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ANNUAL REPORT

EFFECT OF TEMPERATURE ON COMPOSITE SANDWICH STRUCTURES SUBJECTED TO LOW VELOCITY IMPACT

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INTRODUCTION

The use of graphite/epoxy (G/E) composites and composites fabricated out of similar fibrous materials in the design of secondary components of aircraft is gaining momentum in recent years. These secondary structural components are generally designed with honeycomb core sandwiched between composite facings. In normal operational mode, these components may be exposed to foreign object damage such as the dropping of hand tools, runway debris, etc. Consequently, it is of interest to study impact related damage caused by foreign objects and develop design criteria in the use of composite sandwich structures. Researchers such as Slepetz [1]*, et al., Rhodes [2,3, 4], Awerbuch and Hahn [5] have conducted several studies on composites. These composites, besides G/E, include graphite/S-glass, boron/aluminum, borsic/titanium and other combinations. Different test procedures and specimen geometries have been used in the above studies. In particular, the studies of Rhodes are of interest and the findings of the present report are related to the earlier studies by Rhodes.

Rhodes in his studies has performed impact tests using G/E and Kevlar-49/epoxy sandwich specimens at room temperature. Some of these studies were published [3] and other results have been made available to the author through private communications. Visible damage-and failure thresholds have been developed. Preload and impact energy necessary to initiate catastrophic failure of specimens were determined.

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* Numbers refer to bibliography.

The impact velocity was in the range of 16-67 meters/second (52-220 ft/sec.). The residual strengths of specimens that survived the impact at a particular energy level were also measured.

The effect of moderately high-and low-temperatures on the strength carrying ability of composites under impact is reported here. Since the number of specimens tested was small, only few conclusions with regards to the existance of failure threshold and residual strength may be drawn. However, in conjunction with room temperature test results, some trends could be seen in the behavior of selected composites under impact damage.

SPECIMENS

The specimens were of sandwich beam type with a honeycomb core. The nominal dimensions of the specimen were 56 cm (22 in.)_long by 8 cm (3 in.) wide with a thickness of 2.5 cm (1 in.). The test face (front) was a laminate and the back of the honeycomb was supported by a steel plate. A view of the specimen is shown in Figure 1. A typical core, 8 cm (3 in.) by 8 cm (3 in.) with a thickness of 2.5 cm (1 in.), was located in the test area where uniform flexural stress was induced through a four-point beam bending apparatus. Since the two outer sections of the specimen were subjected to high shear stress, a dense aluminum core was used in these two sections.

Two types of composite sandwich beam specimens were tested. The details of these specimens are given below:

Face Sheet Material	No. of Plies	Lamina Orientation	Honeycomb Core in Impact Area
Narmco 5208 - T300	8	$(90, \pm 45, 0)_S$	Alum. 130 kg/m^3 (8.1 lbm/ft^3)
G-5208 - T300, K-5208 - Kevlar	6	$(0_K, 90_G, 0_G)_S$	Nomex 48 kg/m^3 (3.0 lbm/ft^3)

The 8 - ply specimen is designated as Graphite/Epoxy (G/E) and the 6 - ply specimen as Graphite-Kevlar/Epoxy (Hybrid). All the specimens were supplied by the Langley Research Center, NASA.

EQUIPMENT AND TESTS

The schematic of the equipment set-up is shown in Figure 1. The description and operation of the air gun to propel the projectile, an aluminum sphere having a diameter of 1.27 cm (0.5 in.) with a mass of 2.9 grams (0.0065 lbm), was given in [3]. The velocity of the projectile was measured with an electronic counter using start/stop diodes. The four-point beam bending apparatus was enclosed in a heating/cooling chamber. The description and schematics of chamber construction were reported in an earlier report [6]. The testing techniques such as the measurement of load, strain and velocity were described in a paper by Rhodes[3].

Testing at high or low temperatures was performed after attaining a steady temperature in the test chamber. Six temperature sensing probes - one at load cell, one on the surface of the specimen in the vicinity of impact zone, and four others at various points in the chamber volume - were used. A temperature control probe was located in the vicinity of the specimen. Initiation of actual testing (loading/impacting) took place after the predetermined surface temperature was reached. In general, two specimens at low temperatures were tested back to back whereas only one specimen was tested at a time at high temperatures. The average total heating/cooling times and the corresponding temperatures are given below:

	Heating	Cooling
Surface Temp:	366 ± 1° K (199°F)	223 ± 1°K (-59°F)
Ambient Temp:	369 ± 1° K (204°F)	216 ± 1°K (-71°F)
Temp. at load cell:	371 ± 1° K (208°F)	248 ± 1°K (-14°F)
Time to attain surface temp.	135 minutes	150 minutes

Trial runs were conducted prior to actual testing of specimens to assess the free expansion/contraction characteristics of the G/E beam as well as the four-point loading frame. The load cell was built into the loading frame. The absolute value of thermal strains (loading screw was not contacting the specimen) on the surface of a 12-ply G/E laminate was found to be less than 10^{-3}. Since thermal environment also creates deformations of the loading frame structure which in turn may induce thermal load on the specimen, it was decided to measure the temperature induced load on the load cell. It was found that this load was less than 7 kg (15 lb.). In actual testing of specimens these initial values were rebalanced to zero.

The following types of tests were performed:

	G/E	Hybrid
Heating:	Tension/Compression	Tension/Compression
Cooling:	Tension/Compression	Tension/Compression

RESULTS

In the testing of G/E and hybrid composite sandwich beams, approximately 5-8 specimens were tested for each case such as heating/tension, etc. Two to three specimens were used in the evaluation of ultimate strength and the balance of specimens were used to study the failure/non-failure mode under impact. Those specimens that survived the impact were subjected to further loading to calculate the residual strength.

Graphite/Epoxy Beams

Heating/Tension: The variation of normalized stresses and strains with respect to kinetic energy of impact is shown in Figures 2 and 3. The impact energy level, by design, was held almost constant. At an energy level between 1.2 joules and 1.5 joules (11 in-lb and 14 in-lb), two of the specimens survived the impact at a pre-stress level of 43% of the ultimate strength. The loading was continued to assess the residual strength of the above two specimens. It was found that they both failed at about 51% of the σ_u (ultimate strength). Another virgin (no preload) specimen failed at 50% of σ_u. It was noticed that a fourth specimen has failed by debonding at a stress level of 91% of σ_u. The term debonding is used here when there is a separation of either the laminate or steel back plate from the core. The strain values corresponding to the above stresses were found to be about 2% higher, i.e., at about 53% of ε_u (ultimate strain). An imaginary line representing the failure threshold has been drawn through these points based on the present data and the data by Rhodes, published [3] and unpublished.

Heating/Compression: Six specimens were tested in this series and the data for σ_u and ε_u against impact energy is shown in Figures 4 and 5. At an energy level of 1.5 joules (13.7 in-lbs), three specimens were impacted. The average pre-stress level for two specimens was around 57% of σ_u. These two specimens survived the impact having a residual strength of 67% of σ_u. The preload and residual strength for a third specimen were just about the same. The last specimen in this series failed catastrophically at higher preload and energy. The strains followed a similar pattern as in the case of heating/tension. The strains for the third specimen, refered above, were not as close as stresses between impact and residual strength evaluation stages.

Cooling/Tension: Seven specimens were tested in this series. The stress/strain variations with impact energy are shown in Figures 6 and 7. Even though the impact energy was not exactly the same, two of the specimens were pre-loaded to a stress level of 44% of σ_u. These did not fail and had an average residual strength of 50% of σ_u. One of the other specimens failed at 58% of σ_u even though the energy level was less than the two previous specimens. The values of strain at the level of residual strength was about 48% of ε_u. One of the specimens appeared to have failed by debonding but the absolute values of strains and stresses were in the range of values for ε_u and σ_u.

Cooling/Compression: The impact energy levels in this series of 6 specimens tested were higher. The variation of stress/strain with energy as shown in Figures 8 and 9 has the same pattern as in the case of heating/compression. However, the absolute value of σ_u in this case was about 69 MPa (10 ksi) higher than in the other case. The strains were also higher but this difference was of the order of 10^{-4}.

Kevlar-Graphite/Epoxy Hybrid Beams

Heating/Tension and Compression: Due to debonding of the specimens in this series, σ_u in both tension and compression tests were not measured. However, the hybrid specimens were able to withstand a stress level of 807 MPa (117 ksi) in tension and 276 MPa (40 ksi) in compression before they failed by debonding. The corresponding strain levels were 1% and 0.48%, respectively. Some of the specimens in this series were subjected to impact in tension. It was found that they were able to sustain a pre-load of 393 MPa (57 ksi) at 1.7 joules (15 in-lbs) of impact energy. The residual strength for these specimens was found to be around 490 MPa (71 ksi).

Cooling/Tension: Six hybrid specimens were tested in this series. The ultimate stress (σ_u) level was found to be 820 MPa (119 ksi) with a corresponding strain (ε_u) of 1%. The variation of stresses and strains with respect to energy of impact is shown in Figures 10 and 11. The residual strength of two specimens that survived the pre-load (43% of σ_u) impact was about 56% of σ_u. However, the corresponding values of strains were not proportional but higher (Figure 11). The failure threshold in this case was slightly less than 50% of σ_u.

Cooling/Compression: Nine specimens were tested in this series. The average value of σ_u was found to be 352 MPa (51 ksi) with a corresponding value of ε_u at 0.5%. As shown in Figures 12 and 13, the impact energy range is wide for this series. The width of failure threshold is also wide.

DISCUSSION & CONCLUSION

One of the objectives of these tests was to see the degradation of properties, if any, of composite sandwich beams at moderately high and low temperatures as compared to room temperature data reported by Rhodes ([3] and unpublished data). Consequently, it has been observed that:

1. Failure threshold can be established as a function of impact energy level.
2. The G/E specimens in heating/tension have a value of σ_u of 631 MPa (91.5 ksi) which is about 8% lower than the room temperature value of 686 MPa (99.5 ksi).
3. The G/E specimens have shown similar percentage drop of σ_u in heating/compression, 455 MPa v.s 563 MPa (66 ksi v.s 81.6 ksi), tests.
4. Although the ultimate strength, σ_u, in heating/tension, 631 MPa (91.5 Ksi) is higher than in heating/compression, 455 MPa (66 Ksi), the specimens in compression were able to withstand a higher percentage (57% vs 43% of σ_u) value of pre-impact loads. The residual strength of these specimens also was higher (67% vs 51%).
5. The ultimate strength of G/E specimens remained same in both cooling/heating (tension) tests.
6. Low impact energy would cause catastrophic failures at higher pre-load can be seen in Figure 6.
7. The ultimate strength in cooling/compression is about 68.9 MPa (10 ksi) higher than the corresponding value in heating/compression.

8. The ultimate strain values in heating/cooling were in the range of 0.9% to 1%. The strain values in cooling appeared to be slightly higher than those in heating with a difference of 0.1%.

9. The Kevlar-Graphite/Epoxy composites (called hybrids in this report) have failed by debonding in tests at high temperatures. This failure was attributed to improper fabrication procedures.

10. Eventhough debonding occured in heating, the ultimate strength values for hybrids in tension (heating/cooling) were found to be close. The corresponding strain values were also very close.

11. The ultimate strength in cooling/tension was found to be about 10% lower than that of the corresponding room temperture values whereas in cooling/compression, the difference was about 4%.

12. The failure threshold for hybrids in cooling/compression was found to be higher (60% of σ_u) than that in cooling/tension (50%).

Based on the limited amount of testing, it can be said that degradation of the strength of composites exists at moderately high/low temperatures over that of room temperature values. This degradation was found to be less than 10%.

RECOMMENDATIONS

As a result of the limited number of tests performed, some trends in the behavior of sandwich composites under thermo-mechanical loading and impact can be seen. However, it is desirable to have positive conclusions leading to design criteria. In view of this, it is recommended that:

1. Further testing be conducted to ascertain the strength degradation of composites under thermal environment;

2. Specimens be tested after they have been exposed to thermal cycles with a 12 hour duration of heating at constant temperature followed by cooling;

3. The variables such as impact velocity, preload levels be limited so that positive conclusions as to strength degradation may be drawn.

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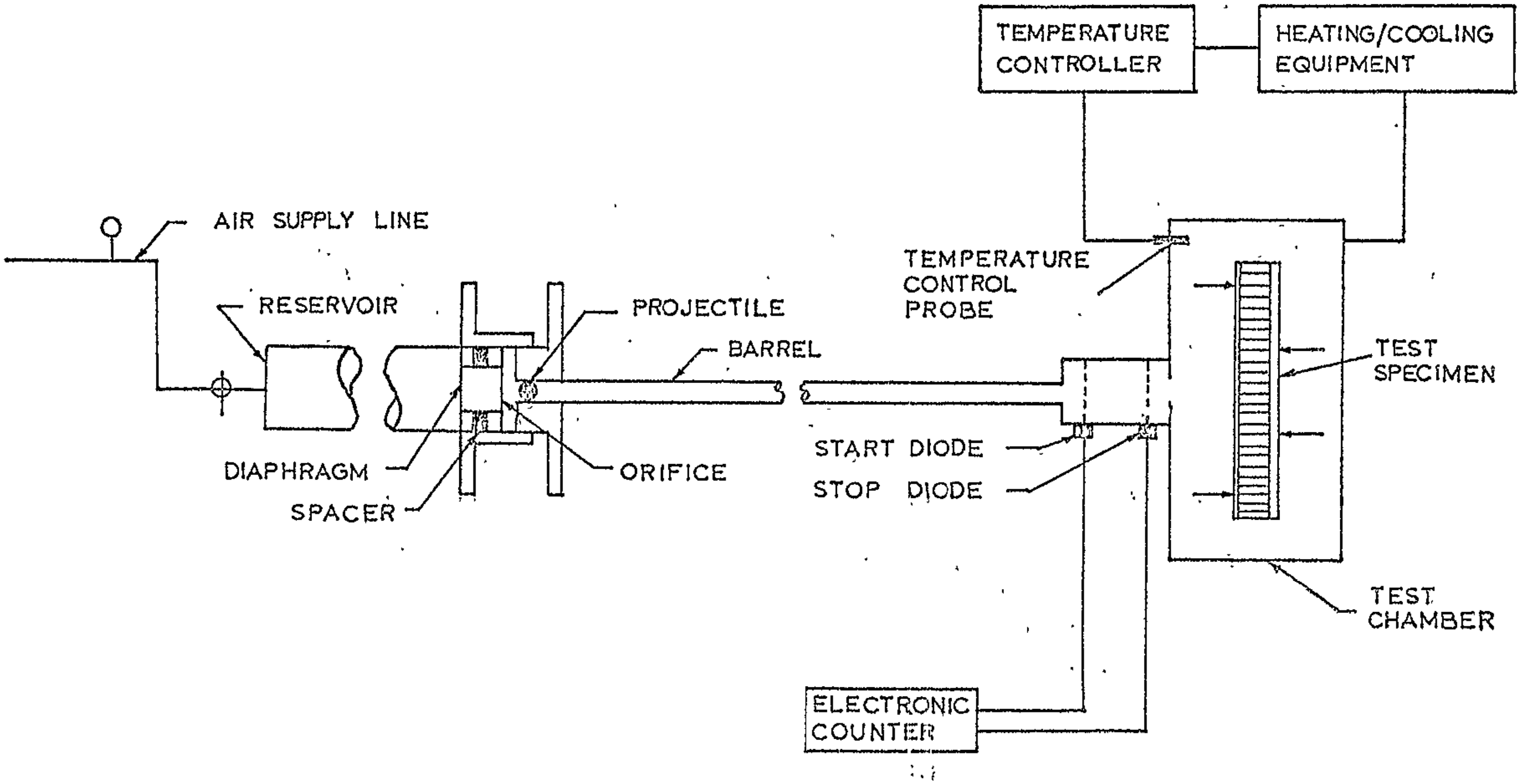


FIG. 1. SCHEMATIC OF EQUIPMENT SET-UP

$(90, \pm 45, 0)_5$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE : 366 ± 1°K

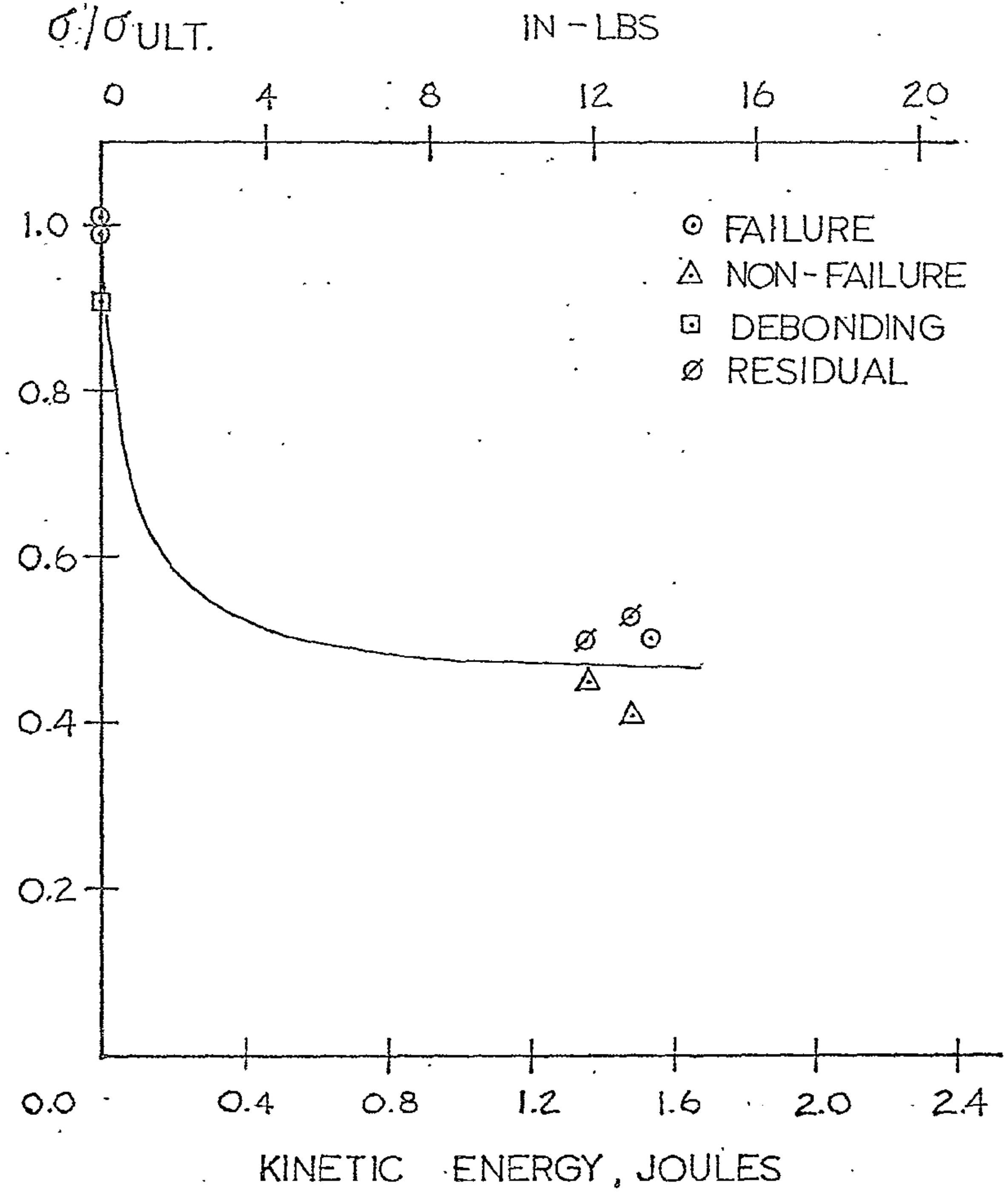


FIG 2. HIGH TEMPERATURE, TENSION

$(90, \pm 45, 0)_S$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE 366± 1° K

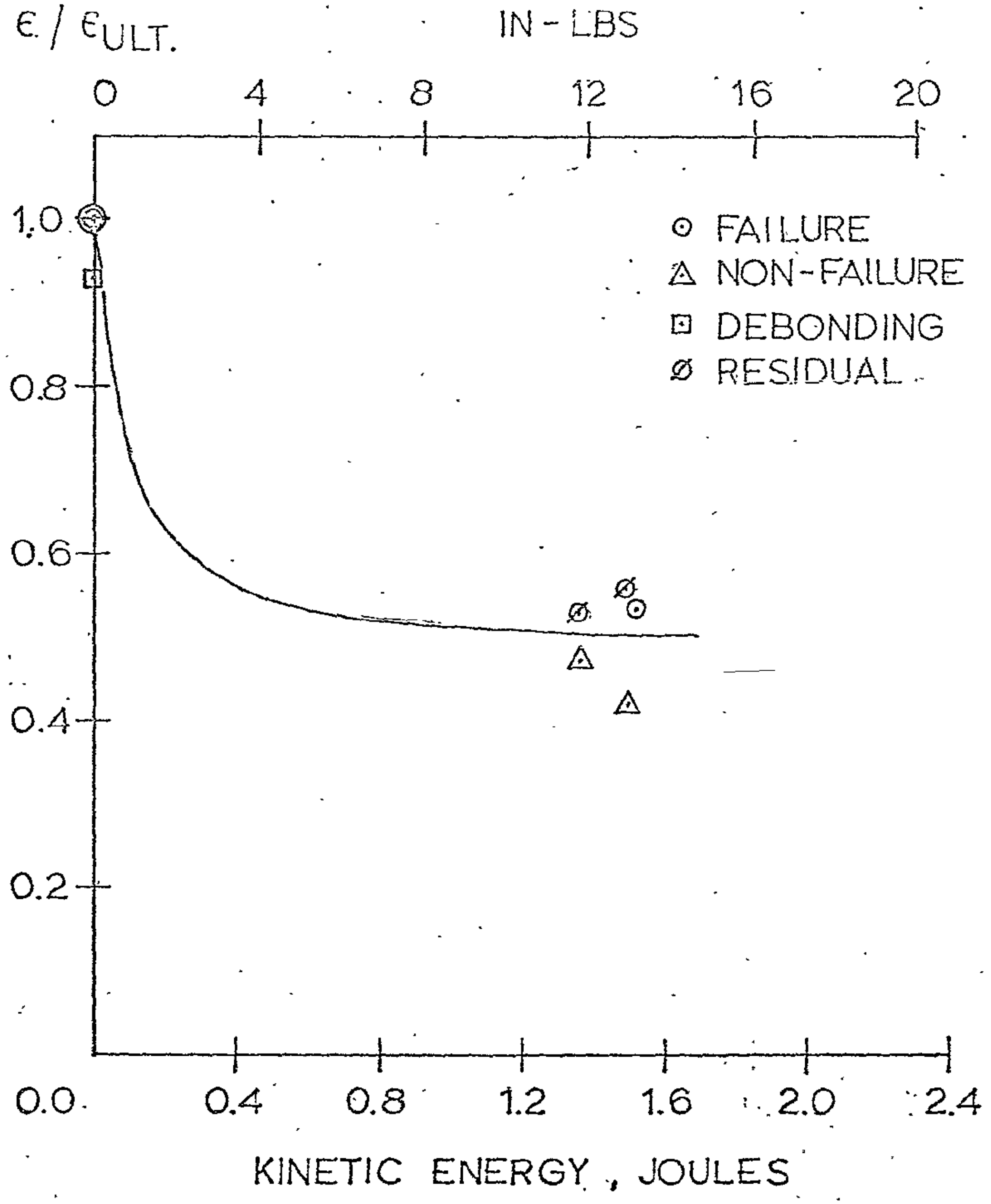
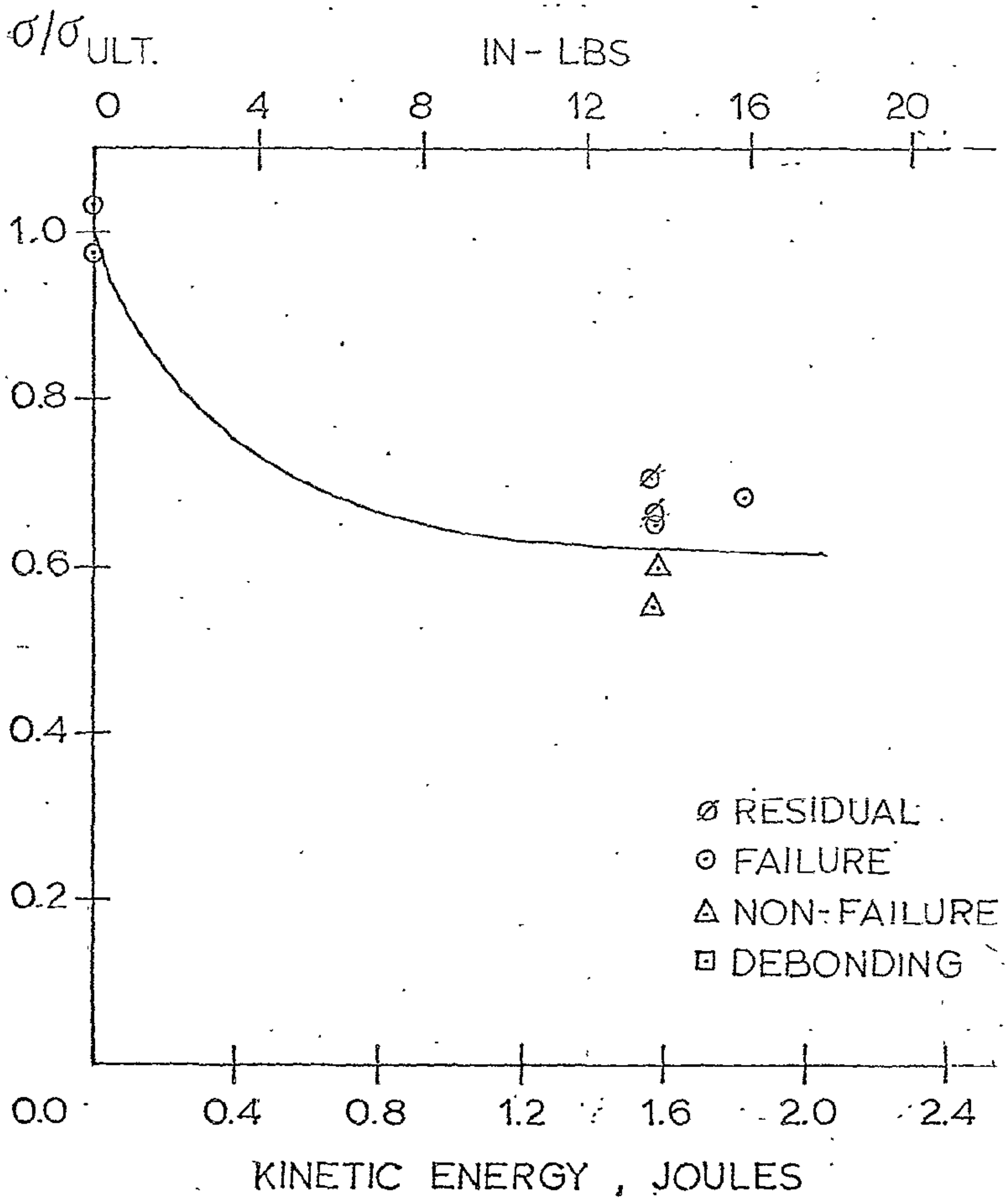


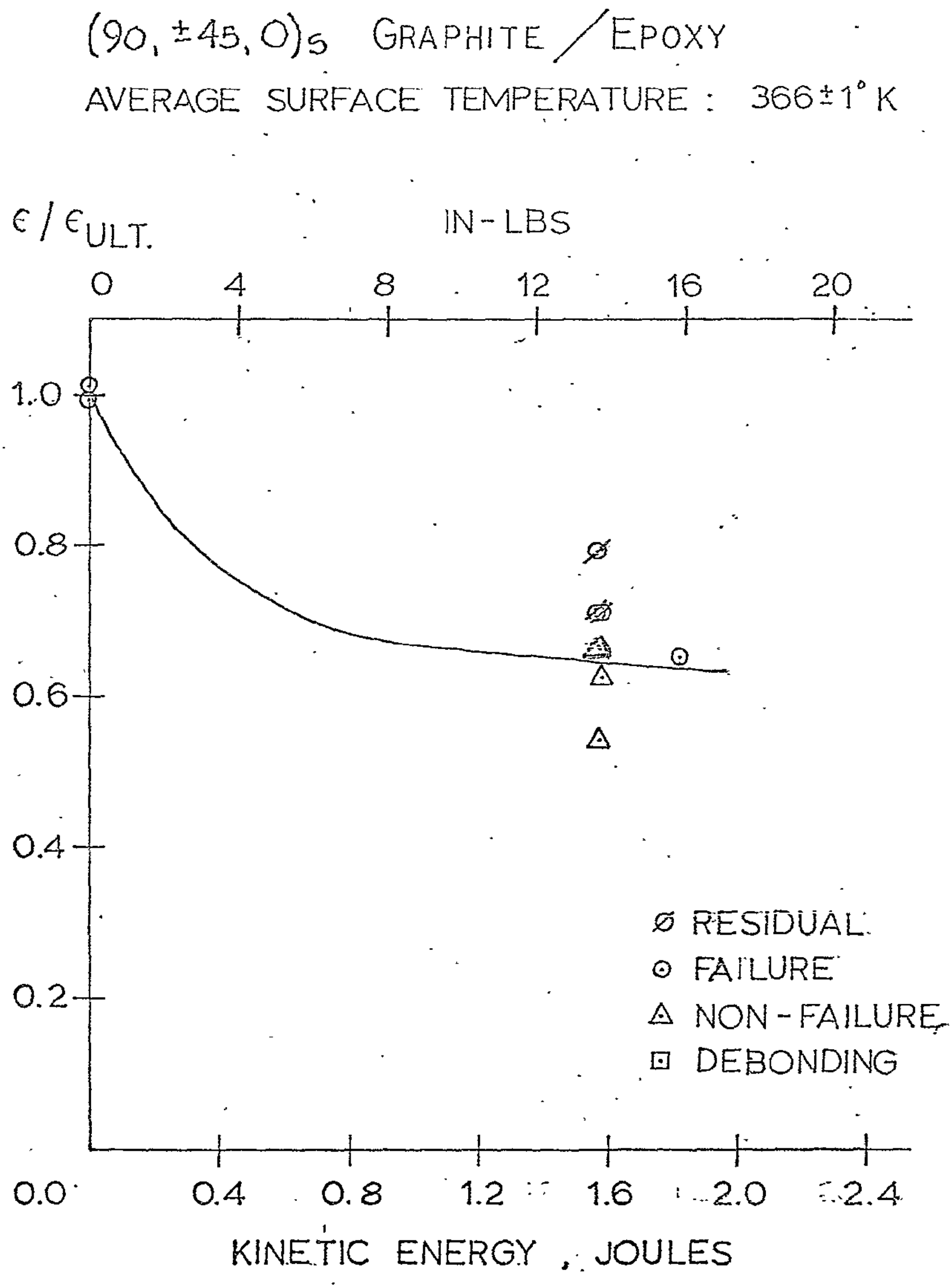
FIG 3. HIGH TEMPERATURE, TENSION



$(90, \pm 45, 0)_5$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE : 366 ± 1° K

FIG 4. HIGH TEMPERATURE, COMPRESSION



$(90, \pm 45, 0)_S$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE : 366±1° K

FIG 5. HIGH TEMPERATURE, COMPRESSION

$(90, \pm 45, 0)_s$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE 223 ± 1°K

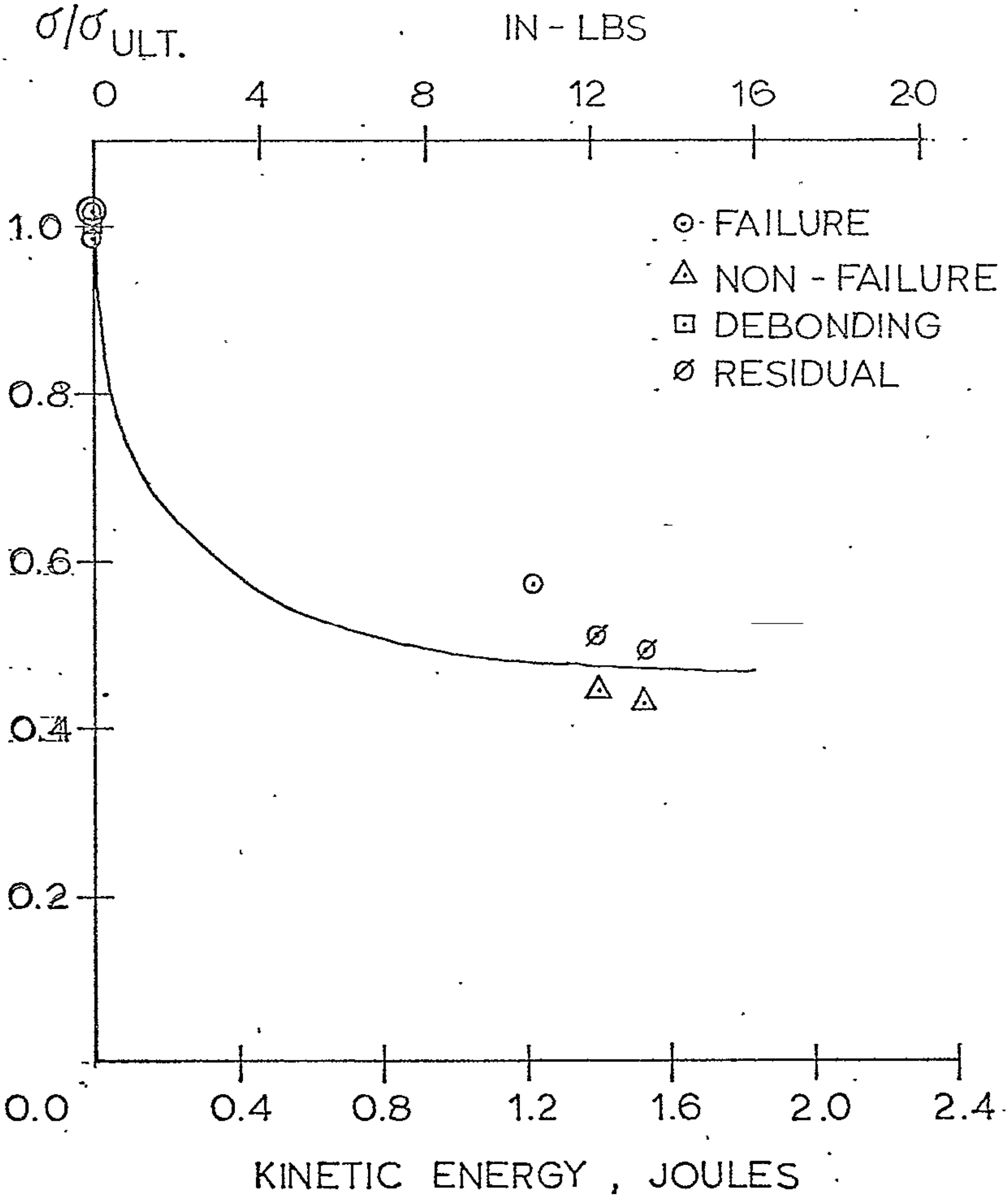


FIG. 6. LOW TEMPERATURE, TENSION

$(90, \pm 45, 0)_s$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE 223 ± 1° K

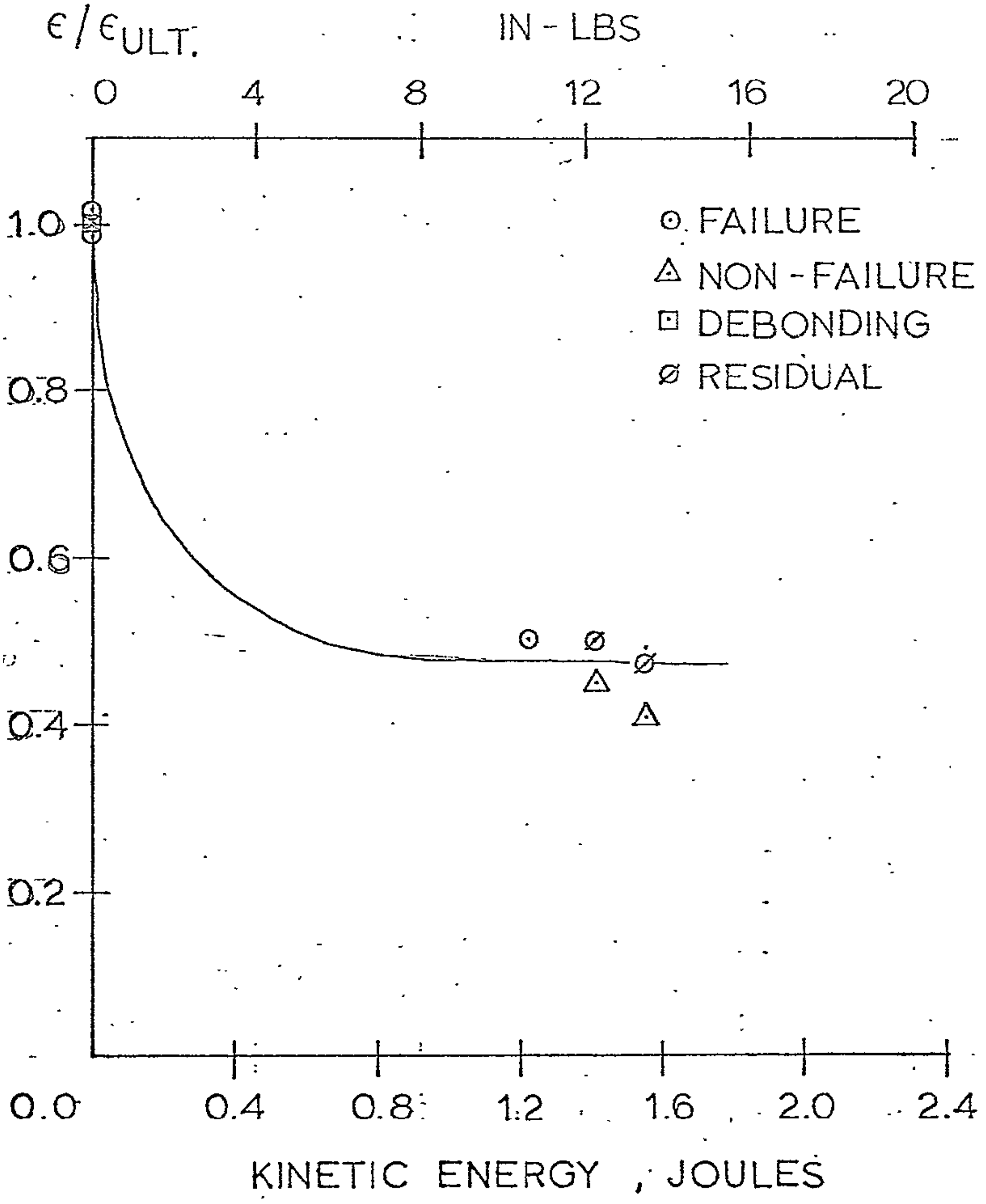


FIG. 7. LOW TEMPERATURE, TENSION.

$(90, \pm 45, 0)_S$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE 223 ± 1°K

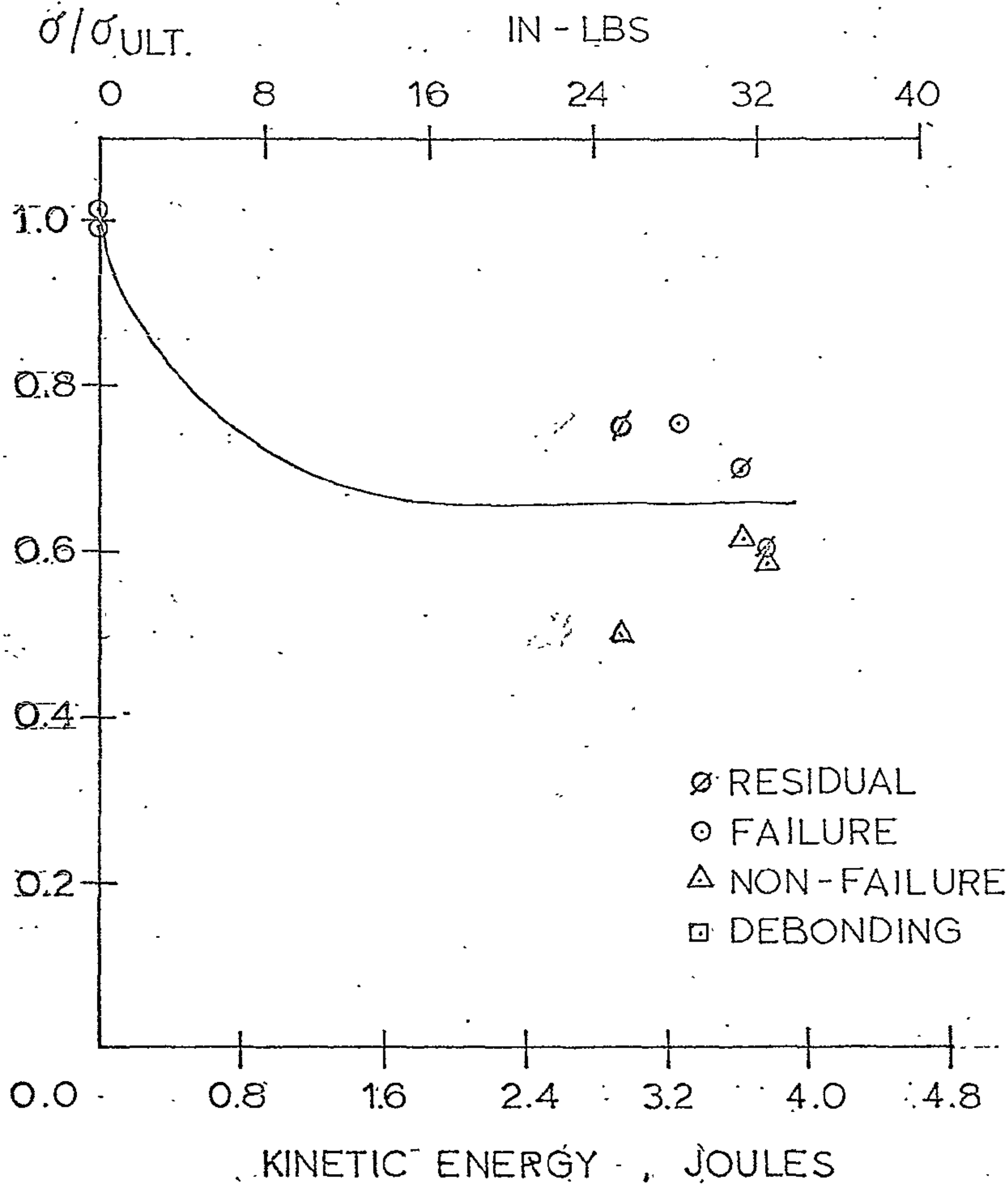


FIG. 8. LOW TEMPERATURE, COMPRESSION

$(90, \pm 45, 0)_s$ GRAPHITE / EPOXY

AVERAGE SURFACE TEMPERATURE 223 ± 1°K

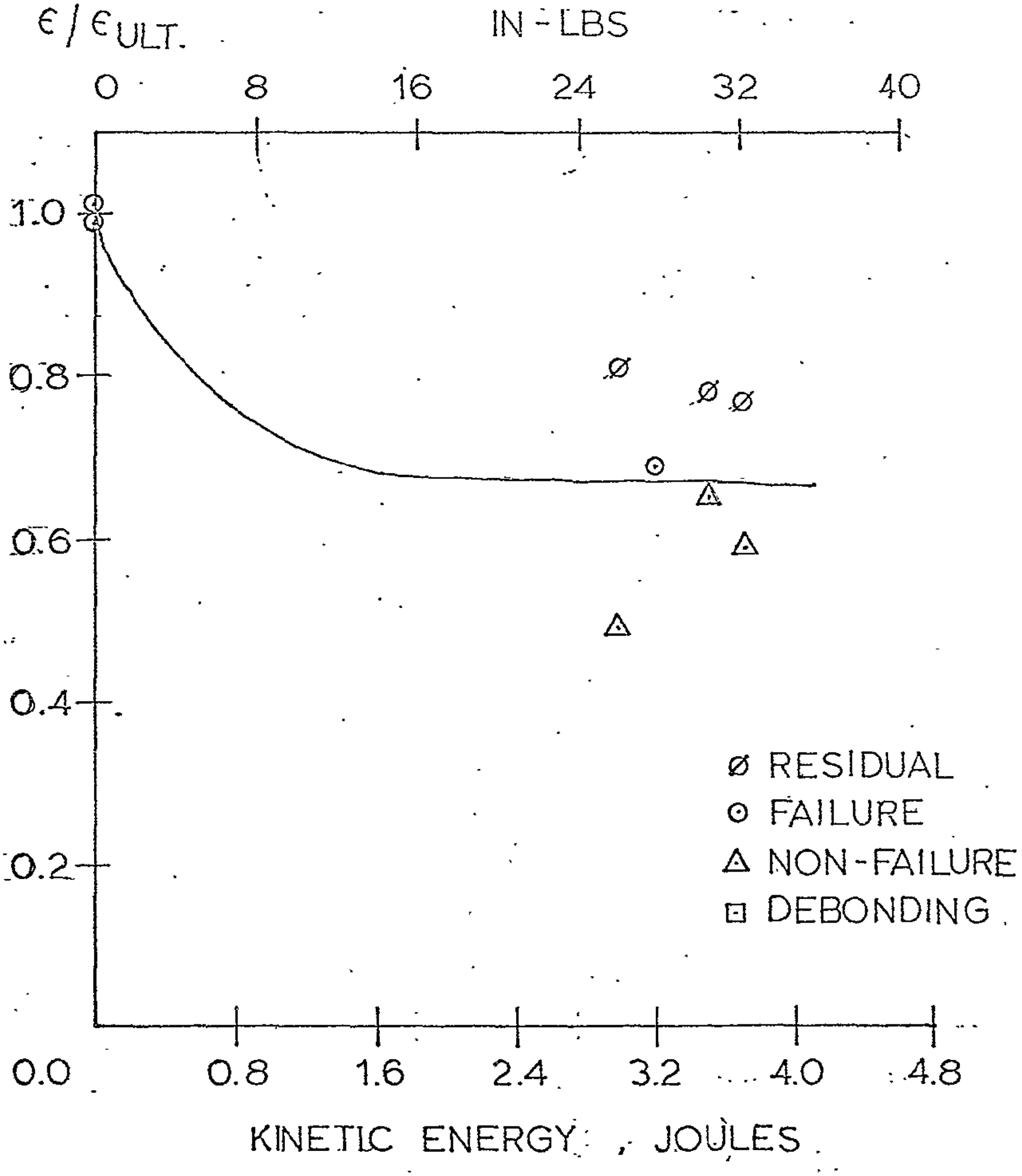
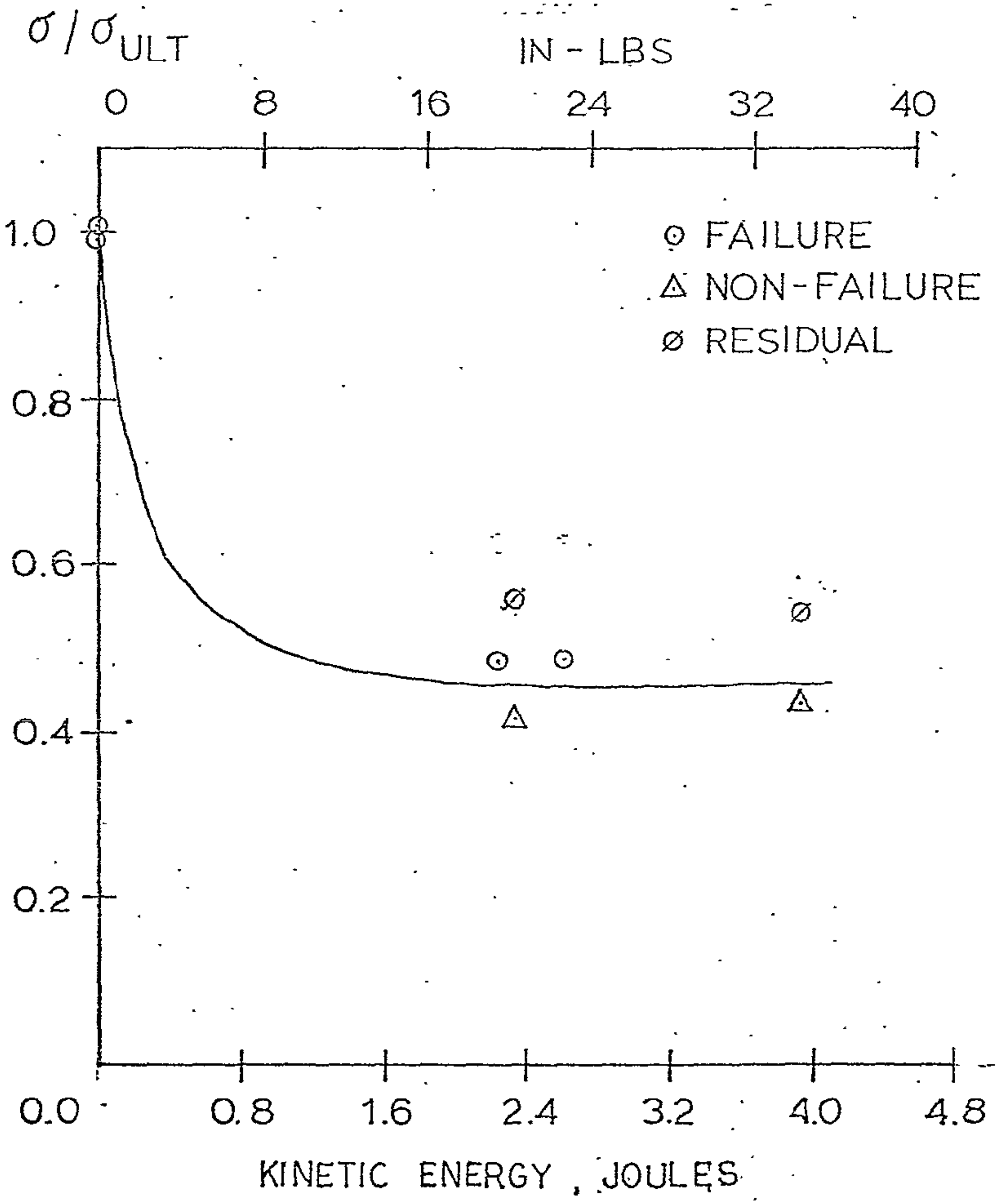


FIG 9. LOW TEMPERATURE, COMPRESSION



$(0_K, 90_G, 0_G)_5$ KEVLAR - GRAPHITE / HYBRID

AVERAGE SURFACE TEMPERATURE 223 ± 1° K

FIG 10. LOW TEMPERATURE, TENSION

$(0_K, 90_G, 0_G)_S$ KEVLAR-GRAPHITE/ HYBRID

AVERAGE SURFACE TEMPERATURE : 223 ± 1 K

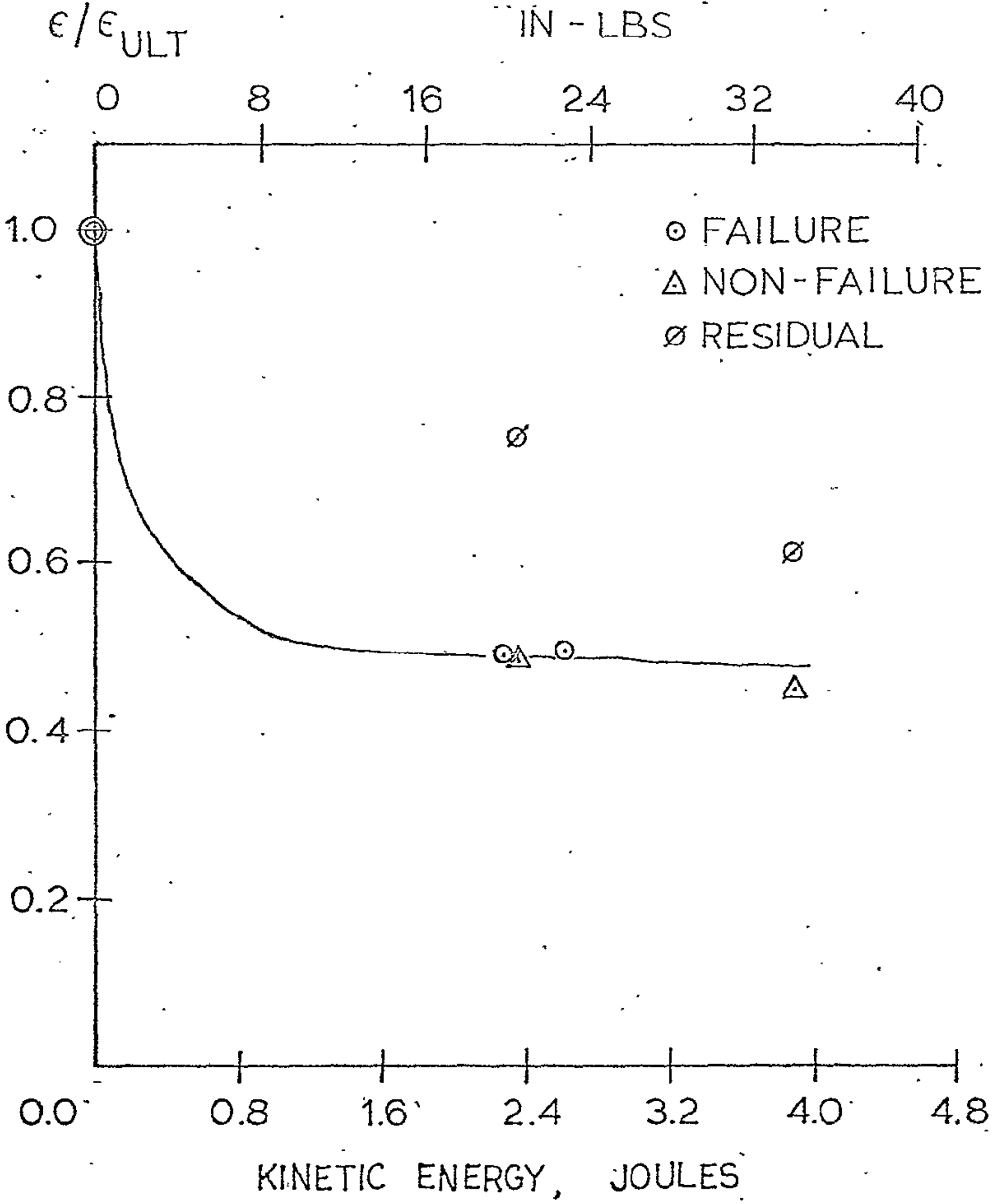


FIG 11. LOW TEMPERATURE, TENSION

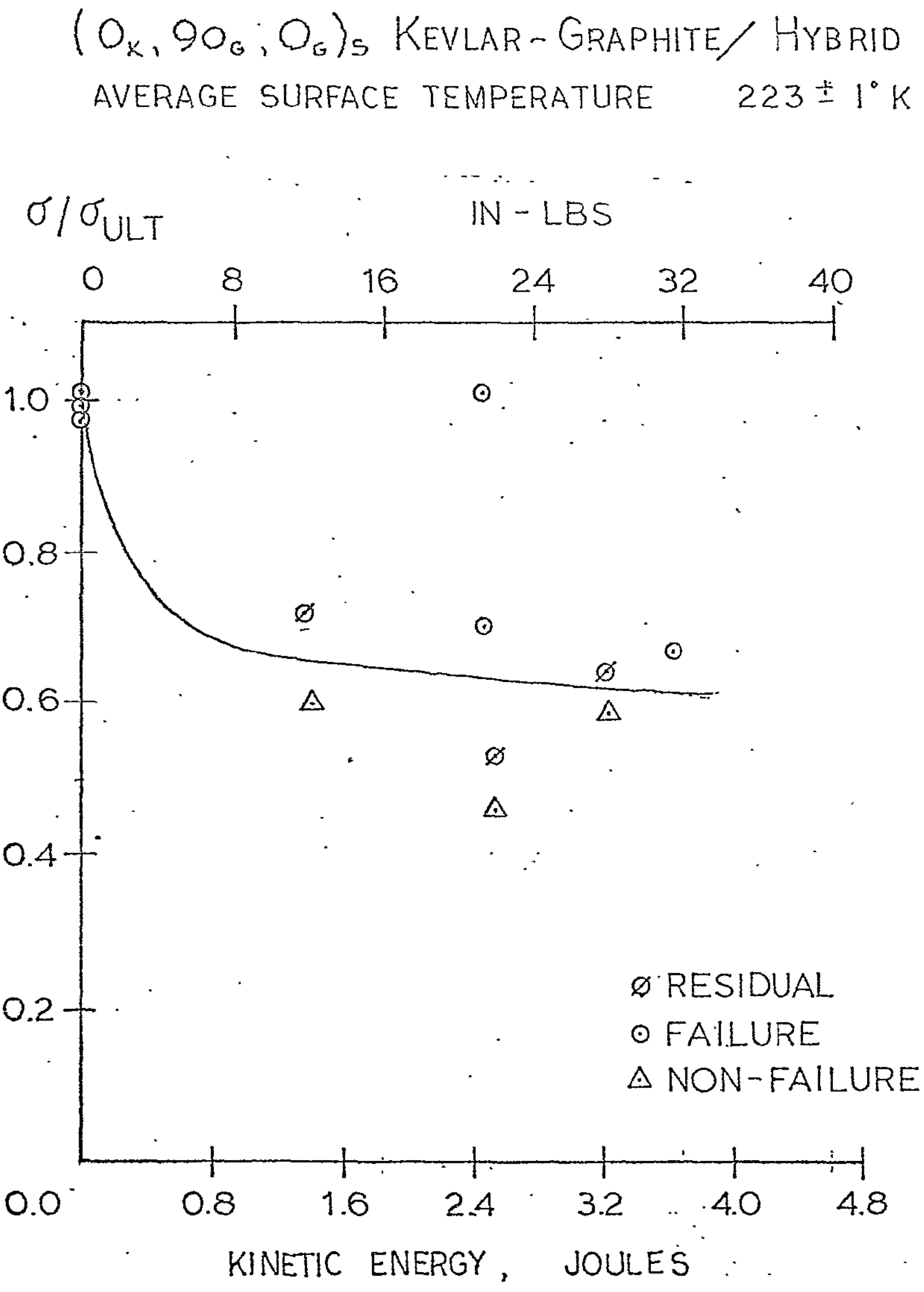
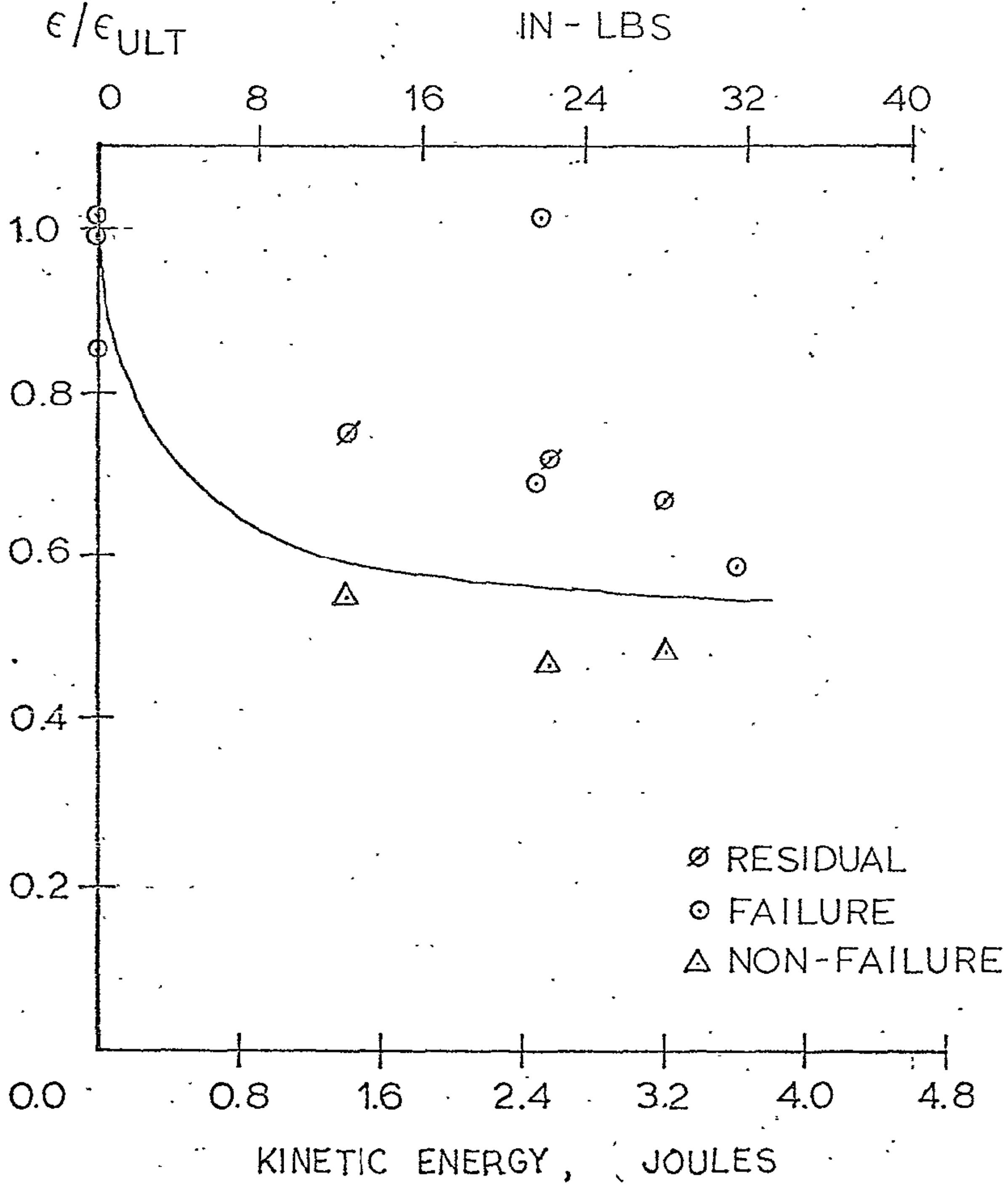


FIG. 12. LOW TEMPERATURE, COMPRESSION



$(0_K, 90_G, 0_G)_S$ KEVLAR - GRAPHITE/HYBRID

AVERAGE SURFACE TEMPERATURE 223 ± 1° K

FIG. 13. LOW TEMPERATURE, COMPRESSION