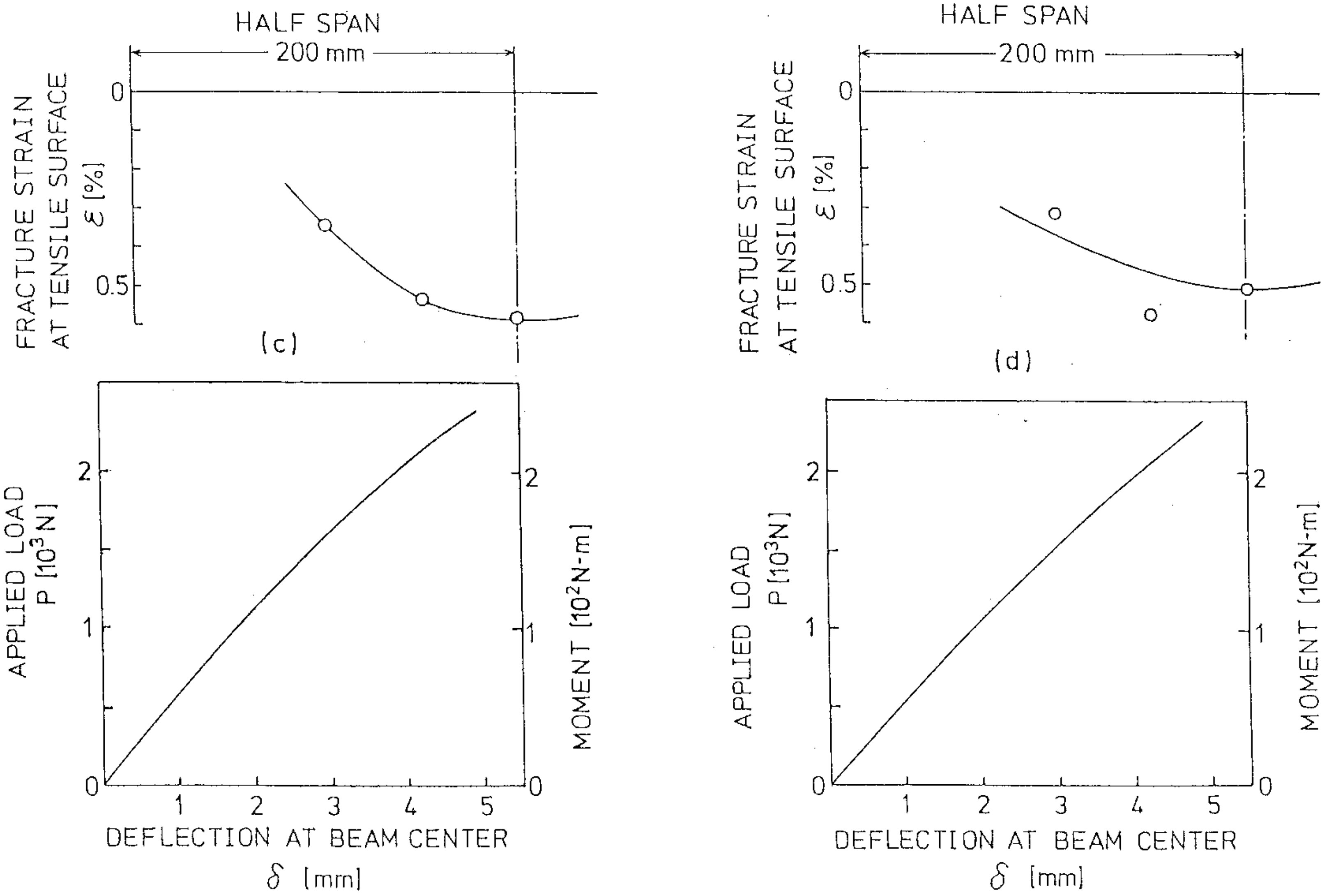


Fig. 17 Results of bending tests of IG-11 graphite specimens without ribs. (continued)

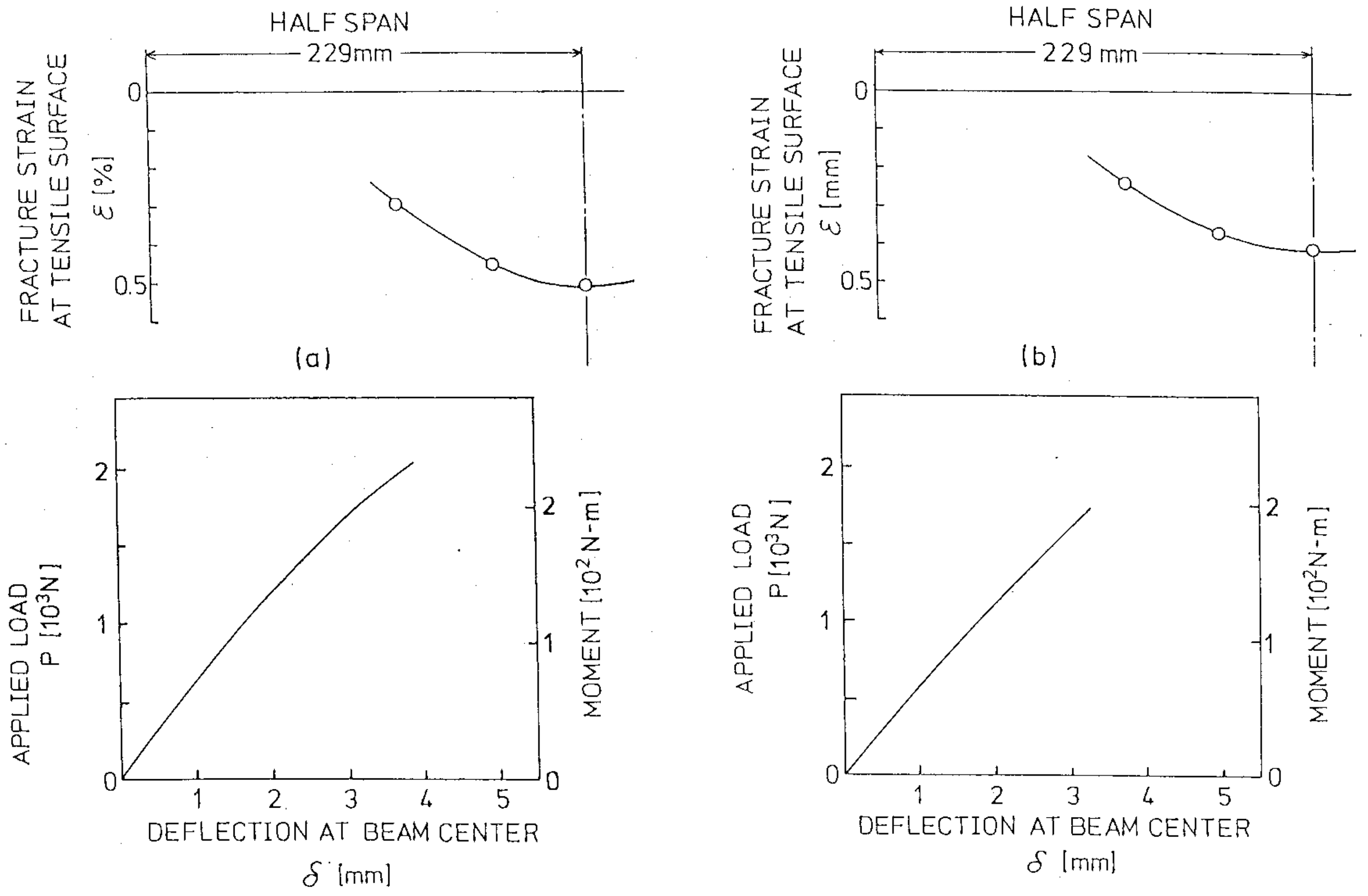


Fig. 18 Results of bending tests of IG-11 graphite specimens with ribs.

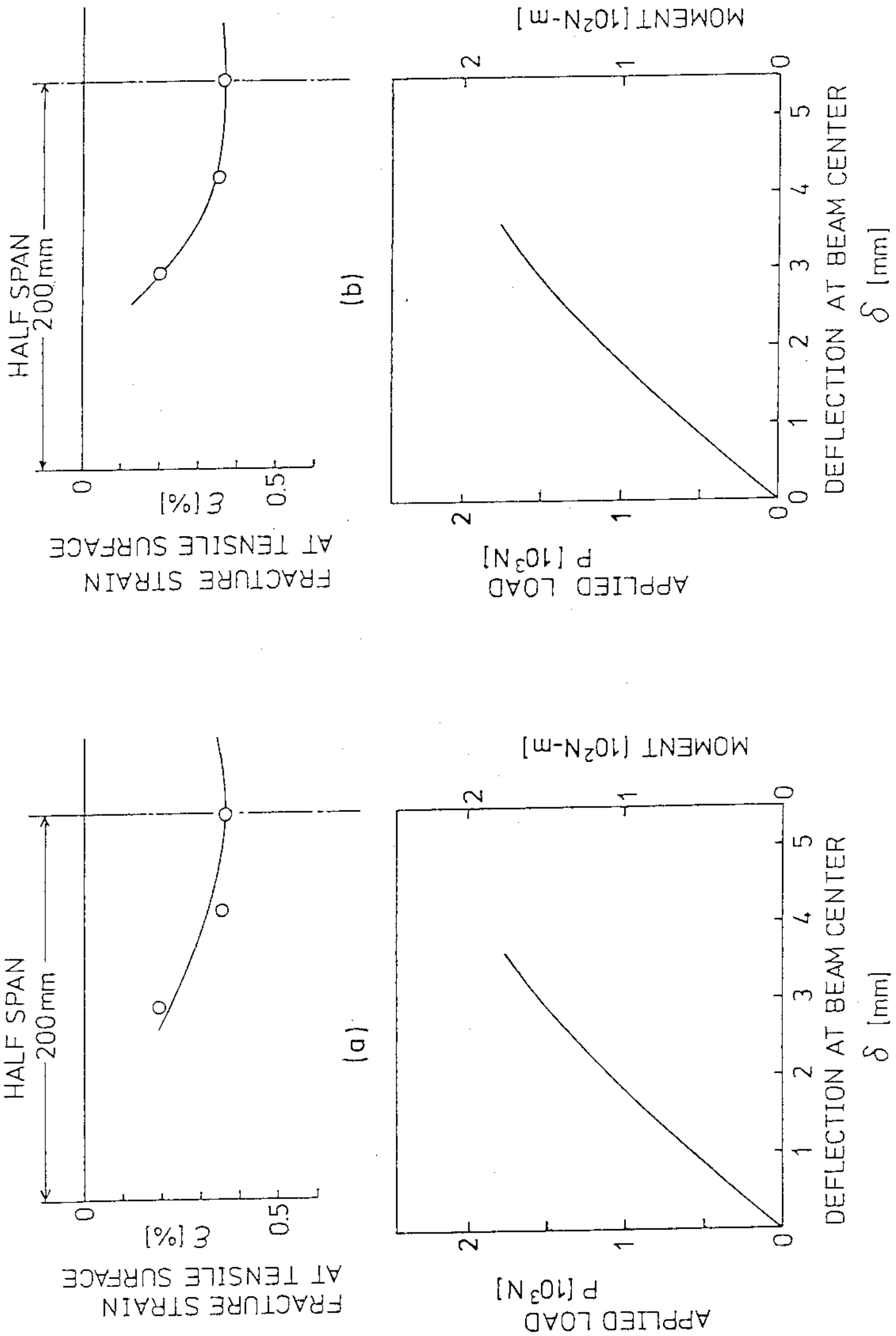


Fig. 19 Results of bending tests of H451 graphite specimens without ribs.

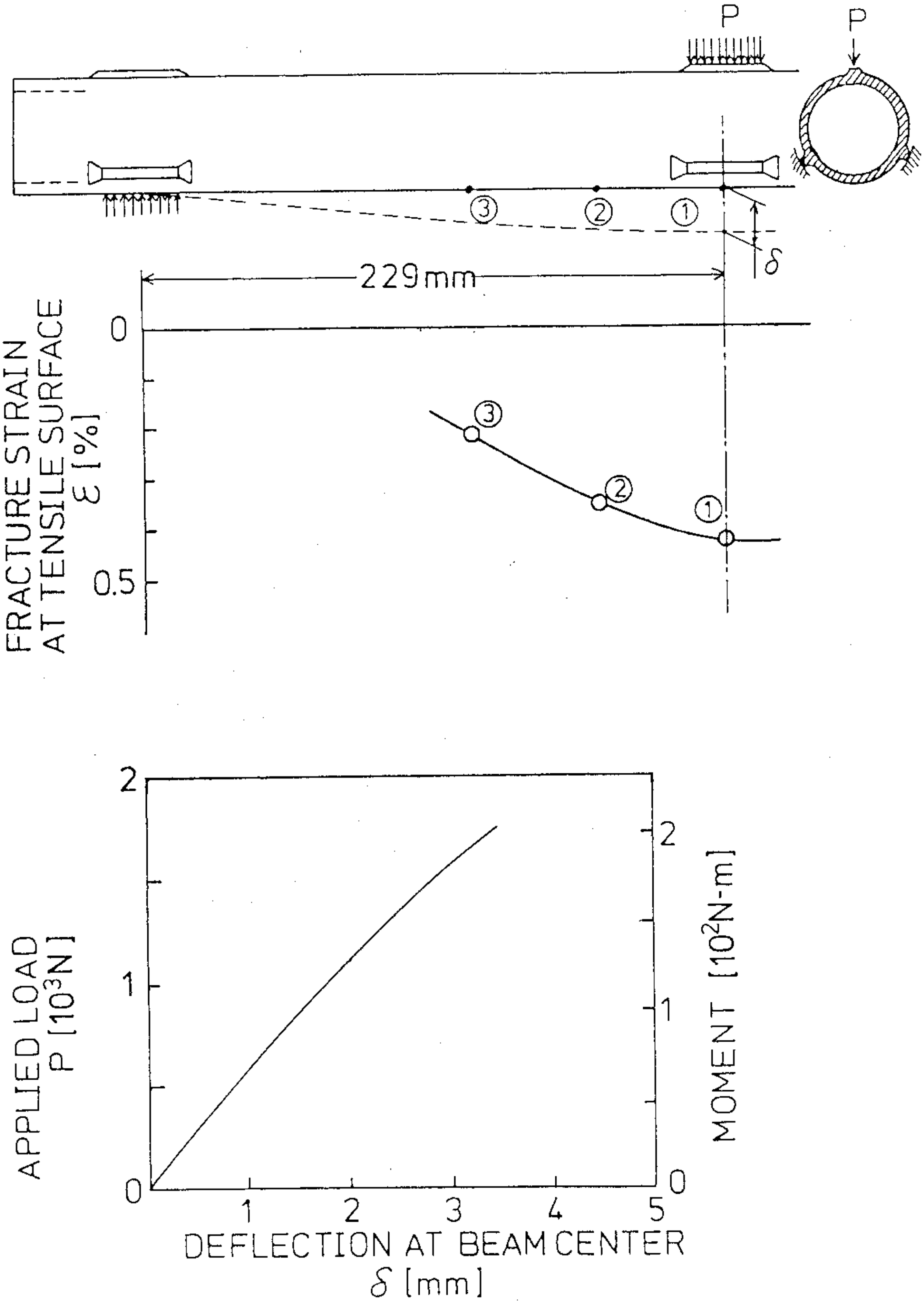


Fig. 20 An example of the result of the bending test of H451 graphite specimen with ribs.

Appendix

Program for the processing of experimental data

using a Hewlett Packard microcomputer, Model 9835A

```
* PRINTER IS 7,1
10    ! RE-SAVE "TEST:T15"
20    !
30    ! Job_no=1 or 2 :: Data sampling main routine
40    !
50    OPTION BASE 1
60    COM INTEGER Job_no,Dvm,Scanner,Print,Clock,Crt
70    COM Temp,Job_label$(4)[40],Plotter$[8],Msusd$,Msusp$
80    DIM File_name$[6],Date$[14],Scan_rate$[25],Remarks$[160]
90    SHORT Data(35)
100   !
110   Range=3               ! Dvm range parameter :: select [ 1 volt ]
120   Chan_no=35            ! Scanning channel number
130   IF Job_no=2 THEN Chan_no=3
140   REDIM Data(Chan_no) ! Same as Data(*)
150   !
160   First_chan=0          ! First scanning channel
170   IF Job_no=2 THEN First_chan=35
180   Last_chan=34          ! Last scanning channel
190   IF Job_no=2 THEN Last_chan=37
200      !
210      DISP " NOW SUBROUTINE LINKING. WAIT JUST MOMENT !! "
220      LINK "KEY-IN"&Msusp$,Link
230      DISP
240      OUTPUT Crt;CHR$(27)&"E";
250      !
260      REMOTE Dvm
270      RESET Dvm
280      OUTPUT Scanner;"C"
290      !
300       Over_flow=0
310       OUTPUT Crt;CHR$(27)&"E";
320       OUTPUT Crt;CHR$(27)&"&a0r0C";RPT$("*",80)
330       OUTPUT Crt;CHR$(27)&"&a1r19C";"JOB No.   =";Job_no
340       OUTPUT Crt;CHR$(27)&"&a2r19C";"JOB NAME = ";Job_label$(Job_no)
350       OUTPUT Crt;CHR$(27)&"&a3r0C";RPT$("*",80)
360       DISP "IF READY PRESS  CONTINUE  KEY !!"
370       BEEP
380       PAUSE
390       !
400 Rep_:GOSUB Key_in
410       !
420       Over_flow=0
430       GOSUB Disk_create
440       IF Over_flow THEN Rep_
450       !
460       DISP " NOW SUBROUTINE LINKING. WAIT JUST MOMENT !! "
470       IF Job_no=1 THEN LINK "SAMP-1"&Msusp$,Link
480       IF Job_no=2 THEN LINK "SAMP-2"&Msusp$,Link
490       GOSUB Sampling
500       !
510 End: SERIAL
520       BEEP
530       OUTPUT Crt;CHR$(27)&"m";
540       DISP "JOB END !"
550       STOP
560       DISP
570       PRINT PAGE;
580       DISP " NOW PROGRAM LOADING. WAIT JUST MOMENT !!"
590       GET "DRIVER"&Msusp$
600       END
610       !
620 Link:    ! RE-SAVE "KEY-IN:T15"
630          !
640 Key_in:! *******************************  ****
650          ! * Subroutine PARAMETERS KEY INPUT *
```

```
660          ! ......
670          !
680          IF Over_f... THEN OUTPUT Crt;... ;CHR$(27)&"&m";
690          IF Over_flow THEN GOTO In_rep
700          Remarks$[1,160]=""
710          OUTPUT Crt;CHR$(27)&"&a4r0C";CHR$(27)&"J";
720          OUTPUT Crt;CHR$(27)&"&a5r19C";"SCANNING RATE            =                    [
 sec ]"
730          OUTPUT Crt;CHR$(27)&"&a6r19C";"SCANNING TIME LENGTH =                    [
 minutes ]"
740          OUTPUT Crt;CHR$(27)&"&a7r19C";"No. of SCANNINGS        =                    [
 times ]"
750          OUTPUT Crt;CHR$(27)&"&a8r19C";"[...] RATIO              =                    [
 (kg/cm2)/(volt) ]"
760          OUTPUT Crt;CHR$(27)&"&a9r19C";"DISPLACEMENT RATIO    =                    [
 (mm)/(volt) ]"
770          OUTPUT Crt;CHR$(27)&"&a11r0C";RPT$("-",17)&"  REMARKS  "&RP...
780          OUTPUT Crt;CHR$(27)&"&a12r0C";Remarks$[1,80]
790          OUTPUT Crt;CHR$(27)&"&a13r0C";Remarks$[81,160]
800          OUTPUT Crt;CHR$(27)&"&a14r0C";RPT$("-",80)
810           !
820 In_rep:  !
830 In1:      INPUT "SCANNING RATE = ? :  [ sec ]",Scan_rate
840                IF Scan_rate<=0 THEN In1
850           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a5r42C";Scan_rate
860           OUTPUT Crt;CHR$(27)&"&a5r55C";" [ sec ]"
870           !
880 In2:      INPUT "SCANNING TIME LENGTH = ? : [ min ]",S_time
890                IF S_time<=0 THEN In2
900           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a6r42C";S_time
9 PRINTER IS 7,1
10    ! RE-SAVE "TEST:T15"
20    !
30    ! Job_no=1 or 2 :: Data sampling main routine
40    !
50    OPTION BASE 1
60    COM INTEGER Job_no,Dvm,Scanner,Print,Clock,Crt
70    COM Temp,Job_label$(4)[40],Plotter$[8],Msusd$,Msusp$
80    DIM File_name$[6],Date$[14],Scan_rate$[25],Remarks$[160]
90    SHORT Data(35)
100   !
110   Range=3                  ! Dvm range parameter :: select [ 1 volt ]
120   Chan_no=35               ! Scanning channel number
130   IF Job_no=2 THEN Chan_no=3
140   REDIM Data(Chan_no) ! Same as Data(*)
150   !
160   First_chan=0             ! First scanning channel
170   IF Job_no=2 THEN First_chan=35
180   Last_chan=34             ! Last scanning channel
190   IF Job_no=2 THEN Last_chan=37
200       !
210       DISP " NOW SUBROUTINE LINKING. WAIT JUST MOMENT !! "
220       LINK "KEY-IN"&Msusp$,Link
230       DISP
240       OUTPUT Crt;CHR$(27)&"E";
250       !
260       REMOTE Dvm
270       RESET Dvm
280       OUTPUT Scanner;"C"
290       !
300        Over_flow=0
310        OUTPUT Crt;CHR$(27)&"E";
320        OUTPUT Crt;CHR$(27)&"&a0r0C";RPT$("*",80)
330        OUTPUT Crt;CHR$(27)&"&a1r19C";"JOB No.   =";Job_no
340        OUTPUT Crt;CHR$(27)&"&a2r19C";"JOB NAME  = ";Job_label$(Job_no)
350        OUTPUT Crt;CHR$(27)&"&a3r0C";RPT$("*",80)
```

```
360        DISP "IF READY PRESS  CONTINUE  KEY !!"
370        BEEP
380        PAUSE
390        !
400 Rep_:GOSUB Key_in
410        !
420        Over_flow=0
430        GOSUB Disk_create
440        IF Over_flow THEN Rep_
450        !
460        DISP " NOW SUBROUTINE LINKING. WAIT JUST MOMENT !! "
470        IF Job_no=1 THEN LINK "SAMP-1"&Msusp$,Link
480        IF Job_no=2 THEN LINK "SAMP-2"&Msusp$,Link
490        GOSUB Sampling
500        !
510 End:  SERIAL
520        BEEP
530        OUTPUT Crt;CHR$(27)&"m";
540        DISP "JOB END !"
550        STOP
560        DISP
570        PRINT PAGE;
580        DISP " NOW PROGRAM LOADING. WAIT JUST MOMENT !!"
590        GET "DRIVER"&Msusp$
600        END
610        !
620 Link:   ! RE-SAVE "KEY-IN:T15"
630         !
640 Key_in:! ***********************************
650         ! * Subroutine PARAMETERS KEY INPUT *
660         ! ***********************************
670         !
680         IF Over_flow THEN OUTPUT Crt;CHR$(27)&"H";CHR$(27)&"m";
690         IF Over_flow THEN GOTO In_rep
700         Remarks$[1,160]=""
710         OUTPUT Crt;CHR$(27)&"&a4r0C";CHR$(27)&"J";
720         OUTPUT Crt;CHR$(27)&"&a5r19C";"SCANNING RATE            =                    [
 sec ]"
730         OUTPUT Crt;CHR$(27)&"&a6r19C";"SCANNING TIME LENGTH =                    [
 minutes ]"
740         OUTPUT Crt;CHR$(27)&"&a7r19C";"No. of SCANNINGS        =                    [
 times ]"
750         OUTPUT Crt;CHR$(27)&"&a8r19C";"LOAD RATIO               =                    [
 (kg/cm2)/(volt) ]"
760         OUTPUT Crt;CHR$(27)&"&a9r19C";"DISPLACEMENT RATIO   =                    [
 (mm)/(volt) ]"
770         OUTPUT Crt;CHR$(27)&"&a11r0C";RPT$("-",17)&"  REMARKS  "&RPT$("-",52)
780         OUTPUT Crt;CHR$(27)&"&a12r0C";Remarks$[1,80]
790         OUTPUT Crt;CHR$(27)&"&a13r0C";Remarks$[81,160]
800         OUTPUT Crt;CHR$(27)&"&a14r0C";RPT$("-",80)
810          !
820 In_rep:  !
830 In1:      INPUT "SCANNING RATE = ? :   [ sec ]",Scan_rate
840                IF Scan_rate<=0 THEN In1
850           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a5r42C";Scan_rate
860           OUTPUT Crt;CHR$(27)&"&a5r55C";" [ sec ]"
870           !
880 In2:      INPUT "SCANNING TIME LENGTH = ? : [ min ]",S_time
890                IF S_time<=0 THEN In2
900           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a6r42C";S_time
NAME  PRO TYPE REC/FILE  BYTES/REC   ADDRESS
T15         2

AUTOST     PROG      1        256          5
9876A      BPRG    161        256          6
MAGCON     DATA     11        256        176
```

```
autost     DATA      1         256          187
MANG-2     DATA    111         256          189
TEST       DATA     34         256          300
MANG-1     DATA    110         256          559
DRIVER     DATA     23         256          679
KEY-IN     DATA     20         256          702
SAMP-1     DATA     25         256          722
SAMP-2     DATA     24         256          747
NAME   PRO TYPE REC/FILE  BYTES/REC    ADDRESS
T15          2

AUTOST     PROG      1         256            5
9876A      BPRG    161         256            6
MNGCOM     DATA     11         256          176
autost     DATA      1         256          187
MANG-2     DATA    111         256          189
TEST       DATA     34         256          300
MANG-1     DATA    110         256          559
DRIVER     DATA     23         256          679
KEY-IN     DATA     20         256          702
SAMP-1     DATA     25         256          722
SAMP-2     DATA     24         256          747
NAME   PRO TYPE REC/FILE  BYTES/REC    ADDRESS
T15          2

AUTOST     PROG      1         256            5
9876A      BPRG    161         256            6
MNGCOM     DATA     11         256          176
autost     DATA      1         256          187
MANG-2     DATA    111         256          189
TEST       DATA     34         256          300
MANG-1     DATA    110         256          559
DRIVER     DATA     23         256          679
KEY-IN     DATA     20         256          702
SAMP-1     DATA     25         256          722
SAMP-2     DATA     24         256          747
```

```
10    ! RE-SAVE "TEST:T15"
20    !
30    ! Job_no=1 or 2 :: Data sampling main routine
40    !
50    OPTION BASE 1
60    COM INTEGER Job_no,Dvm,Scanner,Print,Clock,Crt
70    COM Temp,Job_label$(4)[40],Plotter$[8],Msusd$,Msusp$
80    DIM File_name$[6],Date$[14],Scan_rate$[25],Remarks$[160]
90    SHORT Data(35)
100   !
110   Range=3                ! Dvm range parameter :: select [ 1 volt ]
120   Chan_no=35             ! Scanning channel number
130   IF Job_no=2 THEN Chan_no=3
140   REDIM Data(Chan_no) ! Same as Data(*)
150   !
160   First_chan=0           ! First scanning channel
170   IF Job_no=2 THEN First_chan=35
180   Last_chan=34           ! Last scanning channel
190   IF Job_no=2 THEN Last_chan=37
200      !
210      DISP " NOW SUBROUTINE LINKING. WAIT JUST MOMENT !! "
220      LINK "KEY-IN"&Msusp$,Link
230      DISP
240      OUTPUT Crt;CHR$(27)&"E";
250      !
260      REMOTE Dvm
270      RESET Dvm
280      OUTPUT Scanner;"C"
290      !
300       Over_flow=0
310       OUTPUT Crt;CHR$(27)&"E";
320       OUTPUT Crt;CHR$(27)&"&a0r0C";RPT$("*",80)
330       OUTPUT Crt;CHR$(27)&"&a1r19C";"JOB No.   =";Job_no
340       OUTPUT Crt;CHR$(27)&"&a2r19C";"JOB NAME = ";Job_label$(Job_no)
350       OUTPUT Crt;CHR$(27)&"&a3r0C";RPT$("*",80)
360       DISP "IF READY PRESS  CONTINUE  KEY !!"
370       BEEP
380       PAUSE
390       !
400 Rep_:GOSUB Key_in
410       !
420       Over_flow=0
430       GOSUB Disk_create
440       IF Over_flow THEN Rep_
450       !
460       DISP " NOW SUBROUTINE LINKING. WAIT JUST MOMENT !! "
470       IF Job_no=1 THEN LINK "SAMP-1"&Msusp$,Link
480       IF Job_no=2 THEN LINK "SAMP-2"&Msusp$,Link
490       GOSUB Sampling
500       !
510 End: SERIAL
520       BEEP
530       OUTPUT Crt;CHR$(27)&"m";
540       DISP "JOB END !"
550       STOP
560       DISP
570       PRINT PAGE;
580       DISP " NOW PROGRAM LOADING. WAIT JUST MOMENT !!"
590       GET "DRIVER"&Msusp$
600       END
610       !
620 Link:   ! RE-SAVE "KEY-IN:T15"
630         !
640 Key_in: ! ***********************************
650         ! * Subroutine PARAMETERS KEY INPUT *
660         ! ***********************************
```

```
670          !
680          IF Over_flow THEN OUTPUT Crt;CHR$(27)&"H";CHR$(27)&"m";
690          IF Over_flow THEN GOTO In_rep
700          Remarks$[1,160]=""
710          OUTPUT Crt;CHR$(27)&"&a4r0C";CHR$(27)&"J";
720          OUTPUT Crt;CHR$(27)&"&a5r19C";"SCANNING RATE          =               [
 sec ]"
730          OUTPUT Crt;CHR$(27)&"&a6r19C";"SCANNING TIME LENGTH =               [
 minutes ]"
740          OUTPUT Crt;CHR$(27)&"&a7r19C";"No. of SCANNINGS      =               [
 times ]"
750          OUTPUT Crt;CHR$(27)&"&a8r19C";"LOAD RATIO            =               [
 (kg/cm2)/(volt) ]"
760          OUTPUT Crt;CHR$(27)&"&a9r19C";"DISPLACEMENT RATIO   =               [
 (mm)/(volt) ]"
770          OUTPUT Crt;CHR$(27)&"&a11r0C";RPT$("-",17)&"  REMARKS  "&RPT$("-",52)
780          OUTPUT Crt;CHR$(27)&"&a12r0C";Remarks$[1,80]
790          OUTPUT Crt;CHR$(27)&"&a13r0C";Remarks$[81,160]
800          OUTPUT Crt;CHR$(27)&"&a14r0C";RPT$("-",80)
810           !
820 In_rep:  !
830 In1:      INPUT "SCANNING RATE = ? :  [ sec ]",Scan_rate
840              IF Scan_rate<=0 THEN In1
850           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a5r42C";Scan_rate
860           OUTPUT Crt;CHR$(27)&"&a5r55C";" [ sec ]"
870           !
880 In2:      INPUT "SCANNING TIME LENGTH = ? : [ min ]",S_time
890              IF S_time<=0 THEN In2
900           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a6r42C";S_time
910           OUTPUT Crt;CHR$(27)&"&a6r55C";" [ minutes ]"
920           !
930           Scan_no=INT(S_time*60/Scan_rate)+1
940           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a7r42C";Scan_no
950           OUTPUT Crt;CHR$(27)&"&a7r55C";" [ times ]"
960            !
970 In_21:    INPUT "LOAD RATIO = ? : [ (kg/cm2)/(volt) ]",Load
980           OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a8r42C";Load
990           OUTPUT Crt;CHR$(27)&"&a8r55C";" [ (kg/cm2)/(volt) ]"
1000          !
1010 In_22:   INPUT "DISPLACEMENT RATIO = ? : [ (mm)/(volt) ]",Displacement
1020          OUTPUT Crt USING "#,K,MZ.5DE";CHR$(27)&"&a9r42C";Displacement
1030          !
1040          OUTPUT Crt;CHR$(27)&"&a9r55C";" [ (mm)/(volt) ]"
1050 In2_:    INPUT "REMARKS = ? [ 160 character ]",Remarks$[1,160]
1060          OUTPUT Crt;CHR$(27)&"&a12r0C";Remarks$[1,80]
1070          OUTPUT Crt;CHR$(27)&"&a13r0C";Remarks$[81,160]
1080          !
1090 Check:   DISP RPT$("",1000)
1100          INPUT "CHANGE PARAMETER ? (Y/N)",Q$
1110               IF (Q$<>"Y") AND (Q$<>"N") THEN Check
1120               !
1130               IF Q$="Y" THEN In_rep
1140          !
1150          OUTPUT Crt;CHR$(27)&"&a10r19C";"DATA FILE CODE NAME  = "
1160          OUTPUT Crt;CHR$(27)&"&a15r0C";CHR$(27)&"1"
1170          File_size=Scan_no*Chan_no*4+256 ! 256 (byte) is Header size
1180          !
1190          RETURN
1200               !
1210 Disk_create:! ******************************
1220               ! * Subroutine DATA FILE CREATE *
1230               ! ******************************
1240               !
1250               BEEP
1260          DISP "SET DATA DISK TO FLEXIBLE DISK DRIVE : READY PRESS 'CONT'"
1270               PAUSE
```

```
1280                DISP
1290                !
1300            ON ERROR GOTO Create_error
1310            !
1320            OUTPUT Crt USING "#,B,A";27,"H",27,"J"
1330 Cat:       CAT #Print DIV 100,Print MOD 100;Msusd$
1340            !
1350 In3:       BEEP
1360            INPUT "DATA FILE CODE NAME = ? :[XXXXXX] (1 -- 6ch     ",File_na
me$[1,6]
1370                    IF TRIM$(File_name$)="" THEN In3
1380            !
1390            OUTPUT Crt USING "#,B,A";27,"H",27,"m"
1400            OUTPUT Crt;CHR$(27)&"&a10r45C";CHR$(27)&"K";File_name$
1410            OUTPUT Crt;CHR$(27)&"&a15r0C";CHR$(27)&"1";
1420            !
1430            DISP " NOW DATA FILE CREATING . WAIT JUST MOMENT  !!"
1440            Rec_no=File_size DIV 256+(File_size MOD 256<>0)
1450            CREATE File_name$[1,6]&Msusd$,Rec_no
1460            OFF ERROR
1470            !
1480            BEEP
1490            DISP "CREATE END !!"
1500            WAIT 1000
1510            GOTO D_c_ret
1520            !
1530 Create_error:!
1540            OFF ERROR
1550            BEEP
1560            IF (ERRN=63) OR (ERRN=64) OR (ERRN=20) THEN Over_flow
1570            DISP ERRM$;" :: READY PRESS  CONT ! "
1580            PAUSE
1590            GOTO Disk_create
1600            !
1610 Over_flow:!
1620            DISP RPT$("",1000)
1630            DISP " OVER FLOW  : No. of SCANNINGS is LARGER !!  PRESS  CON
T !"
1640            PAUSE
1650            Over_flow=1
1660            !
1670 D_c_ret:   RETURN
```