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Design of automotive structural components using high strength sheet steels

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First Progress Report

DESIGN OF AUTOMOTIVE STRUCTURAL COMPONENTS USING HIGH STRENGTH SHEET STEELS

by

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A Research Project Sponsored by American Iron and Steel Institute

January 1983

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I. INTRODUCTION

In recent years, automobile manufacturers have introduced new lines of lighter vehicles for the purpose of achieving fuel economy. To construct such vehicles, formable and weldable, high strength, sheet steels with yield points ranging up to 140 ksi have been used for parts and structural components.[1.1-1.7] Because various types of newer high strength sheet steels are now available for engineers to reduce car weight and because these steels permit the use of existing production equipment with virtually no change in techniques or production rates, the design criteria for efficient and economical use of these high strength steels in car bodies are going to be needed by engineers.

In February 1981, the "Guide for Preliminary Design of Sheet Steel Automotive Structural Components" was issued by American Iron and Steel Institute (AISI) for assisting automotive structural designers to achieve weight reductions through the efficient utilization of carbon and high strength steels.[1.8] These design recommendations were based primarily on the 1968 Edition of the AISI "Specification for the Design of Cold-Formed Steel Structural Members"[1.9] with the following major differences compared with the AISI Specification written for the design of buildings:[1.5,1.8]

a. The design expressions presented in the Guide are based on an ultimate strength basis.

b. Because the design expressions are sometimes simplified in the Guide, their range of applicability is restricted in some instances.

c. The design expressions are extended to materials with yield strengths up to 80 ksi.

In view of the fact that many types of high strength steels with yield points from 80 to 140 ksi can be economically used for automotive structural components, a comprehensive design guide for the use of a broader range of high strength sheet steels is highly desirable.

Since early 1982, a new research project entitled "Structural Design of Automotive Structural Components Using High Strength Sheet Steels" has been conducted at the University of Missouri-Rolla under the sponsorship of American Iron and Steel Institute. The main purpose of the project has been to determine the material characteristics of typical high strength sheet steels having yield points in the range of 80 to 140 ksi and to develop the design criteria for the cold-formed steel structural members using such high strength steels in automotive structures.

II. OBJECTIVE AND PLANNED PROGRAM

II. 1. Objective

The primary objective of the overall project was to develop the criteria needed for the design of automotive structural components that require high strength sheet steels having yield points up to 140 ksi.

In order to achieve the above objective, the following three phases were planned for the project:

I. Preliminary Study
II. Structural Research
III. Development of the Design Criteria

This report deals only with Phase I of the study, the objectives of which were as follows:

A. Establish the mechanical properties and representative stress-strain relationships of high strength sheet steels having yield points from 80 to 140 ksi.

B. Study the applicability of the AISI Specifications[2.1,2.2] for the design of automotive structural components that require high strength sheet steels having yield points up to 140 ksi.

C. Recommend needed structural research for improvement of the AISI preliminary Guide[1.8] and development of new design criteria.

II. 2. Planned Program

To achieve the objectives outlined in Article II.1 for the preliminary study, the research work was carried out in the following four areas:

- Review of literature on automotive structures
- Experimental investigation
- Review of AISI Specifications
- Recommendations on the needed structural research

All these tasks are briefly discussed in this article. For details, see Chapters III through VI.

A. Review of Literature on Automotive Structures

Before developing the design criteria for automotive structural components, it is important for a designer to be familiar with the types of structures, the design loads, the methods used for structural analysis, and the design practices used in the automotive industry. Chapter III presents a review of the literature on these subjects.

B. Experimental Investigation

In the past, cold-formed steel structural members used for buildings were usually fabricated from steel sheets or strip having yield points in the 25 to 65 ksi range. Many design formulas were derived from the experimental data obtained from relatively low strength material. Because material properties always play an important role in the design of structural members, it is necessary to establish the representative mechanical properties and stress-strain relationships of the high strength steels used for automotive components. Details on the tensile and compressive tests and the test results are presented in Chapter IV.

C. Review of AISI Specifications

Until now two AISI Specifications[2.1,2.2] and one Guide[1.8] have been issued for the design of cold-formed structural members and connections. The tentative recommendations on load and resistance factor design of cold-formed steel have recently been proposed for consideration.[2.3] These documents have been carefully reviewed, particularly for the applicability of the available design formulas for car bodies and the new criteria needed for the use of high strength steel sheets. Chapter V presents the results of the review.

D. Recommendations on the Needed Structural Research

Following a review of the available design criteria and an experimental investigation of material properties, the necessary design criteria were identified. Consequently, the types of structural research needed for the development of new criteria and for the improvement of the existing design methods are recommended in Chapter VI.

III. REVIEW OF LITERATURE ON AUTOMOTIVE STRUCTURES

III. 1. General

The design of automotive structures requires a combination of skills in art, science, and engineering. Even though car bodies can be successfully designed according to a designer's experience and full-scale tests, the economic design of the structural components and the entire structure of the vehicles is often based on the designer's knowledge of the following subjects:

- selection of materials
- material properties
- static and dynamic design loads
- structural function of various components and entire structural system
- techniques used for structural analysis
- criteria for the design of structural components
- method of manufacture and assembly

In order to prepare a comprehensive design specification for using high strength sheet steels in car bodies, it is necessary to review the literature relative to the above mentioned subjects. For this reason, the various publications on materials, design loads, structural analysis, and design of automotive structures are reviewed in this chapter. A detailed review of the design specifications published by American Iron and Steel Institute is given in Chapter V.

III. 2. Materials

In recent years, high strength sheet steels with yield strengths ranging from 35 to 140 ksi have been available for car bodies, building products, various types of equipment, and other items. The AISI publication entitled "High Strength Sheet Steel Source Guide"[1.3] lists most of the high strength sheet steels commercially available in 1982 from North American steel producers. This publication contains a list of 61 different high strength steels that are classified to the AISI Designation System, which designates their strength levels, chemical compositions, and deoxidation practices. For manufacturing practices and related scientific and technical information, the reader is referred to the AISI Products Manual on Sheet Steels.[3.1]

In the selection of materials, consideration is usually given to the weight-cost relationship, design factors (yield strength, tensile strength, ductility, stiffness, dent resistance, energy absorption, fatigue strength, and corrosion) fabrication factors (formability and weldability), and such factors as plant finishing and body repairs. These design considerations are discussed in Refs. 1.1, 1.2, 1.4, and 1.6.

With regard to fatigue design, the state-of-the-art on fatigue behavior of sheet steels for automotive applications has been well summarized by Barsom, Klippstein, and Shoemaker in a report published by American Iron and Steel Institute in 1980.[3.2] This report has been condensed in an AISI publication on sheet steel properties and fatigue design.[3.3] Presently, the fatigue properties of hot-rolled sheet steels and the fatigue behavior of steels in corrosive environments are being studied at United States Steel

Corporation and Bethlehem Steel Corporation, respectively.

It has long been known that the mechanical properties of cold-formed sections are sometimes substantially different from those of steel sheet before forming. The cold-forming operation usually increases the yield strength and tensile strength and at the same time decreases the ductility. For the design of building products, the influence of cold-work on the mechanical properties of steel was investigated extensively by Winter, Karren, Chajes, Britvec, and Uribe at Cornell University.[3.5-3.8] Based on their findings, design equations for computing the yield strength of corners and other related provisions were added to the AISI Specification in 1968. This investigation was supplemented by some additional studies in the 1970s.[3.9-3.12] In Canada, this subject was studied by Lind and Schroff.[3.13,3.14] Recently, investigators have considered residual stress distributions in the cold-formed sections.[3.15-3.17]

For automotive structural components using steel sheets, Tang and Beardmore recently made a computer study of sheet steels and pre-strain effects on bumper damageability.[3.18] The effects of direction of loading and forming on the yield strength of sheet steels are being studied by Hosford at the University of Michigan.[3.4] The objective of his study is to obtain a set of equations to represent stress flow resulting from varying amounts of biaxial deformation caused during forming operations. In addition, the Task Group on Structural Research of the Transportation Department of the AISI Committee of Sheet Steel Producers recently conducted several seminars and conferences for the automobile industry to review the needed research on steel as a material for automotive structures. It was the Group's intention to develop needed information about sheet steels so that users can optimize their material selection and take advantage of modern design techniques. Reference 3.19 contains a comprehensive list of the various tasks involved in the research work.

III. 3. Design Loads

Automotive structures and their components are usually subjected to (a) static load, (b) dynamic and repeated load, and (c) impact. In the design of such structural components, due consideration should be given to strength, stiffness, and energy absorption capacity of the member.

The normal service loading and the safety criteria to be used for the design of automotive structures are well-summarized in several recently published books and research reports.[3.20-3.22] In Reference 3.22, Monasa indicated that under normal service, static, and dynamic loading conditions, the structural members in both the passenger compartment and the chassis members are not highly stressed. He found that under severe dynamic loading induced by road conditions, the member stresses are greater than those obtained through normal operating conditions. Consequently, vehicle structure design for maximum dynamic loads should have adequate fatique resistance.

For detailed information on impact design criteria, the reader is referred to References 3.20 and 3.22 and the Federal Motor Vehicle Safety Standards.[3.23]

III. 4. Structural Analysis

During recent years, computer analysis of automotive structures has often been used for the design of vehicles. Numerous technical papers and research reports concerning the application and development of modern techniques have been presented at various meetings and published in many conference proceedings.[3.24-3.35]

Recently, several books on automotive structural analysis have been published in the United States and abroad.[3.20,3.21] In Reference 3.20, following a historical review of the evolution of the automobile and its structure, the authors discuss structural design criteria and the methods for modeling and analyzing vehicle structures and components. They also include a chapter on structural design optimization wherein the most recent developments and applications of the computer are used for vehicle structural analysis. More than 300 references are cited in this comprehensive book.

The engineering analysis of the structural integrity of buses has been studied by Monasa.[3.22] He used some of the AISI design formulas to predict the ultimate moments of thin-walled sections. The research findings obtained from his study were discussed at two recent engineering conferences.[3.36,3.37]

III. 5. Structural Design

As discussed in References 3.20 through 3.22 and many other technical papers, the configurations of structural components used in automotive structures are more complicated than those used in buildings. In addition, composite sections are often used in car bodies. Figure 3.1 shows some individual members and built-up sections generally used in various parts of automobiles.[3.20-3.22]

Prior to 1981, there were no specific criteria issued for the design of sheet steel, automotive structural components. The designs for car bodies in which high strength sheet steels are to be used have been primarily based on engineering experience and the test results of either structural members or assemblies. In several southern states, bus bodies have been designed according to the AISI Specification, which was originally prepared for the design of buildings but with a reduced yield point of steel to account for the fatique strength of the material.

Because of a lack of design information and the availability of relatively new high strength sheet steels with various strength levels, it has become evident that the development of a new design specification for automotive structures is highly desirable not only because the performance of cold-formed automotive structural components made of such high strength materials may differ from that of building products fabricated from relatively low strength sheet steels but also because the type of design loads and other safety requirements for automotive components differ in many ways from those of building structures. Therefore, in 1981, the American Iron and Steel Institute published a "Guide for Preliminary Design of Sheet Steel Automotive Structural Components"[1.8] to assist automotive structural designers to achieve weight and cost reductions of structural members through the economical use of carbon and high strength sheet steels.[1.5] However the design rules provided in this AISI Specification can only be used for structural members cold-formed from sheet steels having a yield point up to 80 ksi.

For the design of connections, the current AISI Specification[1.8] contains only limited information on connectors in compression elements. It does not include specific design criteria for welds, bolts, screws, adhesives, and other items.

With regard to welded connections, Dickinson's comprehensive report entitled "Welding in the Automotive Industry"[3.38] presents detailed information on spot welding, flash welding, DC butt welding, and other welding processes. The subject of spot welding is well summarized in an AISI publication.[3.39] Additional information on the welding of sheet steel can be found in Refs. 3.40 through 3.44.

When mechanical fasteners are used in structural joints of car bodies, the design loads for a given type of fastener are usually developed by either the car manufacturers or the manufacturers of the fasteners. For the design of buildings using cold-formed steel members, the AISI Specification at the present time (1982) provides design requirements for bolted connections but no specific information for screws. Because various types of screws have been successfully used in cold-formed steel structures, the strength of screwed connections have been studied by several researchers.[3.45-3.50] Consequently, design formulas have been developed from the test data.[3.51]

As far as the use of adhesives is concerned, a handbook entitled "Production Design Guide for Adhesive Bonding of Sheet Steel" contains information on the adhesive selection, joint design, inspection, and selected applications of bonded carbon-steel sheet materials in automotive structures.[3.52]

IV. EXPERIMENTAL INVESTIGATION

IV. 1. Materials

There are a number of high strength sheet steels available for automotive structural components.[1.3] Six different sheet steels were selected by members of the AISI Task Force on Structural Research of the Transportation Department for establishing representative mechanical properties and stress-strain curves. These materials include hot-rolled and cold-rolled sheet steels having yield strengths from 80 to 140 ksi.

All six types of sheet steels used in this phase of the program are listed in Table 4.1. In the first column of the table, the AISI designation system is used to identify the grade of steel. This designation system has the following three basic components:[1.3]

- yield strength in ksi
- chemical composition classification designated by the letters S, X, and D, which are defined as follows:

    S = structural quality

    X = low alloy

    D = dual phase
- classification for the deoxidation practice designated by the letters F and K, which are defined as follows:

    F = killed plus sulfide inclusion control

    K = killed

Additional information on the AISI designation system can be found in Ref. 1.3.

Table 4.2 presents the chemical composition of the sheet steels used in Phase I of the program. These data are based on the test reports received from steel producers.

From the view points of the formability and weldability of sheet steels, the AISI Source Guide[1.3] includes the following product descriptions for the sheet steels designated as SK, XF, DF, and DK in Tables 4.1 and 4.2:

Structural Quality (SK)- One major advantage of structural quality sheet steels is their generally lower cost compared to other high strength grades. Although the formability of structural quality high strength grades is reasonably good, they generally do not form as easily as most low carbon steels. Similarly, these high strength grades usually do not form as easily as most microalloyed sheet steels of the same strength level.

When formed, structural quality grades containing nitrogen additionally have a particularly pronounced strain-aging effect and frequently are specified by users for this characteristic. It is important to note, however, that this hardening effect occurs only where sufficient strain is induced during the forming operation.

Structural quality high strength sheet steel grades are readily weldable with conventional equipment used in joining low carbon sheet steel. Some welding practice modifications, however, are required for certain grades, and individual steel producers should be consulted regarding the need of such modifications.

Low Alloy (XF)- The inclusion control, low alloy grades are frequently referred to as "better forming" steels. This is because the sulfides present are reduced in volume or their shape is modified to allow more severe forming. The X grades exhibit good weldability when conventional equipment is used, but some welding practice adjustments may be required. Producers should be consulted for specific suggestions regarding these grades.

Dual Phase (DF, DK)- In many applications, dual phase steels are more formable and provide greater work hardening characteristics than low alloy steels of comparable strength. In this respect, the 80DF grade may exhibit better formability than the 80XF grade. In certain applications, dual phase steels may permit production of more intricately shaped parts than can be made satisfactorily with other high strength grades. The work hardening effect in dual phase steels occurs only where sufficient strain is induced during manufacture of the part. The weldability of these products is generally similar to low alloy grades.

IV. 2. Material Properties

A. Types of Coupon Tests

During the experimental examination, the mechanical properties and stress-strain curves were developed from tension and compression coupon tests in both longitudinal and transverse directions. The tension and compression coupons were taken from the quarter points of the width as shown in Fig. 4.1. In this figure, four types of coupons are designated:

LT - longitudinal tension

LC - longitudinal compression

TT - transverse tension

TC - transverse compression

The actual dimensions and shapes of the various coupons are discussed in the following paragraphs.

a. Tension Coupons

All tension coupons used for longitudinal and transverse directions were prepared in the Machine Shop of the University of Missouri-Rolla. These specimens were machined according to the dimensions and shapes specified in Standard Methods of Tension Testing of Metallic Materials, ASTM E8.[4.1] The 1/2 in. wide tension coupons shown in Fig. 4.2 were used for all types of sheet steels except for 140 XF steel. For the latter, the radius of the fillet was increased from 3/4 in. to 1-1/2 in. In addition, a gradual taper in width from the ends to the center was used, but the width at either end was not more than 0.005 in. greater than the width at the center.

b. Compression Coupons

The compression coupons were machined for testing in a Montgomery-Templin compression test fixture. The specimens were 5/8 in. wide and 2.68 in. long. Along one edge, two notches were made for installation of the compressometer. The dimensions of the compression coupons are shown in Fig. 4.3.

B. Test Procedure

a. Tension Tests

The tension specimens (Fig. 4.2) were tested in a 120,000 pound Tinius Olsen universal testing machine located in the UMR Engineering Research Laboratory. As shown in Fig. 4.4, the machine was connected to a data acquisition system (Fig. 4.5), a graphic display terminal (Fig. 4.6), an XY Plotter (Fig. 4.7), and a strain rate monitor (Fig. 4.8). The procedure used for testing was based on the ASTM Standard Methods of Tensile Testing of Metallic Materials.[4.1]

Prior to testing, the dimensions of the test specimens were measured and recorded to the nearest 0.001 in. Gage marks for a 2-in. gage length were drawn with ink.

To ensure an axial tensile stress within the gage length, the specimen was placed in the wedge grips in such a manner that its centerline coincided with the center line of the heads of the testing machine. In order to obtain a complete stress-strain curve of the material, a Tinius Olsen extensometer (Fig. 4.9) was used for the test. This extensometer made it possible to record the strain up to failure of the specimen.

During the tests, the load was applied at a strain rate of 0.003 in./in./min. in the initial stage. The stress-strain curve was simultaneously plotted on the graphic display terminal and drawn on the XY plotter. The corresponding stress and strain readings were recorded by a computer. With the aid of a selected scale, these data were used at a later time to plot the stress-strain curve. After the total strain reached the yield strain, the strain rate was increased to 0.03 in./in./min. This procedure was used until the completion of test. Figure 4.10 shows the failure of a tension specimen.

By employing the same procedure described above, four tension specimens were tested for longitudinal and transverse directions of each sheet steel. The results of the tests are presented and evaluated in Article VI. 2.C.

b. Compression Tests

Since 1940, the importance of the compressive properties of sheet materials has received increasing recognition. For compression tests, the types of compression jigs used by Montogomery and Templin, NACA, Moore and McDonald, LaTour and Wolford, Miller, and Sandorff and Dillon are summarized in the ASTM Standard Methods of Compression Testing of Metallic Materials at Room Temperature.[4.2] In Ref. 4.3, LaTour and Wolford discussed the development of a compression jig used for their tests of sheet material having yield strengths of 180 ksi and even greater. For stainless steels, which exhibit a considerable anistropy, a large number of compression tests have been conducted by Johnson[4.4] and Wang[4.5] for studying the structural performance of stainless steel members and for developing a new design specification[2.2].

In the present experimental program, the compression specimens (Fig. 4.3) were tested in the same 120,000 pound Tinius Olsen universal testing machine used for the tension tests except that a specially made subpress and the Montgomery-Templin Compression Jig manufactured by SATEC Systems were used as shown in Figs. 4.11 and 4.12. The test procedure was based on the ASTM Designation E9.[4.2]

Prior to testing, the dimensions of the test specimens were measured and recorded to the nearest 0.001 in. Each notched specimen was cleaned with acetone and placed in the Montgomery-Templin Compression Jig (Item B in Fig. 4.13) with the notched edge facing the compressometer attachment fixture. The PC-5M compressometer made by SATEC Systems (Item C in Fig. 4.13) was then attached to the specimen. For this, a 1-in. gage length with a Microformer at the bottom was used as shown in Fig. 4.14. Care was taken to see that the knife edges in the compressometer coincided with the notches in the specimen. Finally, the compression jig with the compressometer assembled to it was placed on the hardened steel base plate of the compression subpress, which held the specimen, so that the compressive load could be applied axially and uniformly to the specimen.

For the compression tests, the load was applied at a strain rate of 0.003 in./in./min. throughout the course of the tests. The stress-strain curve was plotted simultaeously on the graphic display terminal and on the XY plotter. The stress and strain readings were recorded by a computer. During the test, the compression jig provided lateral support through a series of rollers to prevent buckling of the thin specimen without interfering with the axial deformation. The test was terminated when the total strain reached about 0.015 in./in..

By using the test procedure described above, four compression specimens were tested for longitudinal and traverse directions of each type of sheet steel. The results of the tests are presented and evaluated in Article IV. 2.C.

C. Results of Tests

a. Stress-Strain Curves

Based on the stress and strain readings obtained from the coupon tests, a computer was used to plot the individual stress-strain curves for the different types of tests. In Figs. 4.15 through 4.18, four individual stress-strain curves are shown in each figure for the 80SK sheet steel subjected to longitudinal tension (LT), transverse tension (TT), longitudinal compression (LC), and transverse compression (TC), respectively.

The representative curves shown in Figs. 4.19 through 4.22 were prepared from the original test data of four similar tests by using the Statistical Analysis System (SAS) available at the University Computer Center. These representative stress-strain curves were used to determine the representative proportional limit and yield strength of steel. They were also used for a graphic comparison of four different types of stress-strain curves (i.e., LT, TT, LC, and TC) for a given material. For the 80SK sheet steel, four representative curves are compared graphically in Fig. 4.23. It should be noted that because the unit stress has been computed by dividing the total applied load by the original cross-sectional area of the specimen, all stress-strain curves presented in this report are considered to be engineering stress-strain curves.

Similar types of stress-strain curves are shown in Figs. 4.24 through 4.68 for the other five types of sheet steels (80DF, 80DK, 80XF, 100XF, and 140XF) also studied in the present program. Finally the representative stress-strain curves are compared in Figs. 4.69 through 4.72 for six different sheet steels. These figures illustrate that the stress-strain curve of high strength sheet steels is either a sharp-yielding type or a gradual-yielding type. The types of stress-strain curves are identified in Tables 4.3 through 4.8 for different sheet steels subjected to various types of stress.

In Fig. 4.69 for longitudinal tension and Fig. 4.70 for transverse tension, the curve also shows the spread between the ultimate and yield strength of the steel and the total elongation of a tensile test specimen.

b. Proportional Limit, Yield Strength, and Tensile Strength

Proportional Limit F_{pr}

The proportional limit is the stress at which the stress-strain curve starts to deviate from the straight line of the initial slope of the curve. An approximate value can be determined from the stress-strain diagram.

In the design of airplane structures[4.6] and cold-formed stainless steel structural members,[4.4,4.5] it is customary to use the stress that produces a plastic strain of 0.0001 in./in. as the proportional limit. The value determined by such a method is called the 0.01 percent offset proportional limit. This method is also recommended in the AISI Commentary on the 1980 Edition of the AISI Specification.[4.7]

Two values of the proportional limit were determined for each type of tests. As shown in Fig. 4.19 and other similar figures, a straight line was first drawn from the origin (zero stress and zero strain) parallel to the initial straight portion of the stress-strain diagram. The stress at which the curve starts to deviate from the elastic straight line is the theoretical proportional limit, $(F_{pr})_1$. In addition, the second straight line from the point representing a zero stress and a strain of 0.0001 in./in. was drawn parallel to the straight portion of the stress-strain curve. The intersection of the straight line and the stress-strain diagram is the 0.01 percent offset proportional limit, $(F_{pr})_2$. All the measured values of proportional limit are given in Tables 4.3 through 4.8 for various tests. Also listed in these tables are the ratios between the proportional limit and the yield strength of steel.

The test results presented in Tables 4.3 through 4.8 indicate that the ratio of F_{pr}/F_y depends on the type of sheet steel, the type of test, and the method used for determining the proportional limit. For the sheet steels tested in this present program, the $(F_{pr})_1/F_y$ ratios vary from 0.55 to 0.99, and the $(F_{pr})_2/F_y$ ratios range from 0.69 to 1.00.

Yield Strength, F_y

As shown in Figs. 4.15 through 4.72, high strength sheet steels exhibit one of two types of stress-strain curves. One is the sharp-yielding type represented by Fig. 4.73, and the other is the gradual-yielding type represented by Fig. 4.74.[4.1]

For the sharp-yielding type of steel, the yield point is determined by the level at which the stress-strain becomes horizontal. The upper yield point shown in Fig. 4.42 and similar figures was neglected. All the experimently determined yield points of 80DF, 80XF, 100XF, and 140XF sheet steels are given in Tables 4.4, 4.6, 4.7, and 4.8, respectively.

For the gradual-yielding type of steel, the stress-strain curve is rounded out at the "knee", and the yield strength is determined by either the offset method (Fig. 4.74a) or the extension-under-load method (Fig. 4.74b).[4.1] In Tables 4.3, 4.4, 4.5, 4.7, and 4.8, the yield strength values listed for the gradual-yielding type of sheet steels (80SK, 80DF, 80DK, 100XF, and 140XF) are based on the "offset method" by using the 0.2 percent offset (i.e., in Fig. 4.74a, om = 0.002 in./in.).

As in the AISI Guide,[1.8] the term of "yield strength" is used in this report either as yield strength or yield point.

Based on the test results presented in Tables 4.3 through 4.8, the ranges of yield strengths obtained from the sheet steels used in the present program are summarized as follows:

Longitudinal tension:	54.8 - 142.5 ksi
Transverse tension:	49.2 - 158.3 ksi
Longitudinal compression:	53.1 - 141.6 ksi
Transverse compression:	56.7 - 164.3 ksi

Tensile Strength, F_u

In the tension tests, all specimens were tested to rupture. The maximum stress, which a sheet steel is capable of sustaining, is used as the tensile strength of a given material. Tables 4.3 through 4.8 list the values of the experimentally determined tensile strengths of six different sheet steels tested in the present program.

Because all compression tests were conducted only up to a total strain of approximately 0.015 in./in., values of the compressive strength were not obtained from the tests.

On the basis of the test results presented in Tables 4.3 through 4.8, the ranges of tensile strengths determined for longitudinal and transverse tension are summarized as follows:

Longitudinal tension:	87.5 - 142.5 ksi
Transverse tension:	80.9 - 158.3 ksi

c. Ductility

Ductility is one of the major mechanical properties of sheet steels. It is not only required in the forming processes but is also needed for structural considerations.

For structural steels, the permanent elongation of a tension test specimen is customarily used as the indication of ductility. The values of elongation in a 2-in. gage length are given in Tables 4.3 through 4.8. These values were obtained from the maximum strain recorded by the computer as the specimens broke. They were also verified by the increase in length of the 2-in. gage length by fitting ends of the fractured specimens together and measuring the distance between the gage marks.

For the sheet steels used in this program, the ranges of the measured values of elongation are as follows:

Longitudinal tension:	3.8 - 33.3 percent
Transverse tension:	1.5 - 28.8 percent

In the above summary, the smallest value of elongation is for the 140XF sheet steel and the largest is for the 80DF sheet steel. For details, see Tables 4.3 through 4.8.

d. Modulus of Elasticity

The modulus of elasticity is defined by the slope of the initial straight portion of the stress-strain curve. It is also an important property of sheet steel because the load-carrying capacity of structural members cold-formed from steel sheets is usually governed by the buckling strength and stiffness considerations.

The elastic moduli of Grades A, B, C, and D of ASTM A446 sheet steel have recently been studied by Venkataramaiah, Roorda, and Srinivasaiah.[4.8] From a statistical analysis of 63 tests, they reported that the mean value and the standard deviation for the modulus of elasticity are 30,071 ksi and 658 ksi, respectively.

The values for the moduli of elasticity reported in Tables 4.3 through 4.8 for the tension and compression tests were determined by a linear regression analysis of a selected group of stress and strain readings recorded by the computer. This analysis gives the slope of the initial straight portion of the stress-strain diagram, which is used as the modulus of elasticity. The representative value used in these tables is the average of four individual tests.

By using the values given in Tables 4.3 through 4.8, the experimentally determined moduli of elasticity are summarized as follows:

Longitudinal tension: 24,227 - 30,989 ksi
Transverse tension: 25,129 - 33,473 ksi
Longitudinal compression: 27,481 - 33,627 ksi
Transverse compression: 28,611 - 35,093 ksi

It is of interest to note that for all six types of sheet steels, the modulus of elasticity in compression is larger than the modulus of elasticity in tension.

It has been noted that some of the values for the modulus of elasticity are relatively low, particularly for 80SK, 80DK, and 80XF sheet steels subjected to longitudinal tension as listed in Tables 4.3a, 4.5a, and 4.6a. In order to verify the accuracy of the test equipment used for these tests, strain gages were mounted on some of the tension specimens. The stress-strain curves achieved from both methods are plotted in Fig. 4.75 for the 80DF sheet steel subjected to longitudinal tension. In this figure, the solid line represents the initial slope of the stress-strain curve determined by strain gage measurements, and the dotted line represents the stress and strain relationship determined with the aid of UMR test equipment. It can be seen that the initial slopes of both stress-strain curves are practically identical.

Based on the ASTM Designations E83 and E111, the extensometer and compressometer used for the UMR tests can be classified as Class B-1, which would ordinarily be used for determining approximate values of the modulus of elasticity and for determining values such as the yield strength of metallic materials.[5.67,5.68]

V. REVIEW OF AISI PUBLICATIONS

In Chapter I of this report, it is pointed out that a comprehensive design guide for the use of a broader range of sheet steels is highly desirable because many types of high strength sheet steels can be economically used for automotive structural components. Following a statement of the objective of the present research project, the planned program for developing the additional design information is discussed in Chapter II.

In Chapter III, the available publications on automotive structures concerning materials, design loads, structural analysis, and structural design are briefly reviewed. The material properties of six different high strength sheet steels (80SK, 80DF, 80DK, 80XF, 100XF, and 140XF) are studied in Chapter IV.

With the basic information on high strength sheet steels and automotive structures, the available AISI specifications and design guide for cold-formed steel members and connections are reviewed in this chapter. The following discussions accompanied by a few observations deal with the intended use of each AISI document. The purpose of this review is to achieve a better understanding of the background information on the AISI design criteria in order to develop proper recommendations on the needed structural research.

V. 1. Specification for the Design of Cold-Formed Steel Structural Members[2.1]

The first edition of this Specification was issued by the American Iron and Steel Institute in 1946. It was used primarily for the design of structural members cold-formed to shape from carbon steel sheets having yield points from 25 to 33 ksi even though the use of low-alloy steels having yield points up to 50 ksi was permitted in Section 1.2 of the Specification.

This Specification has been revised in 1956, 1960, 1962, 1968, and 1980. In each revision, the ASTM material references have been brought up to date, and some of the design criteria have been either revised or added in keeping with technical developments and to reflect the results of a continued research program sponsored by the American Iron and Steel Institute. References 5.1 and 4.7 provide background information on the 1968 and 1980 editions of the AISI Specification, respectively.

A. Materials

In the 1980 edition of the AISI Specification,[2.1] the design provisions were prepared for structural members cold-formed to shape from carbon or low-alloy steel sheet, strip, plate, or bar not more than one inch in thickness. Table 5.1 lists the types of steels referred to in Section 1.2.1 of the Specification along with mechanical properties, which include yield point, tensile strength, tensile strength-to-yield point ratio, and elongation.

It can be seen that for the steels specified in the 1980 edition of the AISI Specification for the design of buildings, the ranges of mechanical properties are as follows:

Yield point, F_y:	25-70 ksi
Tensile strength, F_u:	42-85 ksi
F_u/F_y ratio:	1.17-2.22
Elongation:	12-27% in a 2-in. gage length 15-20% in an 8-in. gage length

For steels not listed in Table 5.1, according to Section 1.2.3.1 of the Specification, the required minimum F_u/F_y ratio is 1.08 and the required minimum elongation is 10 percent for a 2-in. gage length or 7 percent for an 8-in. gage length. However, a special provision is now included in the Specification for the use of Grade E of A446 and A611 steel, which have a yield strength of 80 ksi and a tensile strength of 82 ksi. These materials may be used for particular configurations, such as roofing, siding, and floor decking[4.7] but are not intended for use as framing members.

B. Design Procedure

In Section 2 of the AISI Specification, design criteria are provided for the following design considerations:

- Definitions of terms.
- Effective design width of stiffened compression elements with or without intermediate stiffeners.
- Minimum requirements for edge and intermediate stiffeners for compression elements.
- Maximum allowable flat-width ratios.
- Maximum allowable web depth and web stiffener requirements.
- Effective flange width of unusually short beams supporting concentrated loads.

All design provisions and equations are used for the "Allowable Stress Design" method. The following remarks are primarily related to the effective design width of compression elements and the minimum requirements for stiffeners.

a. Effective Design Widths of Compression Elements

The design equations included in the AISI Specification for determining the effective design width of stiffened compression elements are based on the following expression derived by Winter:[5.1,5.3-5.5]

$$b = 1.9t\sqrt{\frac{E}{f_{max}}}\left[1-0.415\left(\frac{t}{w}\right)\sqrt{\frac{E}{f_{max}}}\right] \qquad (5.1)$$

where b = effective design width

t = thickness of the compression element

E = modulus of elasticity of steel

w = width of the compression element

f_{max} = maximum edge stress

The above equation has been used in the United States and some other countries for the design of cold-formed steel members since 1968.

It should be noted that Eq. (5.1) can be used not only for the design of buildings, which are subjected primarily to static loading, but it can also be used for the design of car bodies, highway products, storage racks, bridge construction, and various types of equipment, which are subjected to dynamic loads. This fact has been verified by Culver and his collaborators at Carnegie-Mellon University on the basis of their analytical and experimental studies of thin compression elements, beams, and columns subjected to dynamic or time-dependent loading.[5.6-5.11] Figure 5.1 shows the correlation between Eq. (5.1) and the test data.[5.8]

During recent years, different methods have been used in some other countries for determing the effective design width of stiffened compression elements. Figure 5.2, adapted from Ref. 5.2, shows the differences between various methods being used in the United States,[2.1] Canada,[5.12] Australia,[5.13] United Kingdom,[5.14] France,[5.15,5.16] Japan,[5.17] and some European countries.[5.18] It can be seen that the differences between various methods depend on the flat-width ratio, w/t, and the maximum edge stress, f_{max}.

With regard to the unstiffened compression elements, the following equation was derived by Winter:[5.3]

$$b = 0.8t\sqrt{\frac{E}{f_{max}}}\ [1-0.202(\frac{t}{w})\sqrt{\frac{E}{f_{max}}}\ ] \qquad (5.2)$$

This subject was recently studied by Kalyanaraman, Pekoz, and Winter.[5.19,5.20] The use of Eq. (5.2) for the design of cold-formed steel members having unstiffened compression elements was considered by the AISI Advisory Group on the Specification for the Design of Cold-Formed Steel Structural Members.[5.21]

b. Requirements for Edge Stiffeners

In order to achieve an economical design for cold-formed steel members, an edge stiffener is often added to the unstiffened compression flange to provide a continuous support along its longitudinal edge for the purpose of improving the load-carrying capacity of the member. The AISI Specification includes minimum requirements for edge stiffeners and intermediate stiffeners. These design criteria are based on previous theoretical and experimental investigations of the local stability of flanges stiffened by lips and other types of stiffeners.

The requirements for edge and intermediate stiffeners have also been studied by numerous investigators in the United States and abroad.[5.22-5.27] Design formulas have been proposed by Desmond, Pekoz, and Winter for edge stiffeners[5.22] and intermediate stiffeners.[5.23] In other countries, different formulas are used for the design of stiffeners. Figure 5.3 is a comparison of the AISI and Canadian requirements for edge stiffeners. It can be seen that in most cases, the AISI Specification[2.1] requires slightly larger edge stiffeners compared with the Canadian Standard.[5.12]

c. Maximum Allowable Web Depth and Web Stiffener Requirements

In the 1980 edition of the AISI Specification, the maximum depth-to-thickness ratio, h/t, for single, unreinforced webs has been increased from 150 to 200. For webs with transverse stiffeners, the maximum h/t ratio has been increased from 200 to 300. In addition, new requirements have been added to the 1980 Specification for the design of transverse stiffeners.

All the revisions and additions made in Section 2.3.4 of the Specification are based on the studies of channels, hat sections, and I-sections reported in Refs. 5.28 through 5.32. The following summary gives the ranges of thicknesses and mechanical properties of the steels used in these studies:

Thickness, t:	0.0375-0.1478 in.
Yield point, F_y:	33.46-53.79 ksi
Tensile strength, F_u:	48.31-73.08 ksi
Elongation:	15-42 percent

C. Allowable Design Stresses

Section 3 of the AISI Specification[2.1] provides numerous equations for determining the allowable stresses to be used for the design of tension members, beams, compression members, and beam-columns. The factors of safety for the design of cold-formed steel structural members are given in Table 5.2, which is adapted from the AISI Commentary.[4.7]

a. Tension Members

For the design of tension members, the maximum allowable stress on the net section is the basic design stress, F, which is taken as 0.60 F_y, where F_y is the specified minimum yield strength of steel. The Specification permits the use of the increase in steel strength resulting from cold work of forming provided that the methods and limitations prescribed in Section 3.1.1.1 of the Specification are satisfied.

When bolts or other mechanical fasteners are used as connectors, the maximum allowable tension stress may be limited by the design equations given in Section 4.5.5 of the Specification. For this case, the allowable tension stress depends on the thickness of the connected parts, the use of washers, the type of joints (lap joint or butt joint), and the arrangement of fasteners.

b. Beams

For cold-formed steel beams, the Specification provides numerous equations for computing the allowable bending moment and the moment of inertia to be used for deflection calculation.

With regard to the bending moment, allowable stress equations are used to prevent yielding and local buckling of beam flanges with due consideration given to the post-buckling strength of the compression flange. In order to prevent lateral buckling of beams, design formulas are given in Sections 3.3 and 5.2 for determining the allowable compression stress and for designing the required braces. For unusually short beams supporting concentrated loads, a special design table is provided in Section 2.3.5 of the Specification for those who need to consider shear lag problems.

Since 1980, the AISI Specification permits the use of the inelastic reserve capacity of beams for determining the allowable bending moment on the basis of the research work conducted at Cornell University.[5.48] It should be noted that when this method is used, the conditions prescribed in Section 3.9 of the AISI Specification must be met.

In addition to the above mentioned design features, proper consideration must be given to the allowable strength of beam webs for shear, bending, combined bending and shear, web crippling, and combined bending and web crippling. The design provisions of Sections 3.4 and 3.5 of the AISI Specification were revised extensively in 1980 on the basis of the previous research work conducted at Cornell University,[5.33] a recent study of beam webs conducted at the University of Missouri-Rolla,[5.28-5.32] and some other independent studies.[5.34]

c. Compression Members

In the 1980 edition of the AISI Specification, minor revisions have been made in Section 3.6.1. These revisions include the elimination of the allowable stress equation for bracing and secondary members and the addition of design equations for point-symmetric sections that may be subject to torsional buckling.

With regard to the effect of local buckling on column strength, recent studies conducted at Cornell University by DeWolf, Pekoz, Winter, and Kalyanaraman seem to indicate that the Q-factor method is capable of improvement.[5.36-5.39] It appears that in future editions of the AISI Specification, the effective design width method may also be used for compression members having unstiffened compression elements.[5.21]

d. Beam-Columns

For beam-columns involved with combined axial and bending stresses, the design provisions of Section 3.7 of the 1980 edition of the AISI Specification are the same as those used in the 1968 edition. The design criteria can be used for doubly-symmetric shapes and singly-symmetric shapes that may be subject to torsional-flexural buckling.

e. Cylindrical Tubular Members

The AISI design provisions for cylindrical tubular members in compression or bending have been developed on the basis of the tests conducted by Plantema, Wilson, Newmark, and Olsen in the 1940's.[4.7] Because the structural strengths of cylindrical tubes have been studied by numerous investigators in recent years, a subcommittee has been established in the AISI Advisory Group on the Specification for the Design of Cold-Formed Steel Structural Members to update these criteria.

D. Connections

Section 4 of the 1980 edition of the AISI Specification provides design criteria concerning the following four subjects:

- Welded connections
- Bolted connections
- Connecting two channels to form an I-section
- Spacing of connections in compression elements

For welded connections, the design provisions for fusion welds have been completely revised on the basis of a recent study conducted by Pekoz and McGuire at Cornell University.[5.40] Additional information on the design of welds and welding procedures can be found in the AWS Specification.[3.40]

For bolted connections, the AISI design provisions have also been revised extensively. These revisions are based on the tests conducted at Cornell University,[5.41-5.44] University of Missouri-Rolla,[5.45,5.46] and other organizations.[5.47]

In the 1980 AISI Specification, no revisions have been made in other AISI design provisions for connecting two channels to form an I-section and for determining the spacing of connections in compression elements.

E. Bracing Requirements

In 1980, the design equations included in Section 5.1 of the specification for wall studs have been changed completely. These revisions are based on a comprehensive study conducted by Simaan and Pekoz at Cornell.[5.49,5.50] A computer program for the design of wall studs is available at the American Iron and Steel Institute.[5.51]

In addition, some minor revisions have been made in Section 5 of the Specification regarding the bracing requirements for channels and Z-sections used as beams. Additional requirements for the design of such members braced by attached covering material are being developed by the AISI Advisory Group.

F. Tests for Special Cases

In Section 6 of the AISI Specification, special requirements are given for tests. These provisions may be used for (a) determining structural performance, (b) confirming structural performance, and (c) determining mechanical properties of formed sections or flat material.

G. General Comments

The design provisions included in the AISI Specification are subjected to a constant review. Improvements of various sections of the Specification are being considered by different subcommittees of the Advisory Group. At the Sixth International Specialty Conference on Cold-Formed Steel Structures held in November 1982, Al Johnson presented a comprehensive review of the research work on cold-formed steel structures and discussed the development of design criteria. The following topics on future research needs are adapted from Ref. 5.52:

Simplification

Channel-and Z-sections

Stiffeners (compression flange)

Safety factor for confirmatory tests

Interaction of elements

Web bending-crippling interaction for deck

Load and resistance factor design

Combined axial and bending load (Section 3.7)

Unstiffened compression elements

Columns

Web effective width approach

R/t, w/t, L/r, etc. limits

Perforated elements

Screw fasteners

Warning on use of safety factors

Laterally unsupported compression flanges

Combined axial and bending (Section 5.1)

Moment redistribution

Inelastic reserve of multiple-stiffened elements

Uplift on arc-spot welds

Test procedures

Shear walls

Definition of C_b for flexural members

Uplift on screw or bolt washers

Angles in bending

Resistance welds, high-strength, low alloy

Proof testing for completed structures and for production verification

Composite design of floors (e.g., steel and plywood)

Decision tables

Seismic, cycling loads, dynamic response

Spacing of connectors in relation to deflection prediction

Tolerances

Weld preheat requirements

Shear lag and curling in wide tension flange

Influence of cold-work

Composite walls (e.g., steel studs and metal lath)

Allowable bolt bearing stress for one or no washer when $F_u/F_y < 1.15$

Corrugated sheet design

Computer programs

Small scale stud-sheathing shear strength and stiffness tests

Oversize, slotted, and staggered bolt holes

Bolt installation

Metrication

Sheet bending formula

Sandwich panels

Cross-reference other standards (e.g., composite)

Temperature effects

Redefine web depth

Higher strength steels

Fatigue

Redefine extreme fiber

Cyclindrical tubular members

Increase allowable for construction loads

Stainless.

The above list indicates that in many areas additional studies will be needed for improving the current AISI Specification.[2.1] This information will be very useful to the AISI Task Force on Structural Research of the Transportation Department when it considers future research needs.

V. 2. Specification for the Design of Cold-Formed Stainless Steel Structural Members[2.2]

The first edition of the AISI Specification for the Design of Cold-Formed Stainless Steel Structural Members was issued by the American Iron and Steel Institute in 1968[5.53] on the basis of the extensive research conducted by Johnson and Winter at Cornell University.[5.54,5.55] This document provided design rules for the structural members cold-formed to shape from annealed austenitic stainless steel, Types 201, 202, 301, 302, 304, and 316. The main reason for having a different Specification for the design of stainless steel structural members is because the AISI Specification for carbon and low-alloy steels[2.1] does not apply to the design of stainless steel structures. This is due to the differences in strength properties, modulus of elasticity, and the shape of the stress-strain curve.

In view of the fact that the ¼-and ½-hard temper grades of stainless steels have often been used in various applications because of their greater strength than annealed grades, additional research has been conducted by Wang, Errera, Tang, and Popowich at Cornell University[5.56-5.58] to investigate further the performance of structural members cold-formed from cold-rolled austenitic stainless steels. Subsequently, the Specification was revised in 1974 to include the generalized design formulas for use of different temper grades.[2.2]

A. Material Properties

Compared with carbon steel, stainless steel has the following characteristics:

- Anisotropy
- Nonlinear stress-strain relationship
- Low proportional limits
- Pronounced response to cold work

With regard to anisotropy, Fig. 5.4, adapted from Ref. 5.59, shows the difference between the stress-strain curves of carbon and annealed stainless steels. The stress-strain curves of annealed, half-hard, and full-hard stainless steels are shown in Fig. 5.5.[5.59] These figures also show the nonlinear stress-strain relationships and the low proportional limit relative to the yield strength. Based on the results of the tests, the ratios of effective proportional limit-to-yield strength are given in Table 5.3.[5.60] It can be seen that for some cases, the ratio is even less than 0.50.

Tables 5.4 and 5.5 list the values of the yield strength and initial modulus of elasticity of Grades A, B, C, and D of A666 stainless steel.

B. Design Provisions

Contrary to the AISI Specification for carbon and low-alloy steels,[2.1] different design formulas are used in the AISI Specification for stainless steels [2.2] with regard to the following aspects:[5.60,5.61]

- Factors of safety
- Basic design stress
- Effective design width
- Generalization of design formulas and plasticity reduction factors
- w/t limitations
- Deflection determination
- Service stress limitations
- Column buckling
- Connections

a. Factors of Safety

In the AISI Specification for carbon and low-alloy steels,[2.1] a basic safety factor of 1.67 has been used since 1960. For stainless steel design, a relatively large safety factor of 1.85 is used in the AISI Specification [2.2] because of the lack of design experience and low proportional limits for stainless steels. For column design, web crippling of beams, and connections, the allowable stresses used for stainless steels have been derived on the basis of relatively larger safety factors than for carbon steel.

b. Basic Design Stress

Because the results of tests have indicated that the yield strengths of stainless steels are different for various types of stress (longitudinal tension, transverse tension, longitudinal compression, and transverse compression), the basic design stress is determined by the yield strength according to the grade of steel and the proper type of stress. The safety factor for determining the basic design stress is 1.85.

c. Effective Design Width

Because the research work conducted at Cornell has indicated that Eq. (5.1) is equally applicable to the design of stainless steel structural members having stiffened compression elements, the design formulas included in the AISI Specification[2.2] for computing the effective design width is based on Eq. (5.2) and a safety factor of 1.85. In the derivation of the design formula, a value of 27×10^3 ksi was used for the modulus of elasticity based on the test results of Grades C and D (¼- and ½-hard tempers) subjected to longitudinal compression. This formula is slightly conservative for Grades A and B, for which the initial modulus of elasticity is 28×10^3 ksi.

d. Generalization of Design Formulas and Plasticity Reduction Factors

The allowable stress formulas used to prevent local buckling of compression elements, lateral buckling of beams, shear buckling, and bending failure in beam webs have been generalized in the AISI Specification, which can be applied to any grade of stainless steel by substituting the proper mechanical properties given in the specification.

When the theoretical buckling stress exceeds the proportional limit, the plasticity reduction factors listed in Table 5.6 are used to modify the design formulas that have been derived for elastic buckling.

In Table 5.6, E_o is the initial modulus of elasticity, E_s is the secant modulus, E_t is the tangent modulus, G_o is the initial shear modulus, and G_s is the secant shear modulus. The ratios of E_s/E_o, E_t/E_o, and G_s/G_o are provided in the Specification in tabular and graphic forms.

e. w/t Limitations

In the AISI Specification for stainless steels, the maximum permissible width-to-thickness ratios for flat elements have been reduced to minimize the excessive local distortion of flat elements.

f. Deflection Determination

Because the proportional limit of stainless steel is relatively low and the stress under service load in the extreme fiber may be higher than the proportional limit, special provisions are included in the stainless steel specification for computing deflections in which a reduced modulus of elasticity, $E_r = (E_{ts} + E_{cs})/2$, is used, where E_r is the reduced modulus of elasticity, E_{ts} is the secant modulus in the tension flange, and E_{cs} is the secant modulus in the compression flange.

g. Service Stress Limitations

In view of the facts that for stainless steels the proportional limits are low compared with carbon steel and that the exposed surfaces of stainless steel are important for architectural purposes, the design provisions for determining the allowable stresses for unstiffened and stiffened compression elements are included for two cases, i.e., (1) no local distortion at design loads is permissible, and (2) some slight waiving of the design loads is permissible.

h. Column Buckling

The 1974 Edition of the AISI Specification for stainless steel design contains only the design criteria for compression members that fail through overall column buckling. No design equations are included in the Specification for members subjected to torsional or torsional-flexural buckling because research data are lacking.

Because the stress-strain relationships of stainless steels are different from carbon steel, the allowable stresses for axially loaded compact compression members (not subject to local buckling) are based on the tangent modulus theory. The safety factor applied in the design formula is 2.15 instead of 1.92 which is used for cold-formed carbon steel design. For noncompact sections, a different equation is used for computing the allowable stress.

Also, because of the lack of research data, no design information is included in the stainless steel Specification for combined axial and bending stresses in members subjected to torsional or torsional-flexural buckling.

i. Connections

The AISI design provisions for welded and bolted connections are based on the research work conducted by Errera, Tang, and Popowich at Cornell University.[5.58] For fusion welds, the safety factors used for deriving the design formulas are 1.85 against overall yielding of cold-rolled base metal, 2.2 against fracture of annealed base metal, and 2.5 against fracture of the weld metal.

For resistance welds, a safety factor of 2.5 has been used to determine the allowable shear strength for spot welding.

With regard to the design of bolted connections, the design formulas for stainless steels have been adapted from the 1968 Edition of the AISI Specification for carbon steel with some necessary changes suggested by the Cornell research.[5.58]

V. 3. Tentative Recommendations on Load and Resistance Factor Design Criteria for Cold-Formed Steel Structural Members[2.3]

For the design of cold-formed steel structural members and connections, the "Allowable Stress Design" method[2.1] has long been used in the United States, Canada, and some other countries. The "Load and Resistance Factor Design (LRFD)" method has not yet been adopted in this country as a design standard for steel structures, even though the "Limit States Design" has been included in the Canadian Standard since 1974.[5.12]

During the past few years, a joint research project has been conducted at the University of Missouri-Rolla and Washington University to develop the new "Load and Resistance Factor Design" criteria for cold-formed steel structural members and connections based on the probabilistic approach.[2.3] In this document, separate load factors are applied to specified loads, and appropriate resistance factors are applied to nominal resistances to ensure that the probability of reaching a limit state is acceptably small. These factors reflect the uncertainties of analysis, design, loading, material properties, and fabrication. They are derived from the first order probabilistic methodology that was used for the development of the LRFD recommendations for hot-rolled steel shapes.[5.62]

The "Tentative Recommendations on Load and Resistance Factor Design" contains the following six sections for the design of cold-formed steel structural members and connections:[2.3]

- General
- Design Procedure
- Design of Members
- Connections
- Bracing Requirements
- Tests for Special Cases

The background information on various design criteria is discussed in the Commentary, which is included in Ref. 2.3.

In this proposed document, the load factors and load combinations are specified for dead load, live load, snow load, wind load, earthquake load, and ponding load. They are based on Ref. 5.63. The resistance factors have been developed from the statistical analyses of (a) material properties, (b) results of tests on different types of structural members and connections, and (c) tolerances of cross-sectional dimensions.[2.3] In the main body of the design criteria, equations for nominal resistance are given for various types of structural members and connections. These equations are consistent with those used to derive the formulas for the allowable stress design method.[2.1]

V. 4 Guide for Preliminary Design of Sheet Steel Automotive Structural Components[1.8]

The first edition of the "Guide for Preliminary Design of Sheet Steel Automotive Structural Components"[1.8] was issued by the American Iron and Steel Institute in 1981 in an attempt to assist automotive structural designers to achieve weight reductions through the efficient utilization of modern carbon and high strength steels. This document is based on the 1968 Edition of the AISI "Specification for the Design of Cold-Formed Steel Structural Members,"[1.9] which was developed on the basis of more than 40 years of extensive research and experience in the design and utilization of cold-formed steel structural members as building components. The contents of the Guide and its application to automotive structural components were reviewed by Sam Errera at the International Congress and Exposition held in Detroit, Michigan, on February 22, 1982.[1.5] He also compared the strength predictions based on the Guide with the results of a series of flexural tests of hat sections.

The AISI Guide contains an introduction and four sections as follows:

- General
- Design procedure
- Design stresses and member design
- Connections

These items will be reviewed in the following discussions.

A. Introduction

In the Introduction of the Guide, it is stated that the publication is intended to serve as a guide for preliminary design of automotive structural components for which cold-formed sheet steels of various yield strength levels are used and that the information is based primarily on the 1968 Edition of the AISI "Specification for the Design of Cold-Formed Steel Structural Members." However, these guidelines differ in the following three respects from the AISI Specification for building design:

(1) For convenience of the automotive engineer, the design expressions are presented on an ultimate strength basis; the factors of safety, load factors, or resistance factors are to be provided by the designer.

(2) The design expressions often have been simplified, recognizing that they are intended for preliminary design and that the automotive industry customarily subjects its new products to performance tests. To maintain simplicity, the range of applicability of the design expressions has been restricted in some instances.

(3) The design expressions are extended to materials with yield strengths of up to 80 ksi.

With regard to Item (1), the "Tentative Recommendations on Load and Resistance Factor Design Criteria", when completed, will be useful for the future revision of the AISI Guide. As discussed in Article V.3, the proposed recommendations on the LRFD method provide numerous equations for determining the ultimate strengths of various types of structural members including tension members, flexural members, axially load compression members, beam-columns, and cylindrical tubes. In addition, it provides different load factors and resistance factors for various types of loading and different structural members. The factors of safety used for the allowable stress design are summarized in Table 5.2 for various sections of the 1980 edition of the AISI Specification.

It has been recognized that some of the design expressions included in the Guide have been simplified as stated in Item (2).

The following review contains a discussion of the difference between the simplified and original formulas with some indication regarding the applicability of these simplified formulas.

Because the design expressions presently included in the Guide are applicable only to materials with yield strengths of up to 80 ksi, the following discussion takes into consideration the use of sheet steels having yield strengths greater than 80 ksi and the necessary revision of design expressions for using such high strength materials.

B. General

a. Scope

Section 1.1 states that the Guide is intended for preliminary design of automotive structural components cold-formed to shape from sheet steels. It deals primarily with static loads and members with flat elements, but the principles also can provide some guidance for other design situations.

Because the Guide is limited to the design of structural components for which sheet steels are used, according to the AISI Steel Products Manual on Sheet Steel,[3.1] the maximum thickness of the material is practically 0.23 inches. Even though car bodies are usually subjected to static, dynamic, and impact loads as discussed in Article III. 3, the design expressions included in the Guide are intended for the type of structural components subjected primarily to static load. For other types of loading, appropriate allowance should be considered for dynamic effects, fatigue strength of the material, energy absorption, and other factors.

b. Materials

Section 1.2 of the Guide states that the design expressions can be applied to any structural steel that has a yield strength not greater than 80 ksi, a proportional limit equal to or greater than 70 percent of the yield strength, and adequate ductility to form the part and serve the intended function.

In order to consider the applicability of the present AISI Guide for the sheet steels studied in the present program, the tested mechanical properties of these six different steels are summarized in Table 5.7. This table contains the average values of the proportional limit determined by the 0.01 percent offset method, F_{pr}, yield strength, F_y, tensile strength, F_u, F_{pr}/F_y ratio, F_u/F_y ratio, elongation in a 2-in. gage length, and modulus of elasticity. It can be seen that for all six types of sheet steel, the average values of the proportional limit are equal to or greater than 70 percent. Therefore, the design expressions given in the Guide for inelastic buckling of compression elements and members are appropriate for these materials.

With regard to ductility, the present Guide does not prescribe any requirements concerning the minimum elongation and the ratio of F_u/F_y. Even though the required ductility depends on the forming process of the part and varies with the type of application, it seems that some guidelines may be needed for most automotive structural components.

As discussed in Article V.1.A, the current AISI Specification for carbon and low-alloy steels[2.1] includes the following two requirements on ductility when the steel is used for structural framing members :

F_u/F_y ratio ≥ 1.08

Elongation in a 2-in. gage length $\geq 10\%$

However, special provisions are included in Section 1.2.3.2 of the AISI Specification for the use of A446 (Grade E) and A611 (Grade E) steels for particular configurations. These steels have an F_u/F_y ratio of 1.03 with a very low elongation.

If the above mentioned AISI requirements for building design are considered to be the appropriate criteria for automotive structural framing components, the mechanical properties presented in Table 5.7 show that among the six types of sheet steels, only four types (80SK, 80DF, 80DK, and 80XF) can be used for structural framing members in car bodies except that the F_u/F_y ratio and elongation are inadequate for the 80SK sheet steel subjected to tension in the transverse direction. For 120XF and 140XF sheet steels, the tensile strength is practically the same as the yield strength with a low ductility. Perhaps these materials can be used for special applications in the same manner that A446 (Grade E) steel is used in buildings.

It has been realized that the moduli of elasticity for 80DK and 80XF sheet steels subjected to tension in the longitudinal direction are unexpectedly low compared with the nominal value of 29,500 ksi.

C. Design Procedure

Section 2 of the AISI Guide contains three subsections concerning procedure, definitions, and properties of sections.

a. Procedure

In Section 2.1 of the Guide, it is stated that all computations are based on ultimate strength; that is, the expressions given can be used to predict the load at which failure will occur. Safety factors, load factors, or resistance factors are to be provided by the designer.

As discussed in Article V.4.A, the AISI "Tentative Recommendations on Load and Resistance Factor Design Criteria,"[2.3] when completed, will be a useful reference for designers who can select from it appropriate load factors and resistance factors even though the Tentative Recommendations are being prepared for the design of buildings.

b. Definitions

The definitions of terms included in Section 2.2 of the AISI Guide are the same as those used in the AISI Specifications for the design of carbon, low-alloy, and stainless steels.[2.1,2.2]

c. Properties of Sections

The equation included in Section 2.3.1.1 of the AISI Guide for determining the effective design width is based on Eq. (5.1) of this report; a value of $E = 29,500$ ksi has been used in the calculation. This design formula (Eq. 2.3.1.1) is considered to be appropriate for the design of automotive structural components for the following reasons:

(1) As discussed in Article V.1.B.a, Eq. (5.1) can be used for the design of stiffened compression elements subjected to static or dynamic loads.

(2) Previous studies have indicated that Eq. (5.1) can also be used for stainless steel structural members for which the yield strength ranges up to 120 ksi, and the proportional limit extends from 46 to 67 percent of the yield strength.[5.54-5.57]

(3) Some recent hat section tests conducted at Inland Steel Company indicate that the Guide procedures give reasonable estimates of failure loads for low carbon steel, high strength low-alloy steel, and dual phase steels as well as for the shallower specimens of martensitic steel.[1.5]

(4) The value of the modulus of elasticity used in the derivation of Eq. (2.3.1.1) of the AISI Guide is a reasonable value compared with the tested moduli of elasticity presented in Tables 4.3 through 4.8 and summarized in Table 5.7 for compression in both the longitudinal and transverse directions.

Section 2.3.2 of the Guide includes two equations (Eqs. 2.3.2.1a and 2.3.2.1b) for the design of edge stiffeners. The effect of F_y was eliminated to make them simplified expressions. Compared with the original formulas used in the AISI Specification,[2.1] these simplified equations are conservative for sheet steels having a low yield strength combined with a small value of the w/t ratio. The differences between the simplified equations used in the AISI Guide[1.8] and the original equations used in the AISI Specification[2.1] are shown graphically in Fig. 5.3. For sheet steels having a high yield strength combined with a relatively large w/t ratio, the simplified and original formulas are practically identical.

Section 2.3.3 of the Guide deals with the maximum allowable w/t ratios for stiffened and unstiffened compression elements. These ratios have been adopted from the AISI Specification for buildings.

In the AISI Specification for the design of stainless steel structural members,[2.2] the maximum permissible w/t ratios have been reduced in order to minimize the excessive local distortion of flat elements. In view of the fact that the sheet steel to be used for automotive structural components may have a very high yield strength with a low proportional limit, it appears desirable to reduce the maximum allowable w/t ratios to some lower values.

D. Design Stresses

Section 3 of the AISI Guide provides equations for computing the following design stresses:

- Basic design stress
- Allowable compression stress on flat unstiffened elements

a. Basic Design Stress

Because this Guide presents an ultimate design procedure, the yield strength is now considered to be the basic design stress. No consideration is given, however, to the increase of yield strength occasioned by the cold-work of forming.

A review of the tested mechanical properties summarized in Table 5.7 and the stress-strain curves presented in this report indicates that for 80DF and 80DK sheet steels, the strength increase from the cold-work of forming can be significant because these sheet steels have a large spread between the yield and tensile strengths.

This fact was discussed by Errera in his evaluation of the test results for the shallower hat sections.[1.5]

b. Allowable Compression on Unstiffened Elements

The design formulas included in Section 3.2 of the AISI Guide are based on the basic formulas used in the AISI Specification for the design of buildings. These basic formulas were originally derived from the results of Cornell tests of cold-formed steel beams and stud columns, which were formed to shape from sheet steels having virgin yield strengths ranging from 28 to 50 ksi.[5.3,5.64-5.66] Similar materials were also used in additional recent studies conducted at Cornell.[5.19] It appears that if these formulas are going to be used for the sheet steels having very high yield strengths, additional tests should be conducted for verification of the limiting w/t ratios, such as $63.3/\sqrt{F_y}$, $144/\sqrt{F_y}$, and 25. In case the "effective design width" approach is adopted in the future Guide, the results of additional tests can be used to verify Eq. (5.2).

E. Member Design

In addition to the design stresses, Section 3 also provides design requirements for the various types of structural members listed below:

- Tension members
- Flexural members
- Axially loaded compression members
- Members under combined compression and bending
- Cylindrical tubular members in compression or bending

a. Tension Members

Currently, the maximum stress on the net section of tension members is limited by F_y. Unless additional design formulas are to be added in Section 4 for determining the maximum tension for bolted connections, it appears that new design expressions may be needed in Section 3.3 of the Guide for determining the permissible value on the basis of the d/s ratio, r value, and the tensile strength, F_u. In the above expressions, d is diameter of a bolt, s is the spacing of bolts perpendicular to the line of stress, r is the force transmitted by the bolt or bolts at the section considered divided by the tension force in the member at that section.

b. Flexural Members

For the design of flexural members, the Guide provides requirements for the maximum depth-to-thickness ratio (h/t) of webs, maximum tensile and compressive stresses, maximum bending and shear stresses in webs, combined bending and shear stresses in webs, maximum concentrated loads and reactions, and the effective design width for unusually short beams supporting concentrated loads.

In the 1980 Edition of the AISI Specification,[2.1] extensive revisions were made on the design provisions concerning the maximum h/t ratio, bending stresses in webs, shear stresses in webs, combined bending and shear stresses in webs, web crippling, and combined web crippling and bending. It appears that consideration should be given to the revision of Section 3.4 of the Guide on the basis of the 1980 Edition of the AISI Specification and some additional tests for the study of bending strength of webs and web crippling strength by using a sufficient number of test specimens made of yield strength higher than 80 ksi.

In addition to the above, the design provisions for lateral buckling of beams should also be considered. Torsional analysis and design is one of the important considerations for automotive structural components.

c. Axially Loaded Compression Members

The current design criteria included in Section 3.5 of the Guide deals only with flexural buckling of axially loaded columns. It appears that additional design provisions for torsional-flexural buckling of singly-symmetric shapes would be considered appropriate.

An attempt should also be made to develop some new design criteria by using the effective design width approach for both stiffened and unstiffened compression elements.[5.21] Similar to the design of flexural members, some additional experimental investigation of columns made of high yield strength steels may be necessary.

d. Members Under Combined Compression and Bending

In the same manner as with the design of axially loaded compression members, the addition of design provisions concerning the torsional-flexural failure mode of beam-columns should be reviewed and considered.

In Eq. (3.61), the coefficient C_m appears to be needed for the second and third terms of the equation.

e. Cylindrical Tubular Members in Compression on Bending

The design criteria included in Section 3.7 of the Guide are the same as those used in the AISI Specification. As discussed in Article V.1.C.e, this section is being reviewed by the AISI Advisory Group on Specification.

F. Connections

Currently, the only design criteria included in Section 4.1 of the Guide are related to the spacing of connectors in compression elements. Because Eq. (4.1b) has been developed on the basis of elastic buckling of compression elements, this formula can be modified for buckling in the elastic and inelastic ranges.

In addition, additional design guidelines may be developed for welded connections, bolted connections, screwed connections, and joints using adhesives. Some references related to these subjects were reviewed in Chapter IV.

VI. RECOMMENDATIONS ON THE NEEDED STRUCTURAL RESEARCH

VI. 1. Suggested Revisions of the AISI Guide

Based on the preliminary study conducted in Phase I of this program, the following revisions and additions are suggested for the AISI Guide:

SECTION 1 - GENERAL

1.1 Scope

In the future editions of the Guide, the scope may be extended to consider not only static load but also dynamic and impact loads. In addition, the Guide may be extended to accomodate the design of some typically curved elements as well as flat elements.

1.2 Material

Some specific minimum requirements on ductility (i.e., minimum F_u/F_y ratio and minimum elongation) should be established and added to the Guide for the design of structural framing components. Special provisions may be developed for the use of low-ductility sheet steels for special applications.

The maximum limit on yield strength may be revised to a value greater than 80 ksi depending on the results obtained from future research.

SECTION 2 - DESIGN PROCEDURE

2.1 Procedure

It is suggested that Section 2.1 be revised to include appropriate references on safety standards. In addition, general statements on stiffness and energy absorption should be added in this section.

2.3.1.1 Elements Without Intermediate Stiffeners

Consideration may be given to the revision of Equation (2.3.1.1) by using the buckling coefficient, k, in the formula. This revised equation can be used for the design of stiffened and unstiffened compression elements. The k value can be selected according to the type of edge support and the aspect ratio of the element.

In addition, new design provisions may be developed for the use of stiffened curved elements.

2.3.1.2 Multiple Stiffened Elements and Wide Stiffened Elements with Edge Stiffeners

Equations for determining the effective design width may be added for the case of $w/t > 60$.

2.3.2.2 Intermediate Stiffeners

The limitations on the effectiveness of intermediate stiffeners, such as Items (a), (b), and (c) of Section 2.3.2.2 of the AISI Specification,[2.1] may be added to this section of the Guide.

2.3.3 Maximum Allowable w/t Ratios

The maximum allowable w/t ratios included in this section may be reduced for the purpose of minimizing excessive local distortion.

SECTION 3 - DESIGN STRESSES AND MEMBER DESIGN

3.1 Basic Design Stress

Design provisions for the use of strength increase developed from cold-work of forming may be added to this section.

3.2 Compression Unstiffened Elements

Future revision of the design formulas should provide for the possible interaction of plate buckling.

Consideration should be given to the use of the "effective design width" approach for unstiffened compression elements.

3.3 Tension Members

For tension members that use mechanical fasteners, such as bolts, rivets, or screws, additional design formulas for determining the allowable tension on net section should be added either in this section or Section 4 on connections.

3.4 Flexural Members

In addition to the design considerations already included in this section, consideration should be given to the need of additional design provisions for the following areas:

1. Lateral buckling of beams
2. Torsional resistance of beams
3. Tapered members
4. Beams with curved webs
5. Beams having perforated elements

3.4.1 Maximum Web Depth

3.4.4 Bending Stresses in Webs

3.4.5 Shear Stresses in Webs

3.4.6 Combined Bending and Shear Stresses in Webs

3.4.7 Concentrated Loads and Reactions

Consideration should be given to the revision of these five subsections for the design of beam webs on the basis of the 1980

Edition of the AISI Specification,[2.1] the available research reports, and the results of additional tests in which very high strength sheet steels are used.

Design provisions for the combined web crippling and bending should be added.

3.5 Axially Loaded Compression Members

Consideration should be given to the use of the "effective design width" approach for all types of compression elements instead of using the Q factor.

Consideration may be given to the addition of the design provisions for the following subjects:

1. Torsional-flexural buckling of singly-symmetric shapes
2. Maximum compressive strength of sections consisting of flat and curved elements
3. Maximum compressive strength of sections having perforated elements

3.6 Members Under Combined Compression and Bending

Consideration should be given to the addition of the coefficient C_m to the second and third terms of Eq. (3.6.1).

Additional design provisions for torsional-flexural buckling failure of beam-columns in which singly-symmetric shapes are used are also needed in this section.

3.7 Cylindrical Tubular Members in Compression or Bending

A literature survey should be conducted to up-date the design provisions.

SECTION 4 - CONNECTIONS

4.1 Spacing of Connectors in Compression Elements

Equation (4.1b) should be revised on the basis of elastic and inelastic buckling.

Additional design provisions are needed for the following types of connections:

1. Welded connections
2. Bolted connections
3. Screwed connections
4. Connections joined with adhesives

Consideration should be given to the fatigue strength of sheet steels.

VI. 2. Recommended Structural Research

In order to revise the current AISI Guide and to develop some additional new design criteria as suggested in Article VI.1, the following structural research is recommended:

A. AISI Guide To Be Used for Static Load Only

If the AISI Guide is intended for the design of automotive structural components subjected only to static load, the following tasks are recommended for Phase II of this program:

a. Establishment of specific minimum requirements on ductility for automotive structural framing components

b. Development of design provisions for stiffened curved elements

c. Further study of the structural strength of unstiffened compression elements. This study would involve some tests of beams and stub columns for which very high strength sheet steels are used.

d. Torsional resistance of beams

e. Beams with curved webs

f. Beams and compression members having perforated elements

g. Additional studies of beam web strength for bending, web crippling, and combined web crippling and bending in which beams cold-formed from very high strength sheet steels are used.

h. Maximum compressive strength of sections consisting of flat and curved elements

i. Revision of the design provisions for cylindrical tubes when necessary

j. Development of design provisions for welded connections

k. Development of design provisions for using mechanical fasteners

l. Development of design provisions for using adhesives

The above list does not cover all the suggested revisions because some revisions can be completed on the basis of available information without an extensive study.

B. <u>AISI Guide To Be Used for Static, Dynamic, and Impact Loads</u>

For these conditions, most design provisions must be studied for dynamic effects. Addtional tests in which dynamic loads are applied would be needed to verify the existing design provisions. Detailed recommendations should be made at the completion of the research work suggested in Article VI.2.A.

VII. SUMMARY

During recent years, various types of high strength sheet steels have been used for car bodies in order to reduce the weight of the vehicles and to achieve fuel economy.

In February 1981, the "Guide for Preliminary Design of Sheet Steel Automotive Structural Components" was issued by the American Iron and Steel Institute. However, this Guide can be used only for sheet steels with yield strengths of up to 80 ksi. Because many types of high strength steels with yield strengths from 80 to 140 ksi can be economically used for automotive structural components, a comprehensive design guide for the use of a broader range of high strength sheet steels is highly desirable.

Since early 1982, a research project entitled "Structural Design of Automotive Structural Components Using High Strength Sheet Steels" was conducted at the University of Missouri-Rolla under the sponsorship of American Iron and Steel Institute. The preliminary study (Phase I) of this program included a review of the literature of automotive structures, a study of typical mechanical properties and stress-strain curves for a selected group of high strength sheet steels, and a critical review of various AISI Specifications for the design of cold-formed steel members.

In this report, the need for a comprehensive design guide is discussed in Chapter I, and a planned program is presented in Chapter II. Chapter III includes a literature review of materials, design loads, structural analysis,and structural design of automotive structures.

In the experimental program, a total of 96 specimens were tested for longitudinal tension, transverse tension, longitudinal compression and transverse compression. All the tested mechanical properties and stress-strain curves are reported and evaluated in Chapter IV.

At the present time, three AISI documents are available for the design of cold-formed steel structural members. All these publications and the proposed tentative recommendations on load and resistance factor design criteria are reviewed in Chapter V. Based on the findings of this initial study, some revisions of the Guide are suggested, and needed structural research is recommended at the end of the report. These suggested tasks may be performed in the second phase of the program.

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Table 4.1

Sheet Steels Used in Phase I of the Study

AISI Designation*	Trade Designation	Nominal Sheet Size	Quantity Received from Producer
80SK	Cold-rolled, stress relieved, annealed, killed sheet steel	0.061" x 45" x 96"	5 sheets
80DF	Hot-rolled dual phase sheet steel	0.114" x 33" x 83"	10 sheets
80DK	Cold-rolled sheet steel	0.048" x 48" x 120"	12 sheets
80XF	Hot-rolled sheet steel	0.082" x 48" x 120"	6 sheets
100XF	Cold-rolled sheet steel	0.062" x 52" x 120"	6 sheets
140XF	Cold-rolled sheet steel	0.043" x 45" x 25"	6 sheets

* The AISI designation is illustrated as follows:

80 S K
K — killed
S — structural quality
80 — 80ksi, minimum yield strength

Table 4.2

Chemical Composition of the Sheet Steels Used in Phase I of the Study (Percent)

AISI Designation	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al	N	Ce	Cb	Zr
80SK	0.073	0.30	0.003	0.022	--	--	--	--	--	0.065	--	--	--	--
80DF	0.06	0.94	0.009	0.011	1.61	0.02	0.02	0.50	0.39	0.01	--	0.02	--	--
80DK	0.09	0.52	0.06	0.003	--	--	--	--	--	--	--	--	--	--
80XF	0.08	0.33	0.009	0.021	--	--	--	--	--	--	--	--	--	--
100XF	0.07	0.43	0.006	0.023	--	0.11	--	--	--	0.056	--	--	0.064	0.08
140XF	0.08	0.92	0.006	0.014	0.04	--	--	--	--	0.069	--	--	0.110	0.08

Table 4.3a

Tested Mechanical Properties of 80SK Sheet Steel
Longitudinal Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LT-1	55.9	62.6	80.9	0.69	0.77	87.6	12.6	26,347	G.Y.
LT-2	58.8	67.1	82.7	0.71	0.81	88.7	12.3	27,595	G.Y.
LT-3	53.9	63.7	83.0	0.65	0.77	89.2	13.7	27,550	G.Y.
LT-4	54.9	64.0	82.3	0.67	0.78	89.7	12.3	27,006	G.Y.
Ave. Value	55.9	64.4	82.2	0.68	0.78	88.8	12.7	27,131	N/A
Representative Curve	55.2	64.2	82.0	0.67	0.78	88.7	12.3	27,131	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.99	1.00	1.00	0.99	1.00	1.00	0.97	1.00	N/A

* G. Y. = Gradual yielding

Table 4.3b

Tested Mechanical Properties of 80SK Sheet Steel
Transverse Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TT-1	56.7	67.0	87.0	0.65	0.77	91.6	6.0	29,457	G.Y.
TT-2	60.6	69.8	87.2	0.69	0.80	92.7	7.5	31,067	G.Y.
TT-3	53.3	64.3	87.0	0.61	0.74	92.0	7.4	32,327	G.Y.
TT-4	55.2	64.8	87.0	0.63	0.74	92.1	8.4	27,902	G.Y.
Ave. Value	56.5	66.5	87.1	0.65	0.76	92.1	7.3	30,188	N/A
Representative Curve	54.1	65.1	87.0	0.62	0.75	92.0	7.4	30,188	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.96	0.98	1.00	0.95	0.99	1.00	1.01	1.00	N/A

* G. Y. = Gradual yielding

Table 4.3c

Tested Mechanical Properties of 80SK Sheet Steel
Longitudinal Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LC-1	43.2	52.9	76.2	0.57	0.69	29,885	G.Y.
LC-2	41.8	51.5	75.0	0.56	0.69	28,570	G.Y.
LC-3	43.0	53.5	76.7	0.56	0.70	27,481	G.Y.
LC-4	45.8	54.2	73.7	0.62	0.74	29,988	G.Y.
Ave. Value	43.5	53.0	75.4	0.58	0.70	28,981	N/A
Representative Curve	41.8	52.5	75.6	0.55	0.69	28,981	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.96	0.99	1.00	0.95	0.99	1.00	N/A

* G. Y. = Gradual yielding

Table 4.3d

Tested Mechanical Properties of 80SK Sheet Steel
Transverse Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TC-1	51.7	63.1	90.0	0.57	0.70	30,888	G.Y.
TC-2	50.5	61.9	90.2	0.56	0.69	31,691	G.Y.
TC-3	53.4	64.3	89.5	0.60	0.72	32,000	G.Y.
TC-4	54.9	65.7	89.2	0.62	0.74	29,459	G.Y.
Ave. Value	52.6	63.8	89.7	0.59	0.71	31,010	N/A
Representative Curve	52.2	63.3	89.9	0.58	0.70	31,010	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.99	0.99	1.00	0.98	0.99	1.00	N/A

* G. Y. = Gradual yielding

Table 4.4a

Tested Mechanical Properties of 80DF Sheet Steel
Longitudinal Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LT-1	38.3	46.9	55.2	0.69	0.85	89.0	33.3	27,146	S.Y.
LT-2	38.7	47.2	56.5	0.68	0.84	87.9	30.8	28,695	S.Y.
LT-3	35.2	43.4	56.8	0.62	0.76	88.6	31.3	23,670**	S.Y.
LT-4	36.0	44.1	54.8	0.66	0.80	89.8	30.1	28,079	S.Y.
Ave. Value	37.1	45.4	55.8	0.66	0.81	88.8	31.4	27,973	N/A
Representative Curve	36.5	44.4	55.8	0.65	0.80	88.6	31.3	27,973	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.98	0.98	1.00	0.98	0.99	1.00	1.00	1.00	N/A

* S. Y. = Sharp yielding. ** This value was not used in the calculation of the average value.

Table 4.4b

Tested Mechanical Properties of 80DF Sheet Steel
Transverse Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TT-1	37.6	46.2	58.0	0.65	0.80	88.8	28.1	29,156	S.Y.
TT-2	37.2	46.5	57.1	0.65	0.81	88.6	28.8	29,599	S.Y.
TT-3	36.3	44.8	57.1	0.64	0.78	89.3	27.1	27,587	S.Y.
TT-4	37.7	46.8	57.3	0.66	0.82	89.0	28.3	27,789	S.Y.
Ave. Value	37.2	46.1	57.4	0.65	0.80	88.9	28.1	28,532	N/A
Representative Curve	36.3	45.7	57.3	0.63	0.80	88.8	28.1	28,532	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.98	0.99	1.00	0.97	1.00	1.00	1.00	1.00	N/A

* S. Y. = Sharp yielding

Table 4.4c

Tested Mechanical Properties of 80DF Sheet Steel
Longitudinal Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LC-1	32.2	42.6	58.3	0.55	0.73	32,505	G.Y.
LC-2	34.9	44.0	58.8	0.59	0.75	31,493	G.Y.
LC-3	32.9	42.9	57.3	0.57	0.75	33,627	G.Y.
LC-4	33.9	43.9	57.3	0.59	0.77	31,872	G.Y.
Ave. Value	33.5	43.4	57.9	0.58	0.75	32,374	N/A
Representative Curve	35.4	43.5	58.0	0.61	0.75	32,374	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.06	1.00	1.00	1.05	1.00	1.00	N/A

* G. Y. = Gradual yielding

Table 4.4d

Tested Mechanical Properties of 80DF Sheet Steel
Transverse Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TC-1	43.0	51.5	60.4	0.71	0.85	29,517	G.Y.
TC-2	40.2	50.0	61.4	0.65	0.81	31,781	G.Y.
TC-3	43.8	52.5	64.2	0.68	0.82	31,395	G.Y.
TC-4	38.0	46.9	59.9	0.63	0.78	28,611	G.Y.
Ave. Value	41.3	50.2	61.5	0.67	0.82	30,326	N/A
Representative Curve	42.2	50.3	61.3	0.69	0.82	30,326	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.02	1.00	1.00	1.03	1.00	1.00	N/A

* G. Y. = Gradual yielding

Table 4.5a

Tested Mechanical Properties of 80DK Sheet Steel
Longitudinal Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LT-1	37.2	45.0	57.8	0.64	0.78	87.5	24.8	26,229	G.Y.
LT-2	37.9	46.2	58.2	0.65	0.79	87.6	26.5	25,365	G.Y.
LT-3	38.7	47.1	58.8	0.66	0.80	87.8	25.5	24,227	G.Y.
LT-4	37.4	45.7	58.0	0.64	0.79	87.5	26.0	27,104	G.Y.
Ave. Value	37.8	46.0	58.2	0.65	0.79	87.6	25.7	25,731	N/A
Representative Curve	38.4	46.0	58.1	0.66	0.79	87.8	25.5	25,731	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.02	1.00	1.00	1.02	1.00	1.00	0.99	1.00	N/A

* G. Y. = Gradual yielding

Table 4.5b

Tested Mechanical Properties of 80DK Sheet Steel
Transverse Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TT-1	34.0	41.1	50.0	0.68	0.82	81.8	24.2	29,610	G.Y.
TT-2	32.3	38.9	49.2	0.66	0.79	80.9	25.2	25,129	G.Y.
TT-3	33.1	41.4	53.3	0.62	0.78	84.4	27.1	27,612	G.Y.
TT-4	36.7	44.3	55.3	0.66	0.80	88.0	26.6	33,685 **	G.Y.
Ave. Value	34.0	41.4	52.0	0.66	0.80	83.8	25.8	27,450	N/A
Representative Curve	33.4	41.4	52.6	0.63	0.79	84.4	27.1	27,450	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.98	1.00	1.01	0.95	0.99	1.01	1.05	1.00	N/A

* G. Y. = Gradual yielding. ** This value was not used in the calculation of the average value.

Table 4.5c

Tested Mechanical Properties of 80DK Sheet Steel Longitudinal Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LC-1	40.7	46.9	56.5	0.72	0.83	28,098	G.Y.
LC-2	40.1	45.9	53.1	0.76	0.86	30,530	G.Y.
LC-3	37.3	44.0	53.2	0.70	0.83	32,173	G.Y.
LC-4	41.1	46.6	53.5	0.77	0.87	30,405	G.Y.
Ave. Value	39.8	45.9	54.1	0.74	0.85	30,302	N/A
Representative Curve	41.1	46.1	53.5	0.77	0.86	30,302	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.03	1.00	0.99	1.04	1.01	1.00	N/A

* G. Y. = Gradual yielding

Table 4.5d

Tested Mechanical Properties of 80DK Sheet Steel Transverse Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TC-1	41.2	48.4	59.5	0.69	0.81	31,836	G.Y.
TC-2	38.5	45.6	56.9	0.68	0.80	29,657	G.Y.
TC-3	43.6	49.8	56.7	0.77	0.88	32,131	G.Y.
TC-4	46.8	52.7	58.9	0.79	0.89	31,821	G.Y.
Ave. Value	42.5	49.1	58.0	0.73	0.85	31,361	N/A
Representative Curve	43.5	49.3	57.8	0.75	0.85	31,361	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.02	1.00	1.00	1.03	1.00	1.00	N/A

* G. Y. = Gradual yielding

Table 4.6a

Tested Mechanical Properties of 80XF Sheet Steel Longitudinal Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LT-1	84.9	87.7	88.6	0.96	0.99	98.5	22.4	26,375	S.Y.
LT-2	79.7	85.5	89.1	0.89	0.96	99.1	24.2	26,325	S.Y.
LT-3	76.9	83.6	87.7	0.88	0.95	98.3	21.9	25,089	S.Y.
LT-4	77.3	83.6	87.9	0.88	0.95	98.7	22.6	27,284	S.Y.
Ave. Value	79.7	85.1	88.3	0.90	0.96	98.7	22.8	26,268	N/A
Representation Curve	79.4	84.9	88.3	0.90	0.96	98.7	22.6	26,268	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	N/A

* S. Y. = Sharp yielding

Table 4.6b

Tested Mechanical Properties of 80XF Sheet Steel Transverse Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TT-1	88.1	92.2	93.6	0.94	0.99	100.8	19.3	31,091	S.Y.
TT-2	86.7	92.7	93.7	0.93	0.99	101.7	18.9	30,162	S.Y.
TT-3	85.1	92.1	94.1	0.90	0.98	101.6	18.3	30,899	S.Y.
TT-4	90.6	93.5	93.5	0.97	1.00	101.5	20.0	29,041	S.Y.
Ave. Value	87.6	92.6	93.7	0.94	0.99	101.4	19.1	30,298	N/A
Representation Curve	86.8	92.7	93.7	0.93	0.99	101.7	18.9	30,298	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.99	1.00	1.00	0.99	1.00	1.00	0.99	1.00	N/A

* S. Y. = Sharp yielding

Table 4.6c

Tested Mechanical Properties of 80XF Sheet Steel
Longitudinal Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LC-1	70.6	78.1	88.5	0.80	0.88	29,254	S.Y.
LC-2	64.2	75.2	89.8	0.71	0.84	29,761	S.Y.
LC-3	66.7	78.2	90.1	0.74	0.87	27,986	S.Y.
LC-4	67.9	76.8	89.0	0.76	0.86	28,917	S.Y.
Ave. Value	67.4	77.1	89.4	0.75	0.86	28,980	N/A
Representative Curve	67.4	77.0	89.4	0.75	0.86	28,980	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.00	1.00	1.00	1.00	1.00	1.00	N/A

* S. Y. = Sharp yielding

Table 4.6d

Tested Mechanical Properties of 80XF Sheet Steel
Transverse Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TC-1	74.1	86.4	94.6	0.78	0.91	33,942	S.Y.
TC-2	69.1	84.2	94.9	0.73	0.89	34,699	S.Y.
TC-3	73.4	86.5	93.8	0.78	0.92	33,077	S.Y.
TC-4	71.8	84.9	94.3	0.76	0.90	34,371	S.Y.
Ave. Value	72.1	85.5	94.4	0.76	0.91	34,022	N/A
Representative Curve	77.8	87.5	94.4	0.82	0.93	34,022	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.08	1.02	1.00	1.08	1.02	1.00	N/A

* S. Y. = Sharp yielding

Table 4.7a

Tested Mechanical Properties of 100XF Sheet Steel
Longitudinal Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LT-1	92.3	101.5	113.5	0.81	0.89	113.5	8.3	30,984	S.Y.
LT-2	101.9	110.2	114.4	0.89	0.96	114.4	9.0	27,843	S.Y.
LT-3	96.0	103.9	113.6	0.85	0.91	113.6	7.4	30,143	S.Y.
LT-4	92.9	101.8	110.8	0.84	0.92	110.8	7.5	27,679	S.Y.
Ave. Value	95.8	104.4	113.1	0.85	0.92	113.1	8.1	29,163	N/A
Representative Curve	95.2	104.4	113.1	0.84	0.92	113.5	8.3	29,163	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.99	1.00	1.00	0.99	1.00	1.00	1.02	1.00	N/A

* S. Y. = Sharp yielding

Table 4.7b

Tested Mechanical Properties of 100XF Sheet Steel
Transverse Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TT-1	105.8	115.5	123.2	0.86	0.94	123.2	4.8	32,145	S.Y.
TT-2	106.7	119.6	126.6	0.84	0.94	126.6	3.5	30,881	S.Y.
TT-3	107.1	116.2	126.3	0.85	0.92	126.3	4.2	32,028	S.Y.
TT-4	104.3	114.3	125.4	0.83	0.91	125.4	4.3	33,108	S.Y.
Ave. Value	106.0	116.4	125.4	0.85	0.93	125.4	4.2	32,040	N/A
Representative Curve	108.1	118.2	125.4	0.86	0.94	125.4	4.3	32,040	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.02	0.99	1.00	1.01	1.01	1.00	1.02	1.00	N/A

* S.Y. = Sharp yielding

Table 4.7c

Tested Mechanical Properties of 100XF Sheet Steel
Longitudinal Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LC-1	72.2	85.5	113.8	0.63	0.75	31,238	G.Y.
LC-2	73.0	85.9	112.3	0.65	0.76	30,318	G.Y.
LC-3	72.1	84.0	111.9	0.64	0.75	30,545	G.Y.
LC-4	70.8	83.8	113.5	0.62	0.74	30,319	G.Y.
Ave. Value	72.0	84.8	112.9	0.64	0.75	30,605	N/A
Representative Curve	74.1	84.5	113.3	0.65	0.75	30,605	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.03	1.00	1.00	1.02	1.00	1.00	N/A

* G. Y. = Gradual yielding

Table 4.7d

Tested Mechanical Properties of 100XF Sheet Steel
Transverse Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve
TC-1	109.9	118.2	130.6	0.84	0.91	32,450	G.Y.
TC-2	109.8	116.9	130.7	0.84	0.89	33,727	G.Y.
TC-3	115.8	121.0	128.0	0.90	0.95	33,296	G.Y.
TC-4	110.3	117.9	127.0	0.87	0.93	32,628	G.Y.
Ave. Value	111.5	118.5	129.1	0.86	0.92	33,025	N/A
Representative Curve	112.0	119.8	129.5	0.86	0.93	33,025	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.01	1.01	1.00	1.00	1.01	1.00	N/A

* G. Y. = Gradual Yielding

Table 4.8a

Tested Mechanical Properties of 140XF Sheet Steel
Longitudinal Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LT-1	116.3	130.3	140.6	0.83	0.93	140.6	5.1	30,597	S.Y.
LT-2	123.5	132.7	140.2	0.88	0.94	140.2	4.4	30,007	S.Y.
LT-3	114.7	138.1	141.6	0.94	0.97	141.6	3.8	29,452	S.Y.
LT-4	124.2	134.7	142.5	0.87	0.94	142.5	3.9	30,472	S.Y.
Ave. Value	119.7	133.9	141.2	0.88	0.94	141.2	4.3	30,132	N/A
Representative Curve	122.1	133.3	141.2	0.86	0.94	140.2	4.4	30,132	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.02	1.00	1.00	0.98	1.00	0.99	1.02	1.00	N/A

* S. Y. = Sharp yielding

Table 4.8b

Tested Mechanical Properties of 140XF Sheet Steel
Transverse Tension

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	F_u (ksi)	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TT-1	144.9	153.4	156.4	0.93	0.98	156.4	1.5	31,885	S.Y.
TT-2	140.9	151.8	157.5	0.89	0.96	157.5	1.5	32,286	S.Y.
TT-3	143.2	151.3	155.5	0.92	0.97	155.5	1.5	32,694	S.Y.
TT-4	143.6	153.8	158.3	0.91	0.97	158.3	1.6	33,473	S.Y.
Ave. Value	143.2	152.6	156.9	0.91	0.97	156.9	1.5	32,584	N/A
Representative Curve	150.8	155.8	156.9	0.96	0.99	157.5	1.5	32,584	S.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.05	1.02	1.00	1.05	1.02	1.00	1.00	1.00	N/A

* S. Y. = Sharp yielding

Table 4.8c

Tested Mechanical Properties of 140XF Sheet Steel Longitudinal Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
LC-1	100.5	113.0	139.7	0.72	0.81	29,844	G.Y.
LC-2	105.8	115.6	139.9	0.76	0.83	32,028	G.Y.
LC-3	108.2	117.4	136.2	0.79	0.86	30,490	G.Y.
LC-4	108.3	119.8	141.6	0.76	0.85	29,978	G.Y.
Ave. Value	105.7	116.5	139.4	0.76	0.84	30,585	N/A
Representative Curve	106.2	116.7	139.8	0.76	0.83	30,585	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	1.00	1.00	1.00	1.00	0.99	1.00	N/A

* G. Y. = Gradual yielding

Table 4.8d

Tested Mechanical Properties of 140XF Sheet Steel Transverse Compression

Test No.	$(F_{pr})_1$ (ksi)	$(F_{pr})_2$ (ksi)	F_y (ksi)	$\frac{(F_{pr})_1}{F_y}$	$\frac{(F_{pr})_2}{F_y}$	Modulus of Elasticity (ksi)	Type of Stress-Strain Curve*
TC-1	139.9	152.5	162.6	0.86	0.94	35,093	G.Y.
TC-2	147.2	156.7	162.3	0.91	0.97	34,697	G.Y.
TC-3	141.4	153.6	163.8	0.86	0.94	34,083	G.Y.
TC-4	146.8	156.2	164.3	0.89	0.95	34,619	G.Y.
Ave. Value	143.8	154.8	163.3	0.88	0.95	34,623	N/A
Representative Curve	141.5	152.8	163.1	0.87	0.94	34,623	G.Y.
$\frac{\text{Rep. Curve}}{\text{Ave. Value}}$	0.98	0.99	1.00	0.99	0.99	1.00	N/A

* G. Y. = Gradual yielding

Mechanical Properties of Steels Referred to in Section 1.2.1 of the AISI Specification[5.2]

Trade designation	ASTM designation	Thickness, in.	Minimum yield point or yield strength, F_y ksi	Minimum ultimate strength, F_u ksi	F_u/F_y ratio	Minimum elongation, percent	
						in 2-in. gage length	in 8-in. gage length
Zinc-coated Steel Sheets of Structural Quality	A446 A		33	45	1.36	20	-
	B		37	52	1.41	18	-
	C		40	55	1.38	16	-
	D		50	65	1.30	12	-
	E		80	82	1.03	-	-
	F		50	70	1.40	12	-
Hot-Rolled Carbon Steel Sheets and Strip of Structural Quality	A570 A	0.0255 to 0.2299	25	45	1.80	23-27	-
	B		30	49	1.63	21-25	-
	C		33	52	1.58	18-23	-
	D		40	55	1.38	15-21	-
	E		42	58	1.38	13-19	-
Hot-Rolled and Cold-Rolled High-Strength, Low-Alloy Steel Sheet and Strip with Improved Corrosion Resistance	A606 Hot-Rolled as Rolled Coils		45	65	1.44	22	-
	Hot-Rolled as Rolled Cut Lengths		50	70	1.40	22	-
Hot-Rolled and Cold-Rolled High-Strength, Low-Alloy Columbium and/or Vanadium Steel Sheet and Strip	A607Gr.45		45	60	1.33	Hot-Rolled 25 Cold-Rolled 22	- -
	50		50	65	1.30	Hot-Rolled 22 Cold-Rolled 20	- -
	55		55	70	1.27	Hot-Rolled 20 Cold-Rolled 18	- -
	60		60	75	1.25	Hot-Rolled 18 Cold-Rolled 16	- -
	65		65	80	1.23	Hot-Rolled 16 Cold-Rolled 15	- -
	70		70	85	1.21	14	

Table 5.1 (continued)

Mechanical Properties of Steels Referred to in Section 1.2.1 of the AISI Specification[5.2]

Trade designation	ASTM designation	Thickness, in.	Minimum yield point or yield strength, F_y ksi	Minimum ultimate strength F_u ksi	F_u/F_y ratio	Minimum elongation, percent	
						in 2-in. gage length	in 8-in. gage length
Cold-Rolled Carbon Structural Steel Sheet	A611 A		25	42	1.68	26	-
	B		30	45	1.50	24	-
	C		33	48	1.45	22	-
	D		40	52	1.30	20	-
	E		80	82	1.03	-	-
Hot-Rolled, High Strength, Low Alloy Steel Sheet and Strip with Improved Formability	A715 Gr.50	up to 0.097 in	50	60	1.20	22	-
	60		60	70	1.17	20	-
	A715 Gr.50	over 0.097 in	50	60	1.20	24	-
	60		60	70	1.17	22	-
Structural Steel	A36		36	58-80	1.61-2.22	23	-
High-Strength Low-Alloy Structural Steel	A242	3/4 and under	50	70	1.40	-	18*
		3/4 to 1-1/2	46	67	1.46	21	18
High-Strength Low-Alloy Structural Manganese Vanadium Steel	A441	3/4 and under	50	70	1.40	-	18*
		3/4 to 1-1/2	46	67	1.46	21	18
High-Strength Low-Alloy Columbium-Vanadium Steels of Structural Quality	A572 Gr.42		42	60	1.43	24	20
	45		45	60	1.33	22	19
	50		50	65	1.30	21	18
	55		55	70	1.27	20	17
	60		60	75	1.25	18	16
	65		65	80	1.23	17	15

Table 5.1 (continued)

Mechanical Properties of Steels Referred to in Section 1.2.1 of the AISI Specification [5.2]

Trade designation	ASTM designation	Thickness, in.	Minimum yield point or yield strength, F_y ksi	Minimum ultimate strength F_u ksi	F_u/F_y ratio	Minimum elongation, percent	
						in 2-in. gage length	in 8-in. gage length
High-Strength Low-Alloy Structural Steel with 50 ksi Minimum Yield Point	A588	4 in. and under	50	70	1.40	21	18*
Structural Steel with 42 ksi Maximum Yield Point	A529	1/2 in. Max.	42	60-85	1.43-2.02	-	19*

*For material under 5/16 in. in thickness, a deduction of 1.25 percentage points from the percentage of elongation in 8-in. specified in the above table shall be made for each decrease of 1/32 in. of the specified thickness under 5/16 in.

Notes: The tabulated values are based on ASTM Standards.

Table 5.2

Safety Factors by Subjects of the 1980 AISI Specification for the Design of Cold-Formed Steel Structural Members

Subject	Safety Factor
Effective design width for load determination	1.67 applied to yield point.
Basic design stress	1.67 applied to yield point.
Wind, earthquake and combined forces	A 25% reduction of nominal safety factor is permissable provided that the section thus designed is not less than that required for the combination of dead and live load.
Compression on unstiffened elements	1.67 applied to yield point for small w/t ratios. 1.67 applied to the inelastic buckling stress for moderate w/t ratios.
Lateral buckling of beams	1.67 against yield point and lateral buckling stress.
Shear buckling of beam webs	1.44 against shear yielding. 1.67 against inelastic buckling in shear. 1.71 against theoretical shear buckling stress.
Bending stress in webs	1.67 against theoretical buckling stress.
Web crippling of beams	1.85 against web crippling strength for single unreinforced webs. 2.0 against the web crippling strength for I-beams.
Axially loaded compression	1.92 against flexural and torsional-flexural buckling stress except that for flexural buckling of relatively stocky sections, the safety factor is 1.92 against buckling stress for slender members and of 1.67 for KL/r equals zero.

Table 5.2 (continued)

Safety Factors by Subjects of the 1980 AISI Specification for the Design of Cold-Formed Steel Structural Members

Subject	Safety Factor
Cylindrical tubular members	1.67 against yielding and local buckling stress.
Inelastic reserve capacity of flexural members	1.33 against yield moment and 1.67 against ultimate moment.
Fusion welds	2.50 against the ultimate value obtained from tests.
Resistance welds	2.50 against ultimate shear.
Bolted connections	2.00-2.22 against the failure for minimum edge distance in line of stress. 2.00-2.22 against tension failure in net section. (1.67 against yielding). 2.20-2.33 against failure in bearing. 2.25-2.52 against shear failure of the bolts.
Wall studs	1.92 against column buckling. 1.88 for computing $\bar{q}$ against the ultimate shear load of the test assembly.

Table 5.3

Ratios of the Effective Proportional Limit-to-Yield Strength for A666 Stainless Steel[5.60]

Type of Stress	Grade			
	A (Annealed)	B (Annealed)	C (¼ hard)	D (½ hard)
Longitudinal Tension	0.67	0.67	0.50	0.45
Transverse Tension	0.57	0.57	0.55	0.60
Longitudinal Compression	0.46	0.46	0.50	0.49
Transverse Compression	0.66	0.66	0.50	0.50

Notes: 1. The effective proportional limit is based on the 0.01 percent offset method.

2. Grade A is equivalent to ASTM A167 and A240 and Grade B is equivalent to ASTM A412.

Table 5.4

Yield Strengths of A666 Stainless Steel, ksi

Type of Stress	Grade			
	A	B	C	D
Longitudinal Tension	30	40* 45	75	110* 110
Transverse Tension	30	40* 45	75	100* 110
Longitudinal Compression	28	36* 41	50	65* 65
Transverse Compression	30	40* 45	90	120* 120
Shear	17	23* 25	42	56* 56

* Flat bars

Table 5.5

Initial Moduli of Elasticity and Shear Moduli of A666 Stainless Steel,[2.2] ksi

	Grade		
	A & B	C & D	
	Longitudinal and Transverse Tension and Compression	Longitudinal Tension and Compression	Transverse Tension and Compression
Initial Modulus of Elasticity	28,000	27,000	28,000
Initial Shear Modulus	10,800	10,500	10,500

Table 5.6

Plasticity Reduction Factor

Type of Buckling Stress	Plasticity Reduction Factor
Compression Element Unstiffened	E_s/E_o
Stiffened	$\sqrt{E_t/E_o}$
Lateral Buckling	E_t/E_o
Shear	G_s/G_o
Bending	E_s/E_o

Table 5.7

Summary of the Tested Mechanical Properties of Six Different Sheet Steels

Based on Tables 4.3 Through 4.8

Type of Sheet Steel	Type of Stress*	Ave. F_{pr}** (ksi)	Ave. F_y (ksi)	Ave. F_u (ksi)	F_{pr}/F_y	F_u/F_y	Elongation in 2-in. Gage Length(percent)	Modulus of Elasticity (ksi)	Remarks
80SK	LT	64.4	82.2	88.8	0.78	1.08	12.7	27,131	O.K.
	TT	66.5	87.1	92.1	0.76	1.06	7.3	30,188	$F_u/F_y < 1.08$ Elongation < 10%
	LC	53.0	75.4	-	0.70	-	-	28,981	-
	TC	63.8	89.7	-	0.71	-	-	31,010	-
80DF	LT	45.4	55.8	88.8	0.81	1.59	31.4	27,973	O.K.
	TT	46.1	57.4	88.9	0.80	1.55	28.1	28,532	O.K.
	LC	43.4	57.9	-	0.75	-	-	32,374	-
	TC	50.2	61.5	-	0.82	-	-	30,326	-
80DK	LT	46.0	58.2	87.6	0.79	1.51	25.7	25,731	O.K.
	TT	41.4	52.0	83.8	0.80	1.61	25.8	27,450	O.K.
	LC	45.9	54.1	-	0.85	-	-	30,302	-
	TC	49.1	58.0	-	0.85	-	-	31,361	-
80XF	LT	85.1	88.3	98.7	0.96	1.12	22.8	26,268	O.K.
	TT	92.6	93.7	101.4	0.99	1.08	19.1	30,298	O.K.
	LC	77.1	89.4	-	0.86	-	-	28,980	-
	TC	85.5	94.4	-	0.91	-	-	34,022	-
100XF	LT	104.4	113.1	113.1	0.92	1.00	8.1	29,163	$F_u/F_y < 1.08$ Elongation < 10%
	TT	116.4	125.4	125.4	0.93	1.00	4.2	32,040	$F_u/F_y < 1.08$ Elongation < 10%
	LC	84.8	112.9	-	0.75	-	-	30,605	-

Table 5.7 (continued)

Summary of the Tested Mechanical Properties of Six Different Sheet Steels

Based on Tables 4.3 Through 4.8

Type of Sheet Steel	Type of Stress*	Ave. F_{pr}** (ksi)	Ave. F_y (ksi)	Ave. F_u (ksi)	F_{pr}/F_y	F_u/F_y	Elongation in 2-in. Gage Length (percent)	Modulus of Elasticity (ksi)	Remarks
100XF continued	TC	118.5	129.1	-	0.92	-	-	33,025	-
140XF	LT	133.9	141.2	141.2	0.94	1.00	4.3	30,132	$F_u/F_y < 1.08$ Elongation < 10%
	TT	152.6	156.9	156.9	0.97	1.00	1.5	32,584	$F_u/F_y < 1.08$ Elongation < 10%
	LC	116.5	139.4	-	0.84	-	-	30,585	-
	TC	154.8	163.3	-	0.95	-	-	34,623	-

* LT = Longitudinal tension, TT = Transverse tension, LC = Longtiudinal compression, TC = Transverse compression

** Based on the 0.01 percent offset method

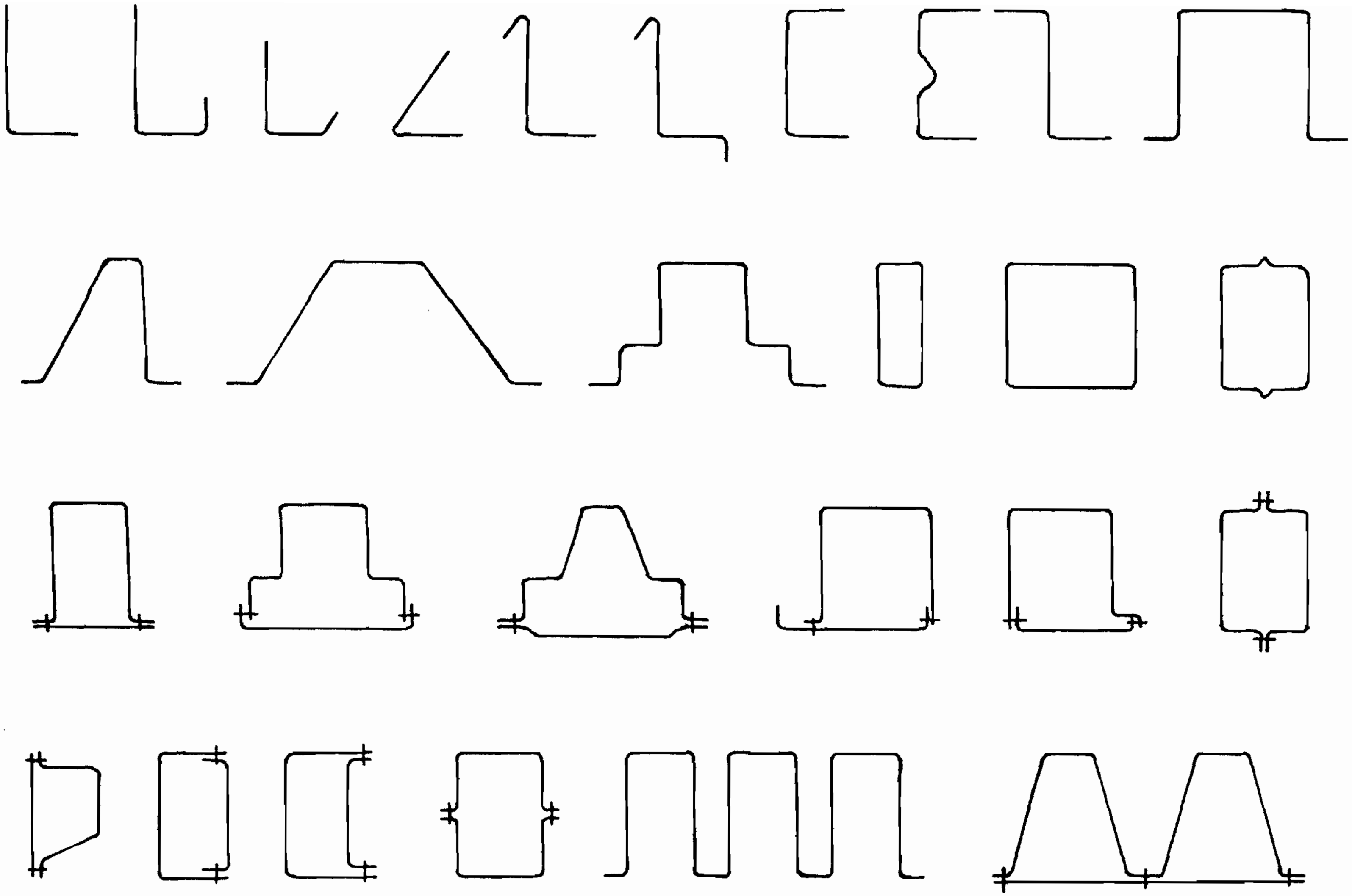


Fig. 3.1 Individual Members and Built-Up Sections Used as Structural Components of Automotive Structures

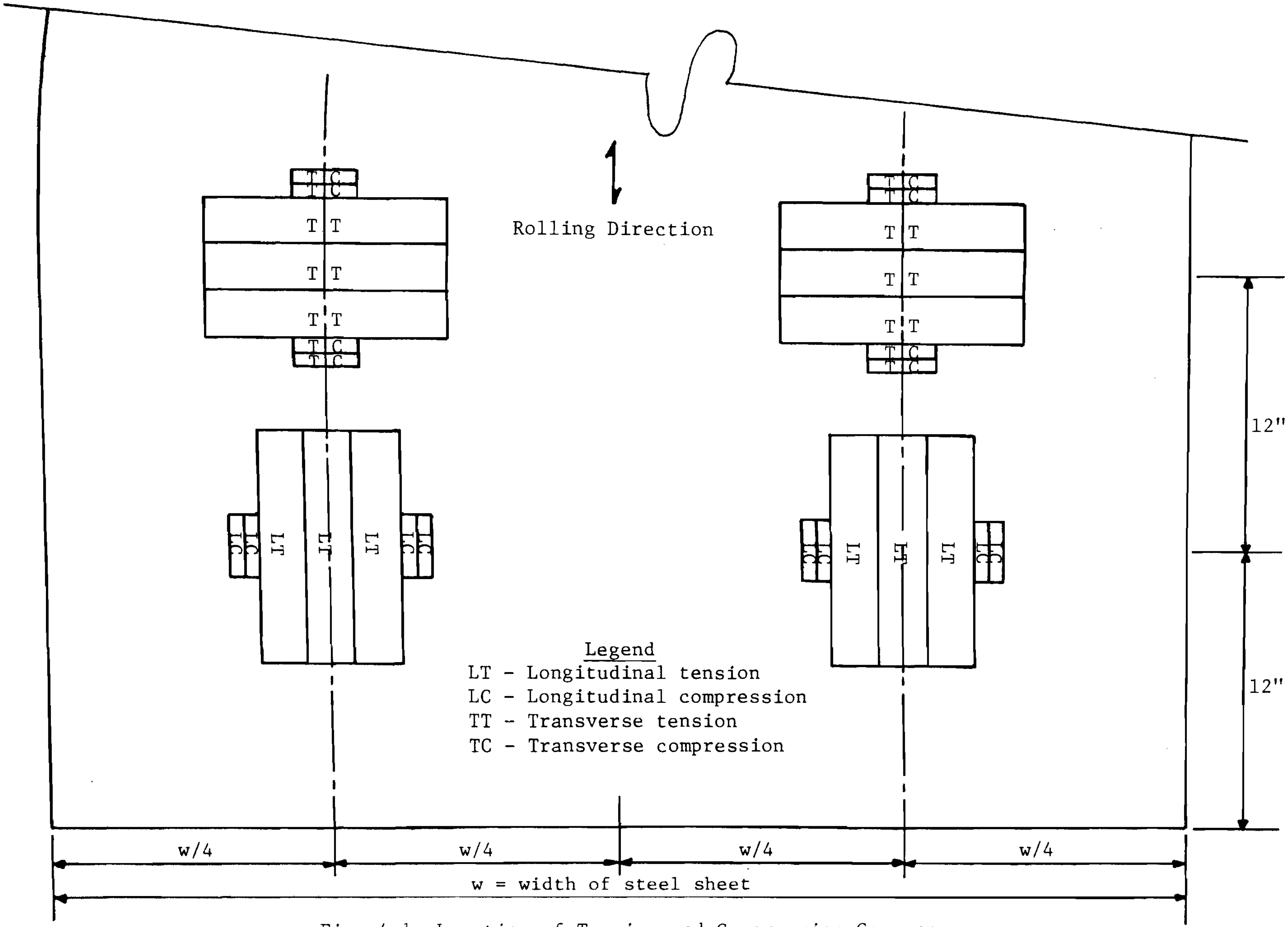


Fig. 4.1 Location of Tension and Compression Coupons

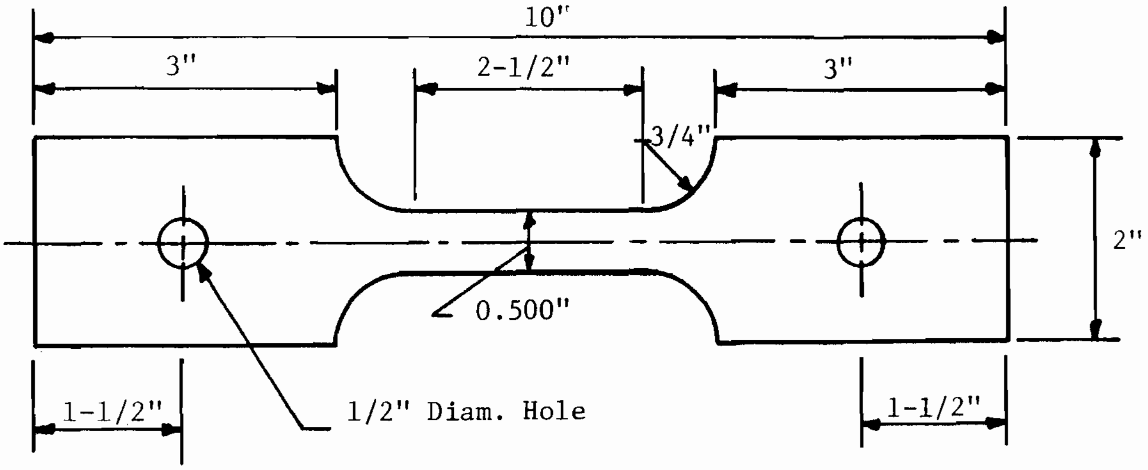


Fig. 4.2 Nominal Dimensions of Tension Coupons Used for 80SK, 80DF, 80DK, 80XF and 100XF

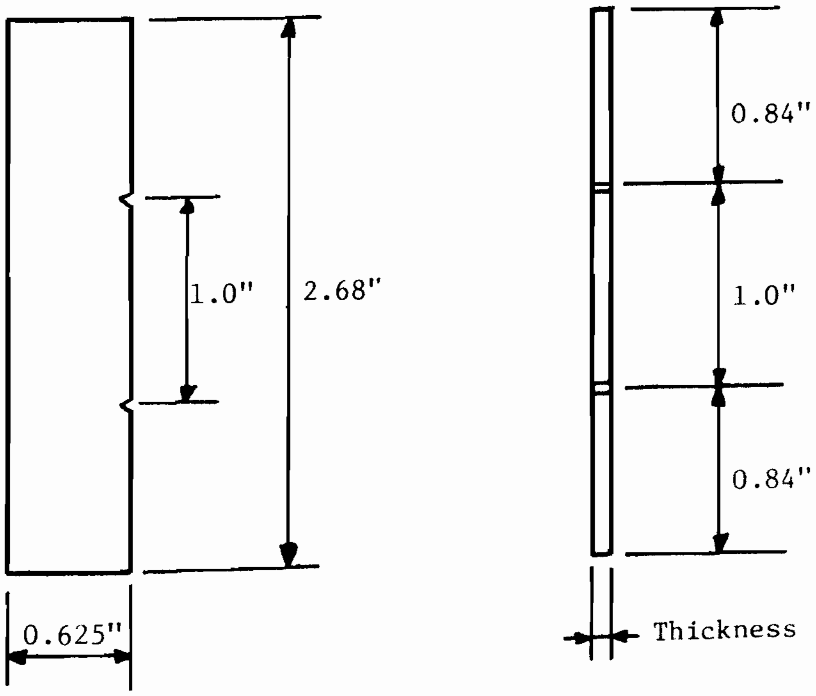


Fig. 4.3 Nominal Dimensions of Compression Coupons Used for All Sheet Steels

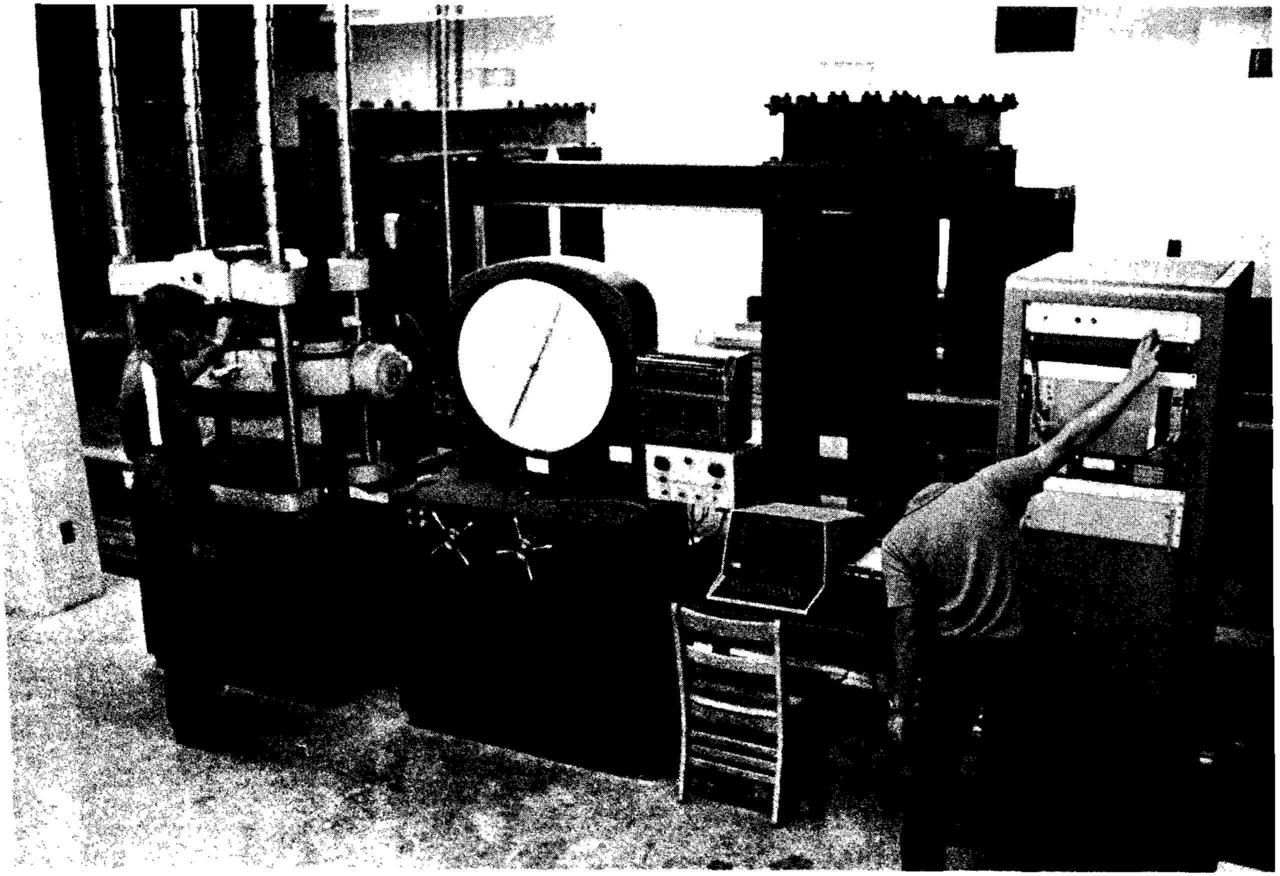


Fig. 4.4 Tinius Olsen Universal Testing Machine Used for Tension Tests

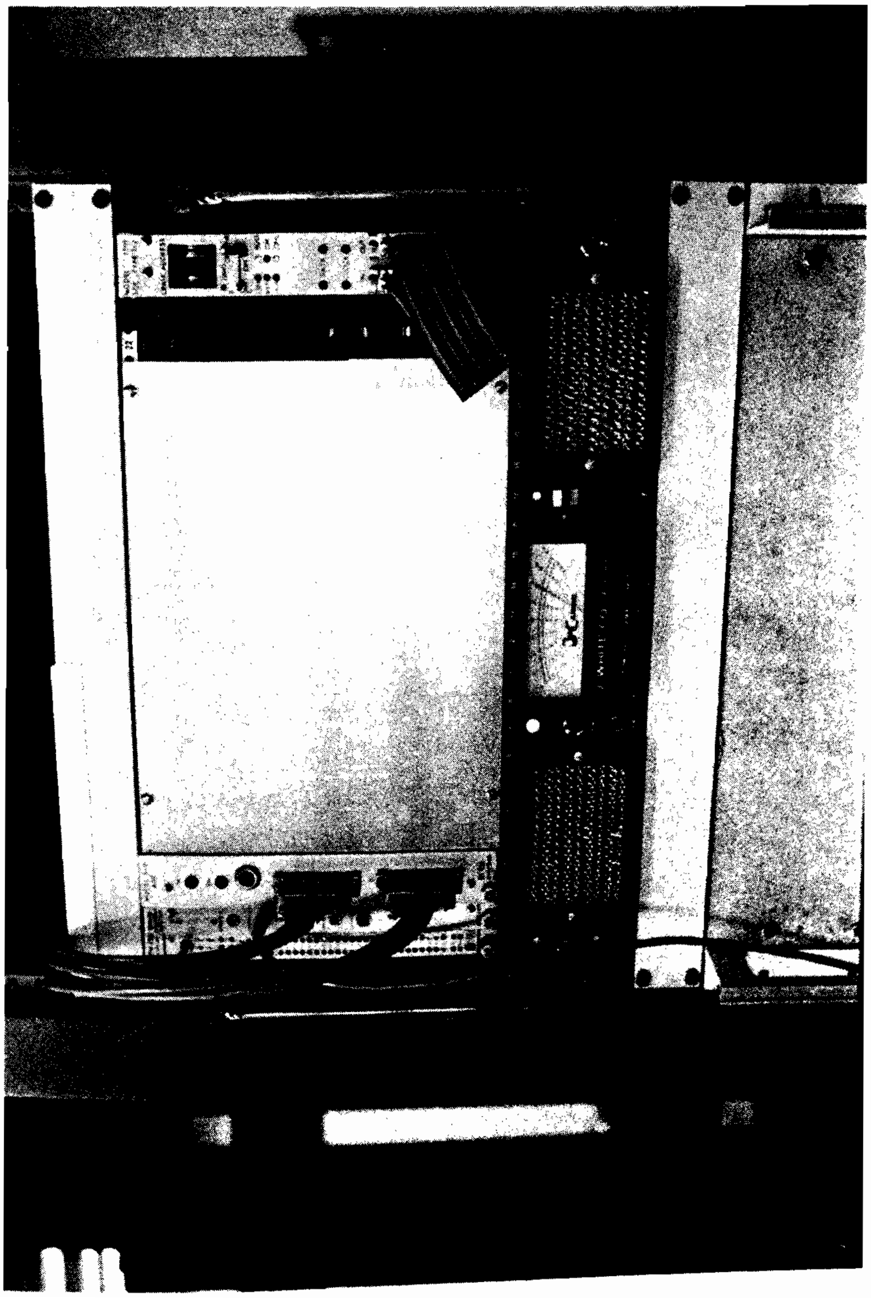


Fig. 4.5 Data Acquisition System

Fig. 4.6 Graphic Display Terminal

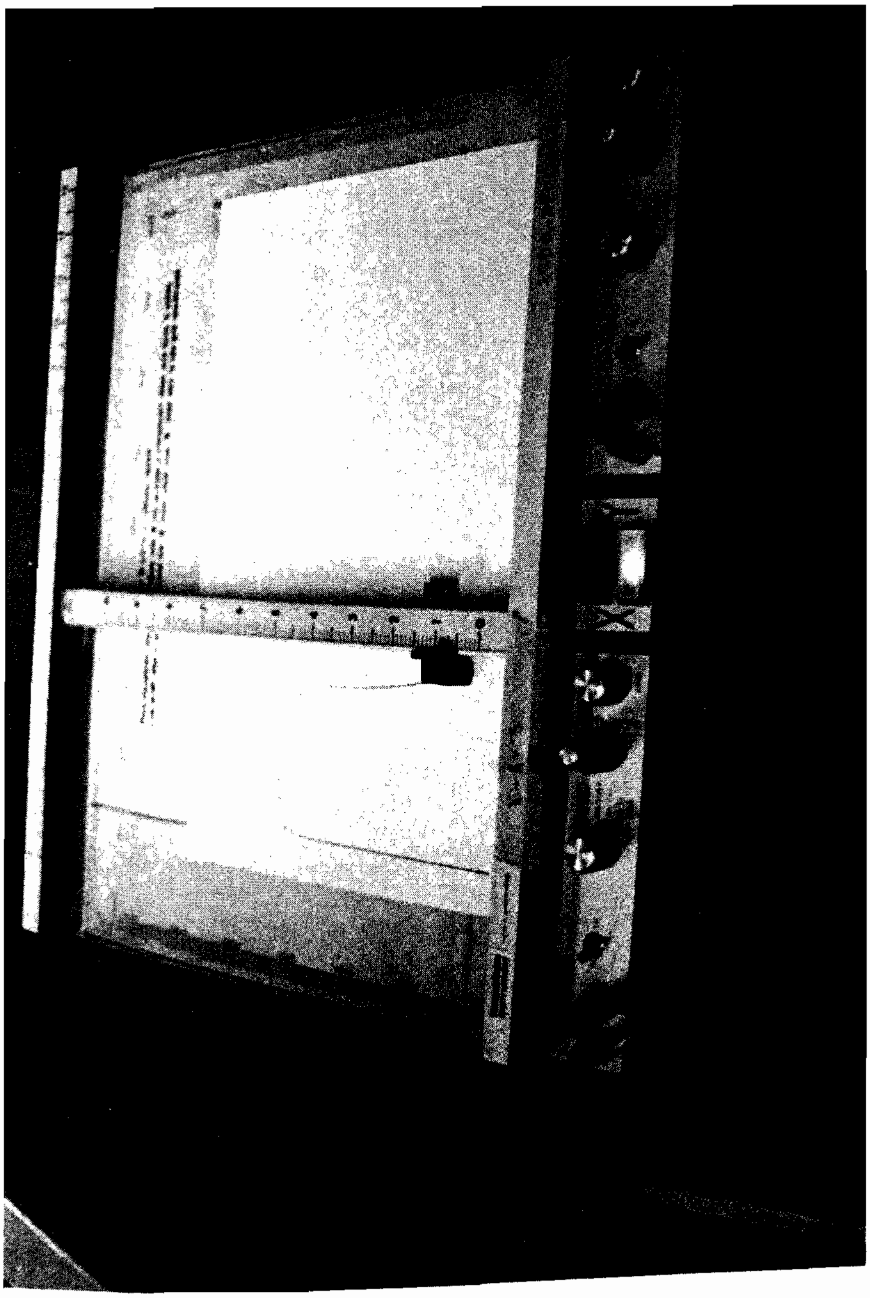


Fig. 4.7 XY Plotter

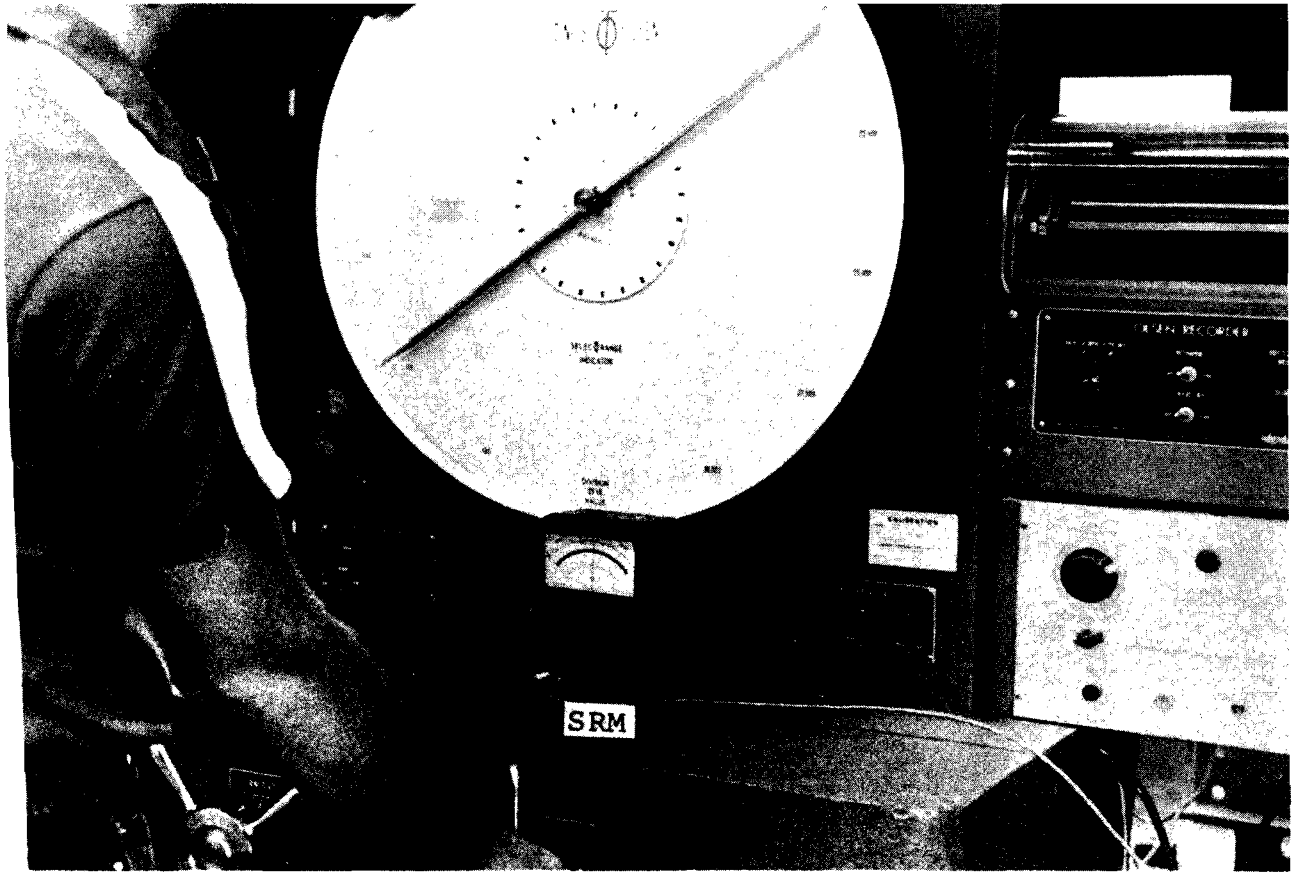


Fig. 4.8 Strain Rate Monitor (Marked as SRM)

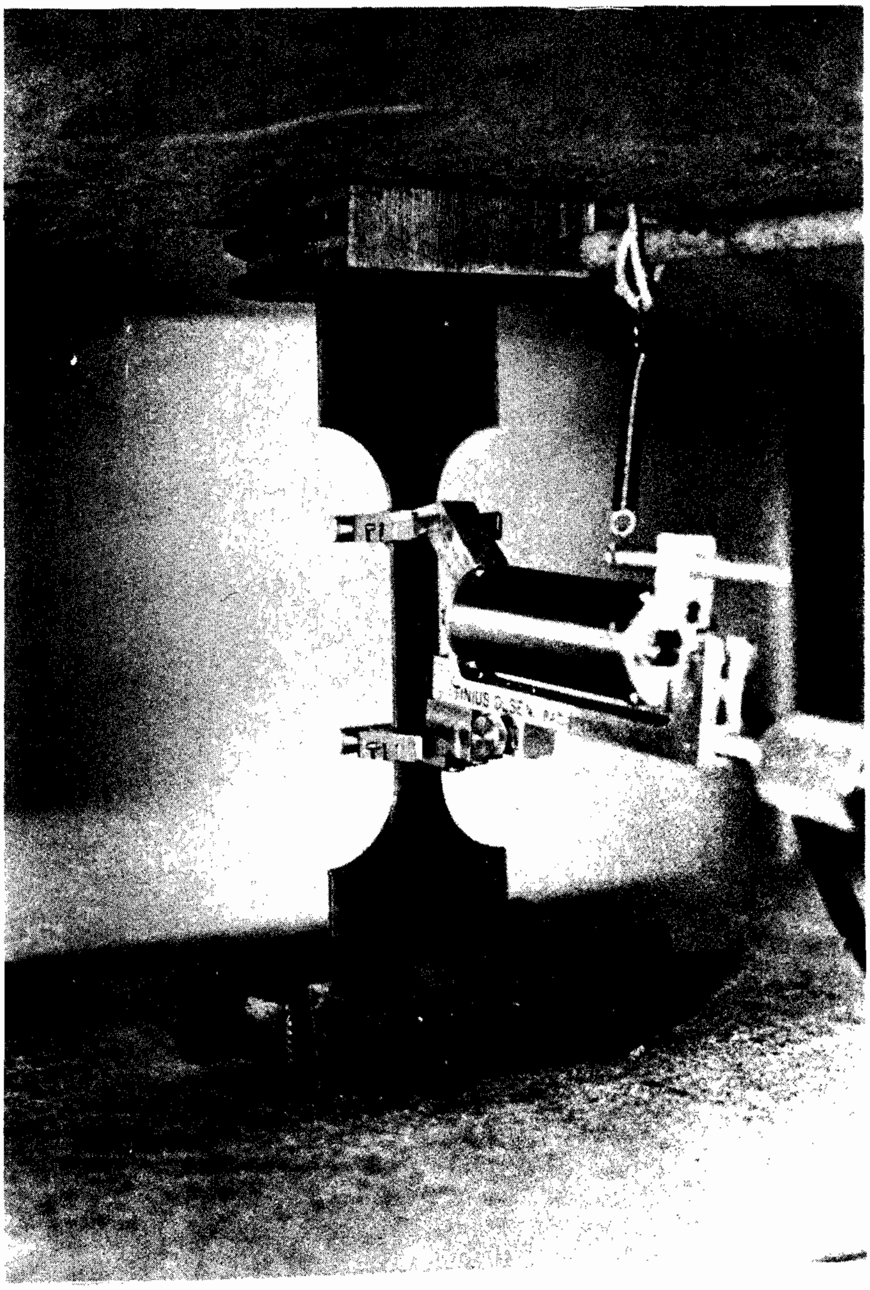


Fig. 4.9a Test Setup Showing the Attachment of Extensometer

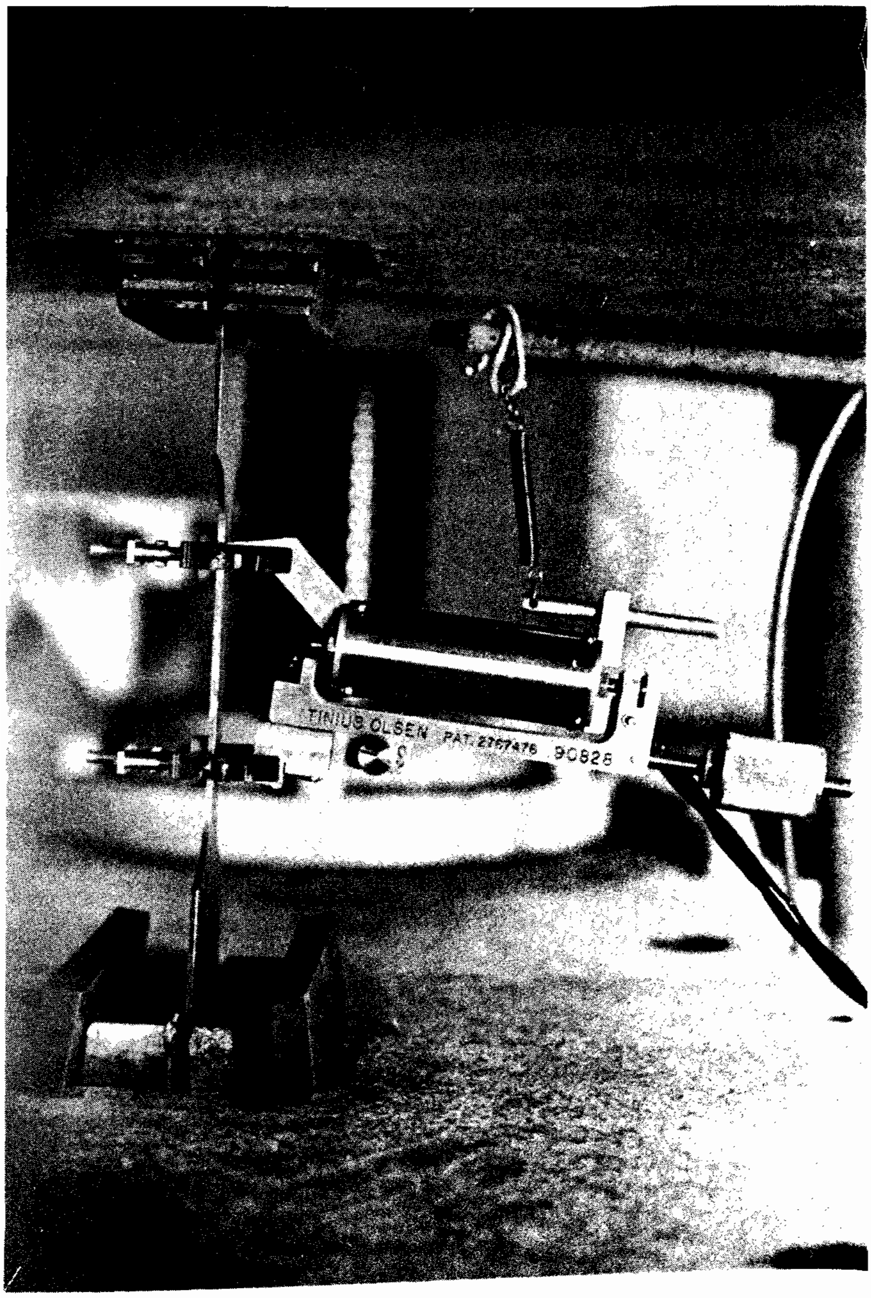


Fig. 4.9b Test Setup Showing the Attachment of Extensometer

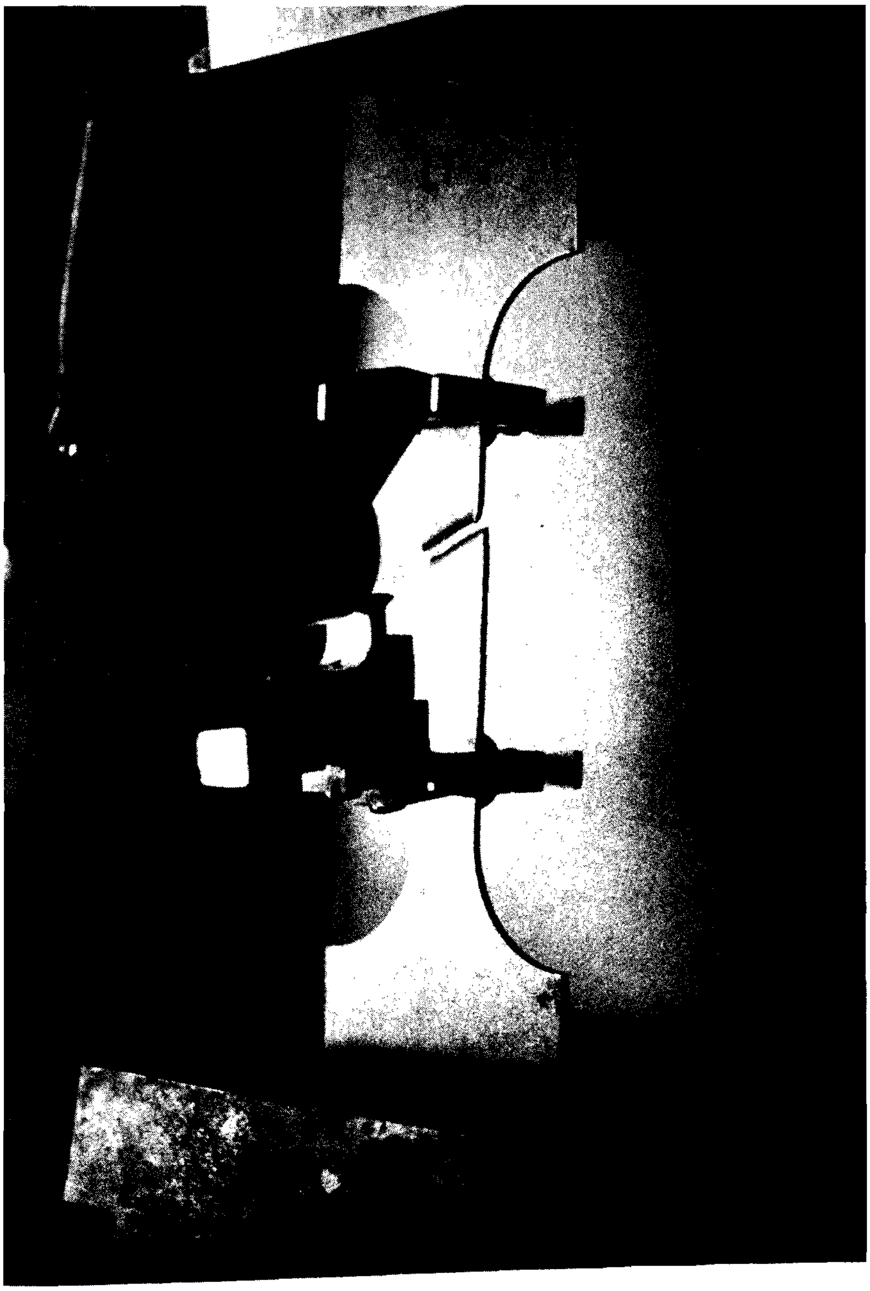


Fig. 4.10 Failure of the Tension Test Specimen

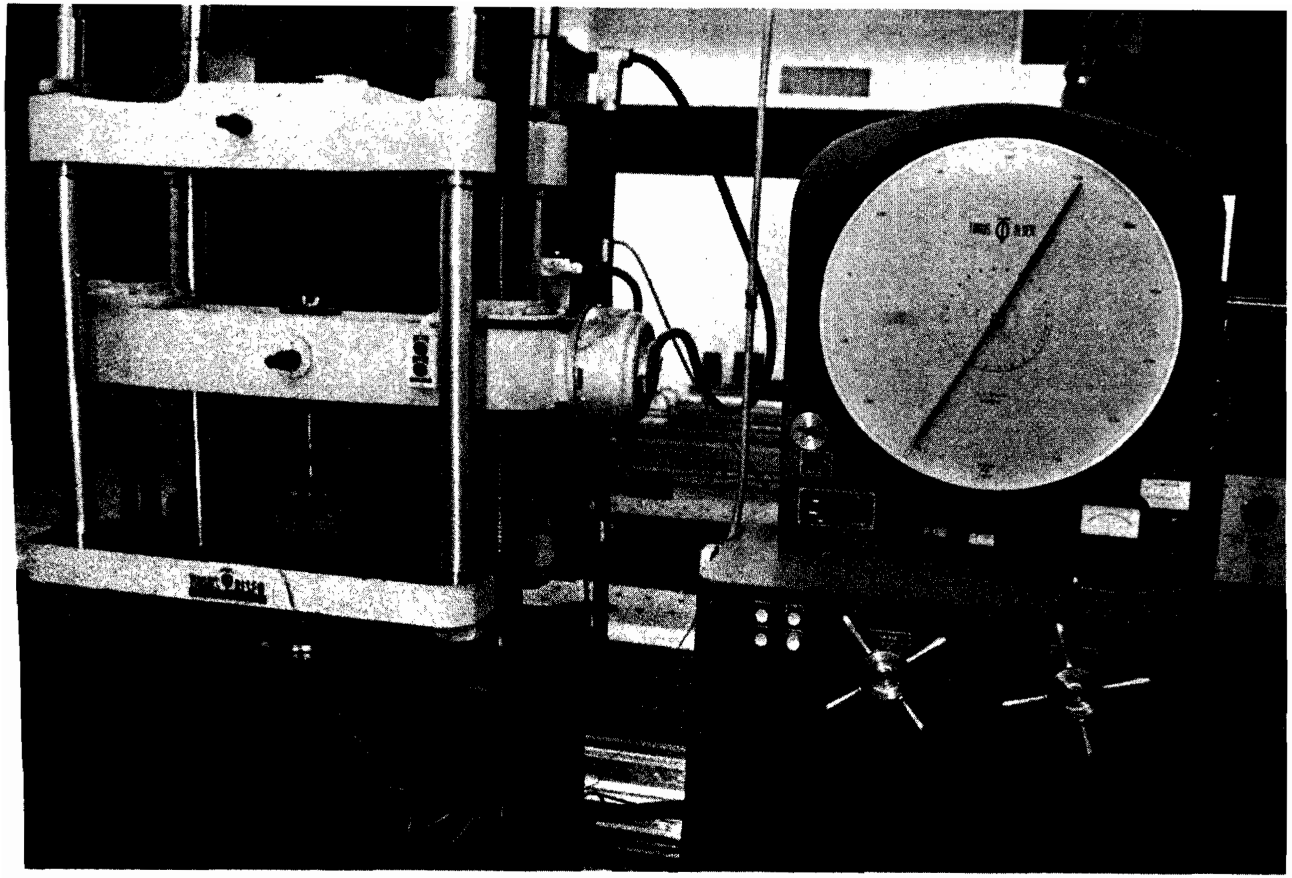


Fig. 4.11 Tinius Olsen Universal Testing Machine Used for Compression Test

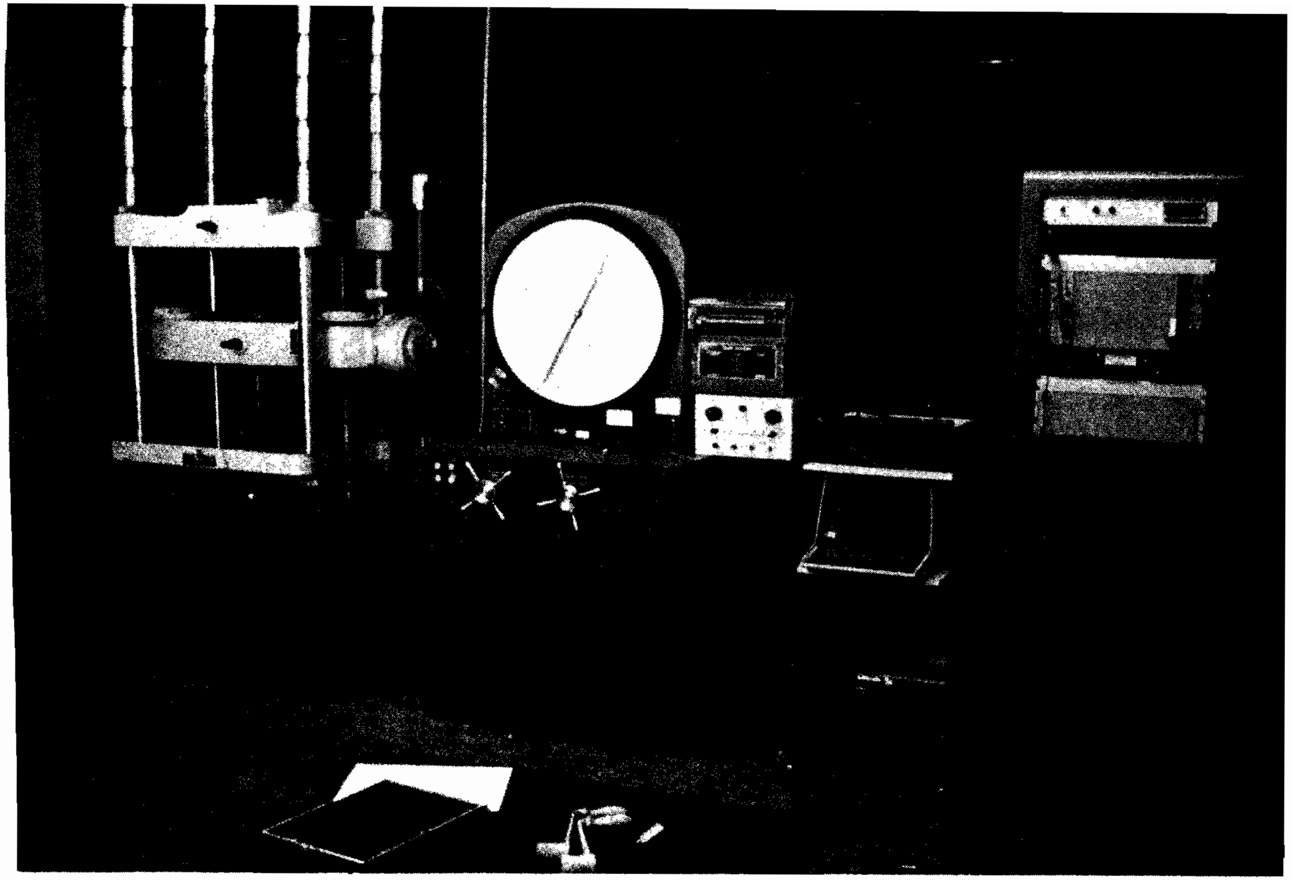
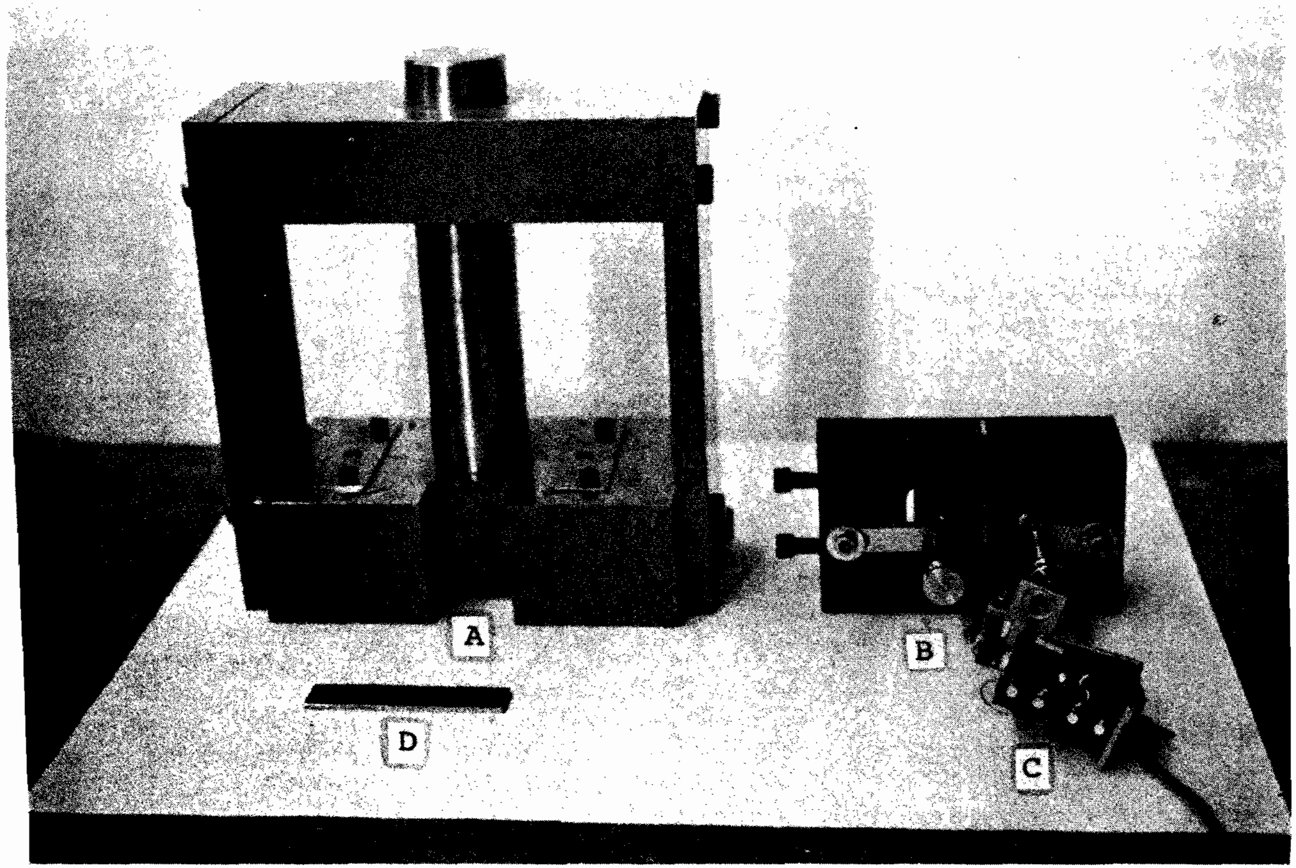


Fig. 4.12 Testing Machine, Data Acquisition System, Graphic Display Terminal, XY Plotter, and Strain Rate Monitor Used for Compression Test



A- Compression Subpress	C- Compressometer
B- Compression Jig	D- Test Specimen

Fig. 4.13 Compression Subpress, Jig, Compressometer and Test Specimen Used for Compression Test

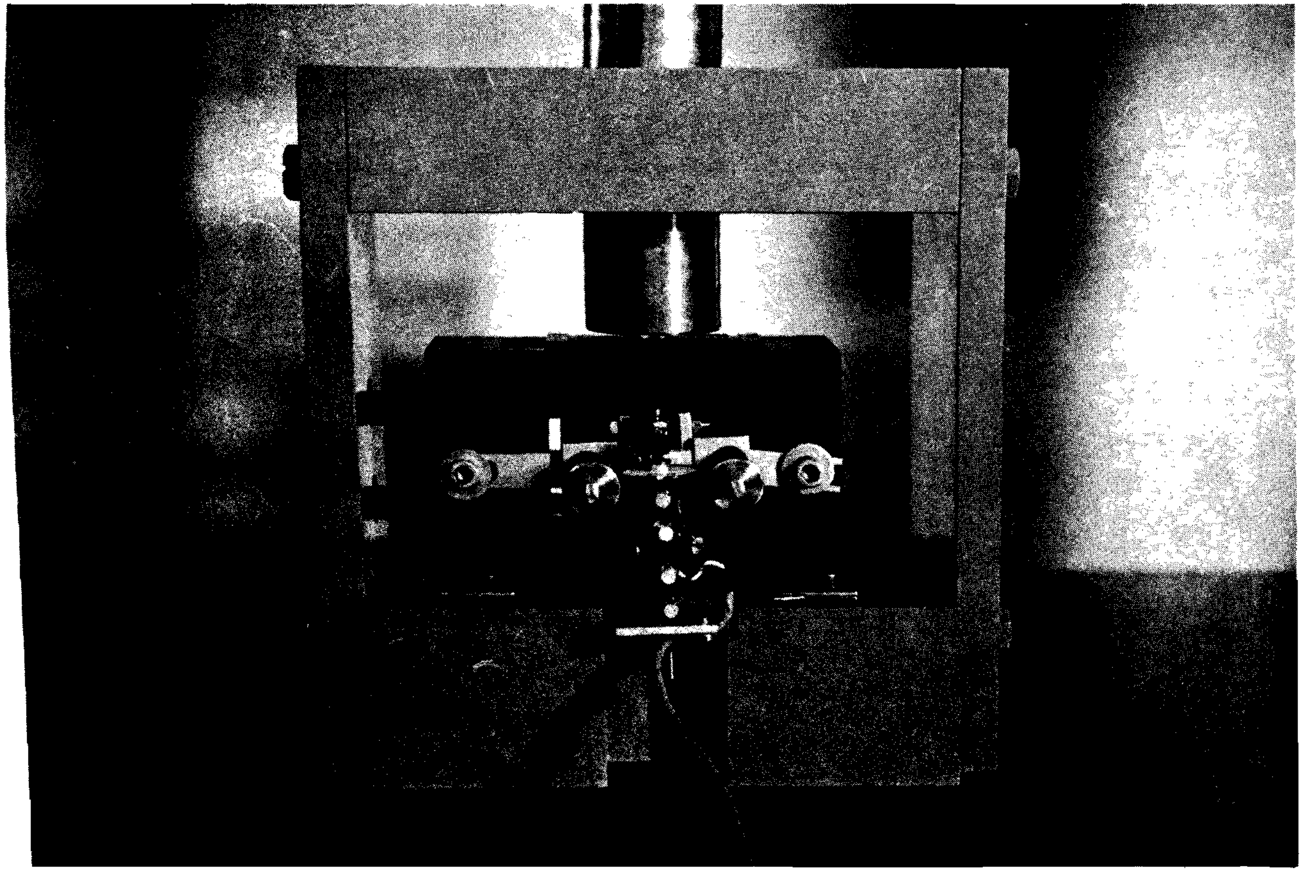


Fig. 4.14 Assembly of Compression Subpress, Jig, and Compressometer

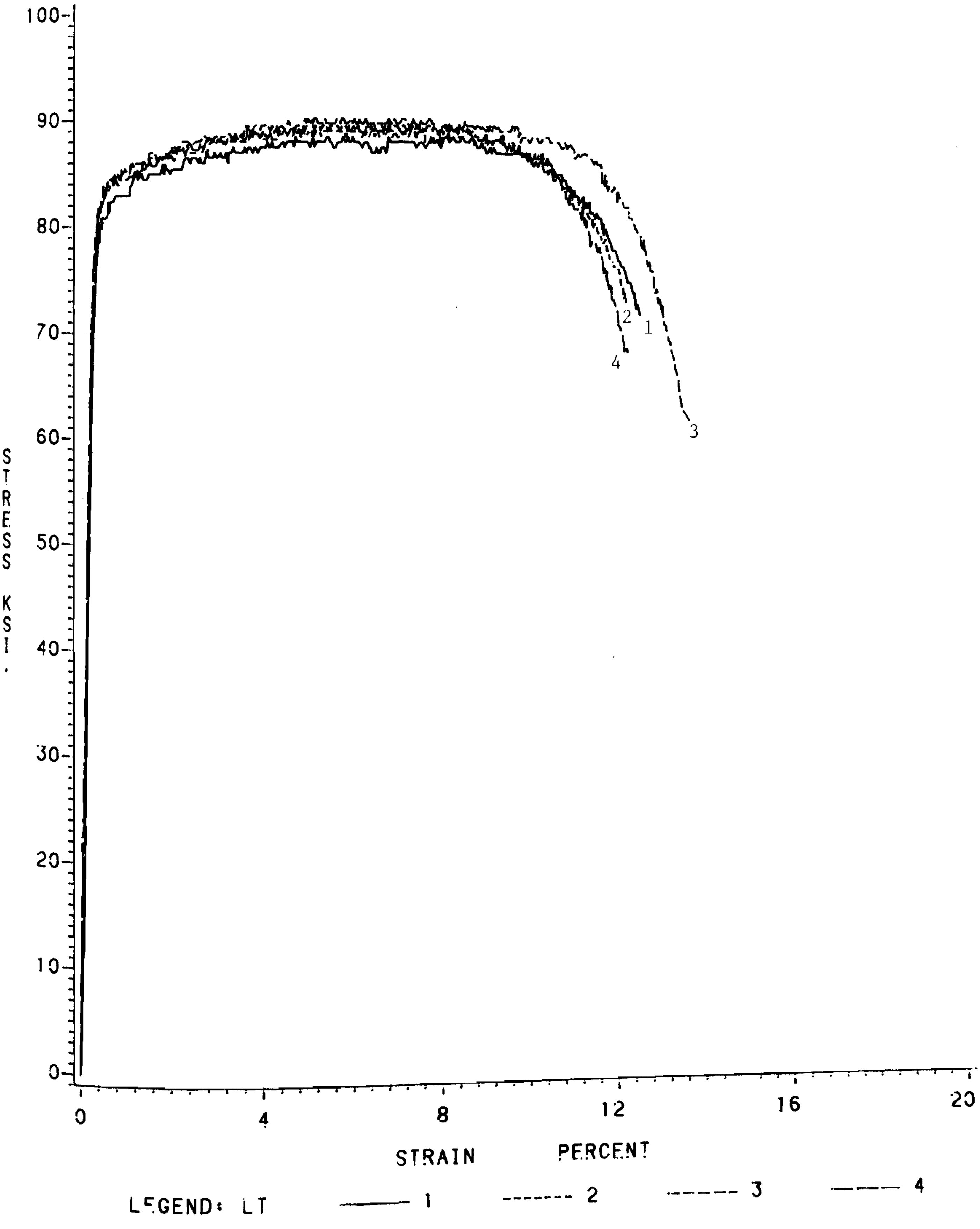


Fig. 4.15

INDIVIDUAL STRESS-STRAIN CURVE FOR 80SK-LT

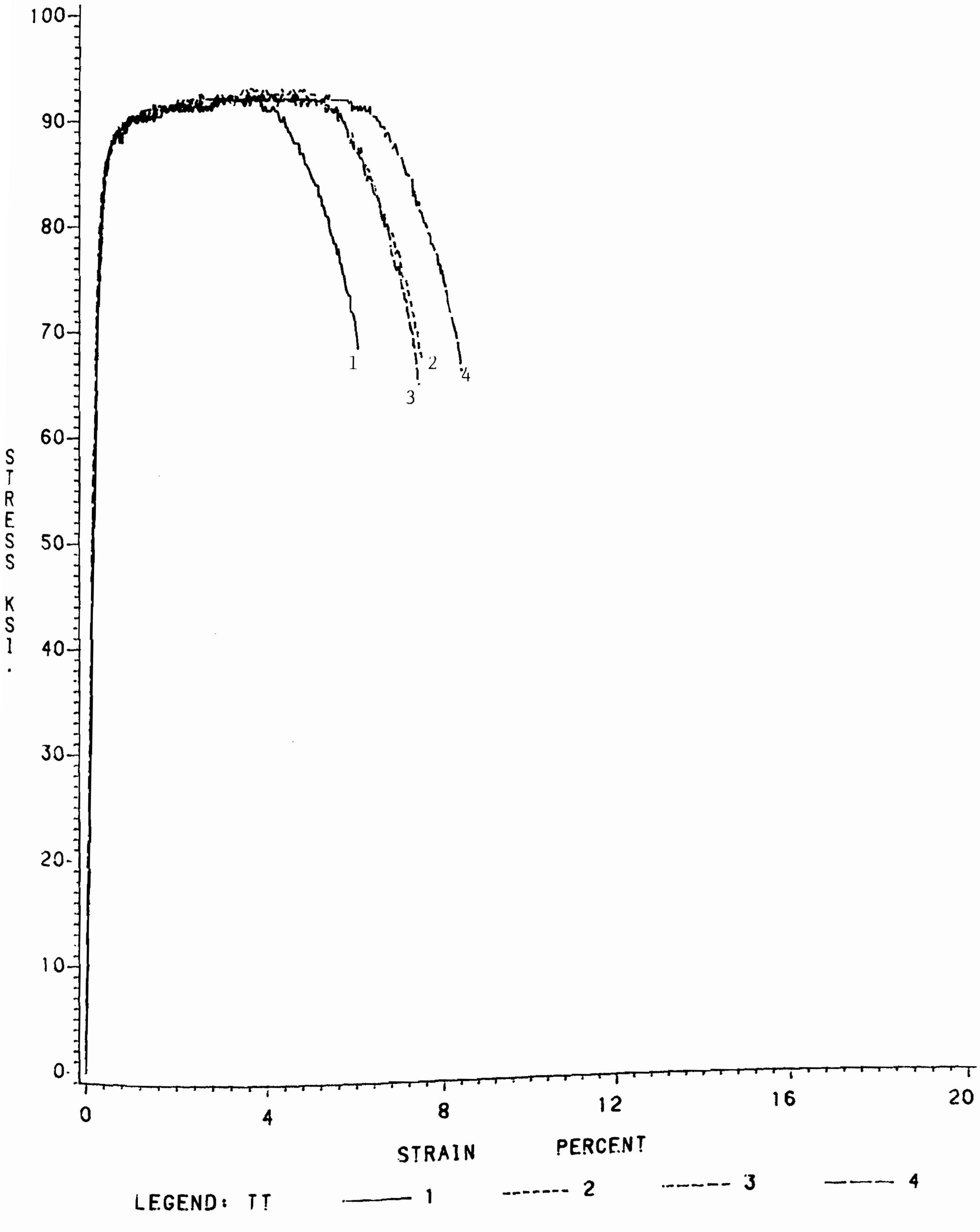


Fig. 4.16

INDIVIDUAL STRESS-STRAIN CURVE FOR 80SK-TT

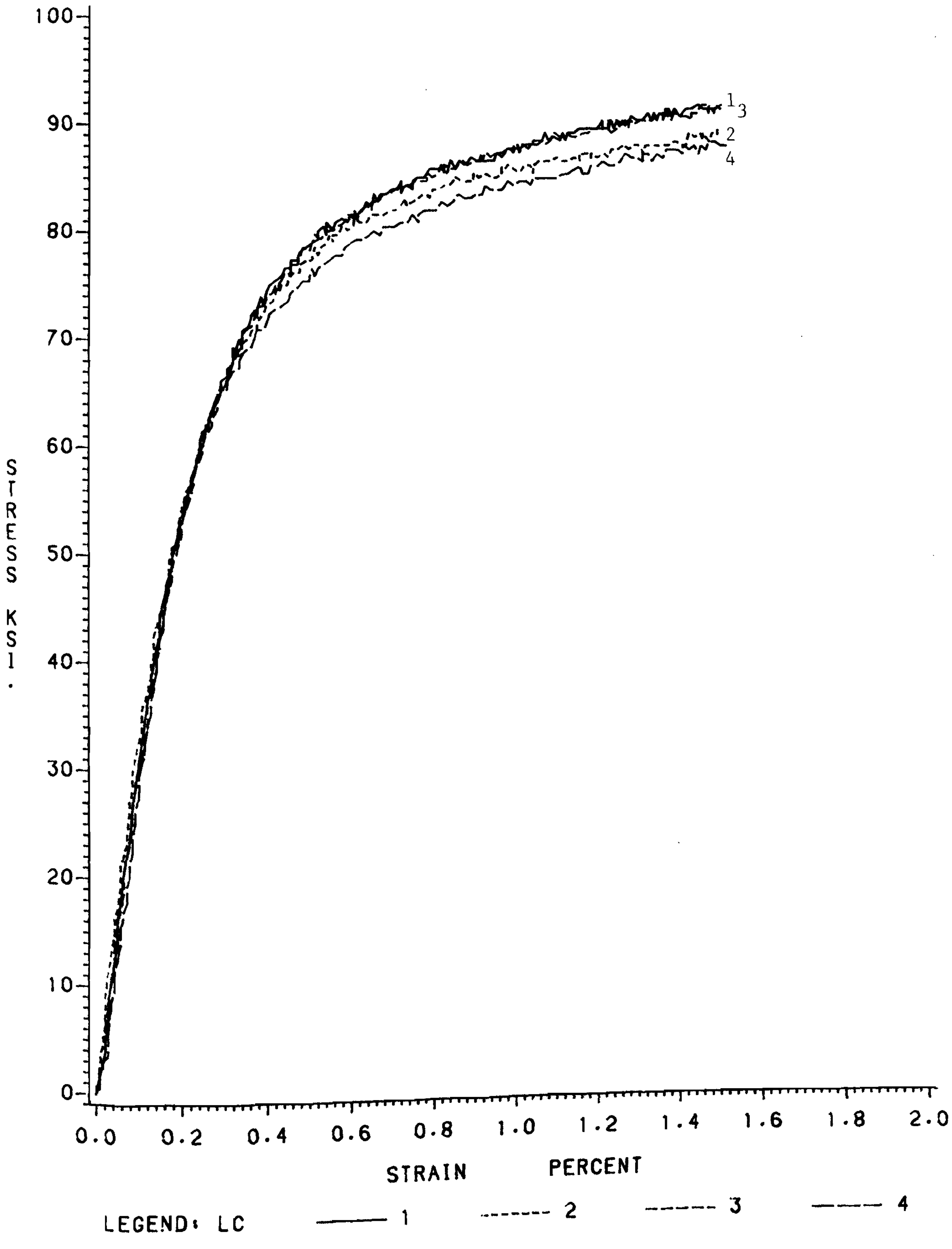


Fig. 4.17

INDIVIDUAL STRESS-STRAIN CURVE FOR 80SK-LC

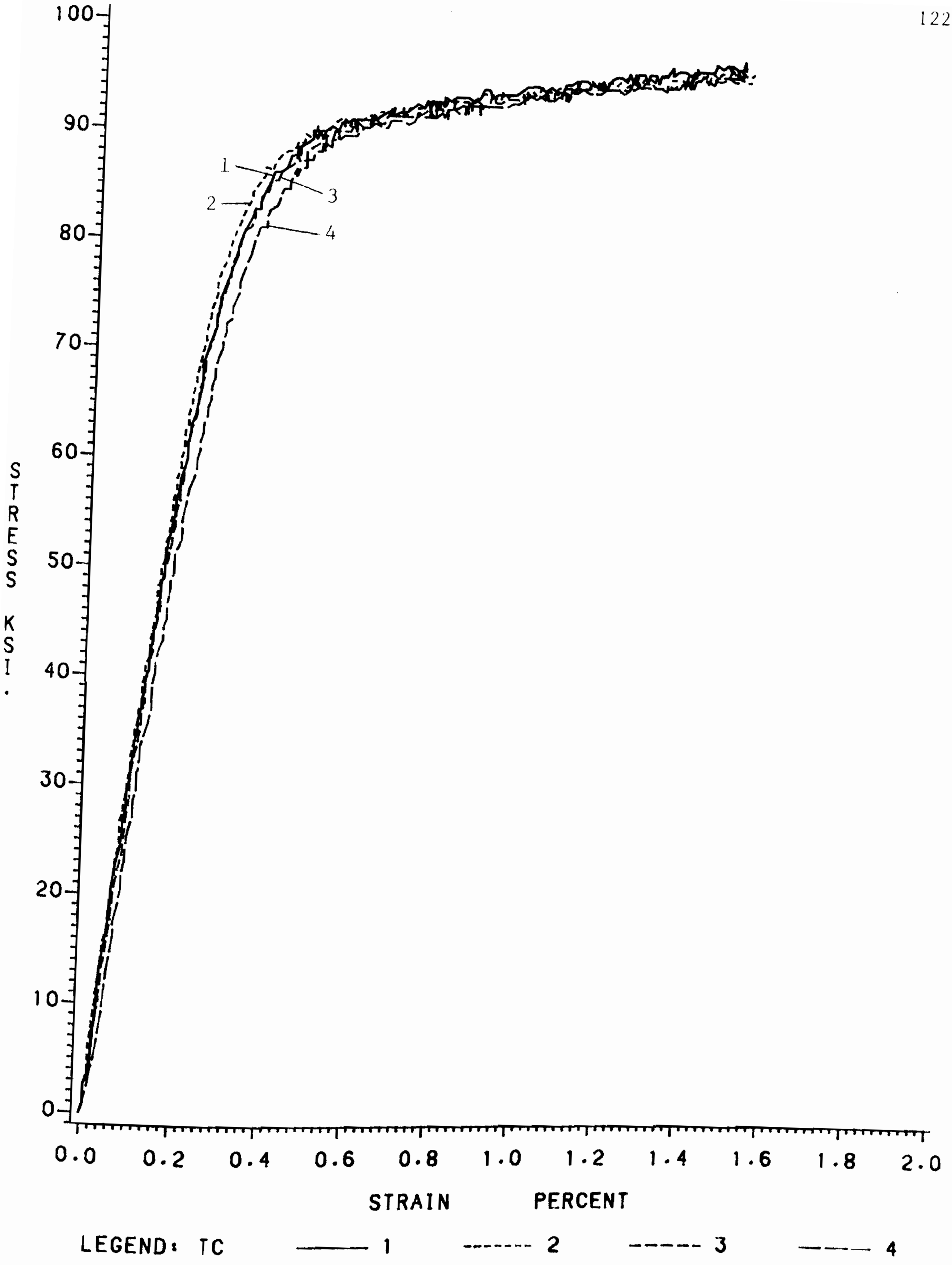


Fig. 4.18

INDIVIDUAL STRESS–STRAIN CURVE FOR 80SK–TC

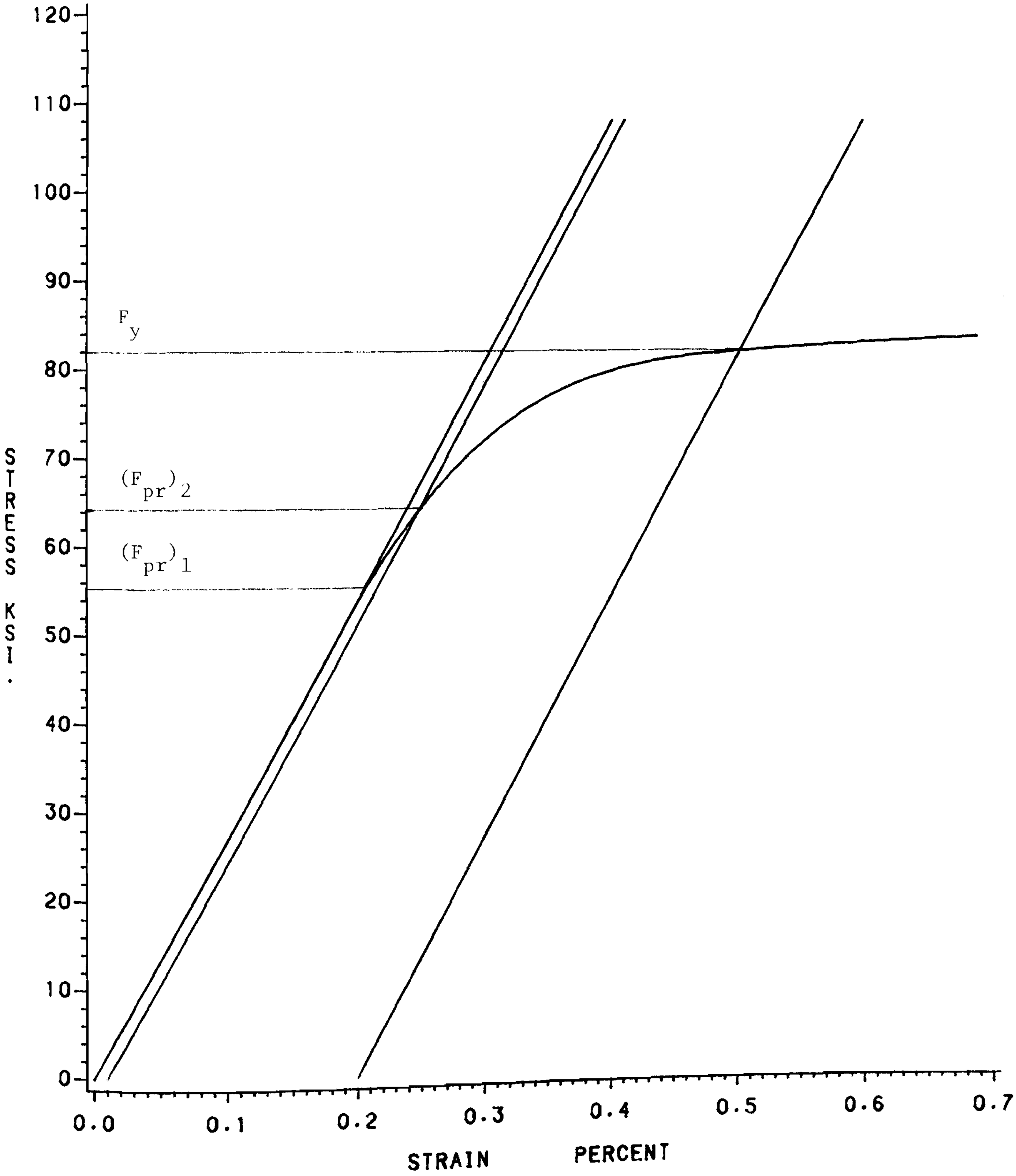


Fig. 4.19

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80SK-LT

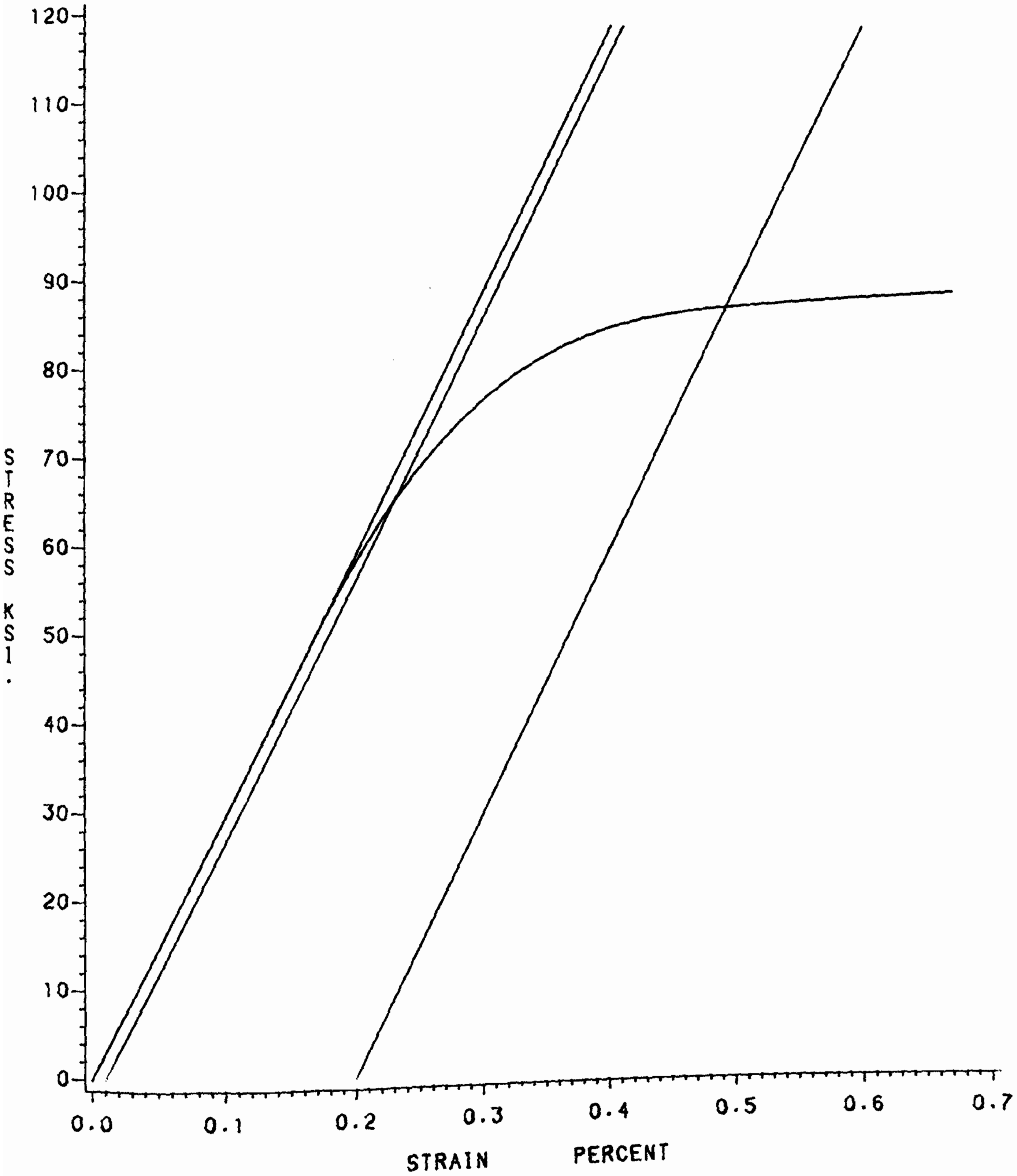


Fig. 4.20

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80SK-TT

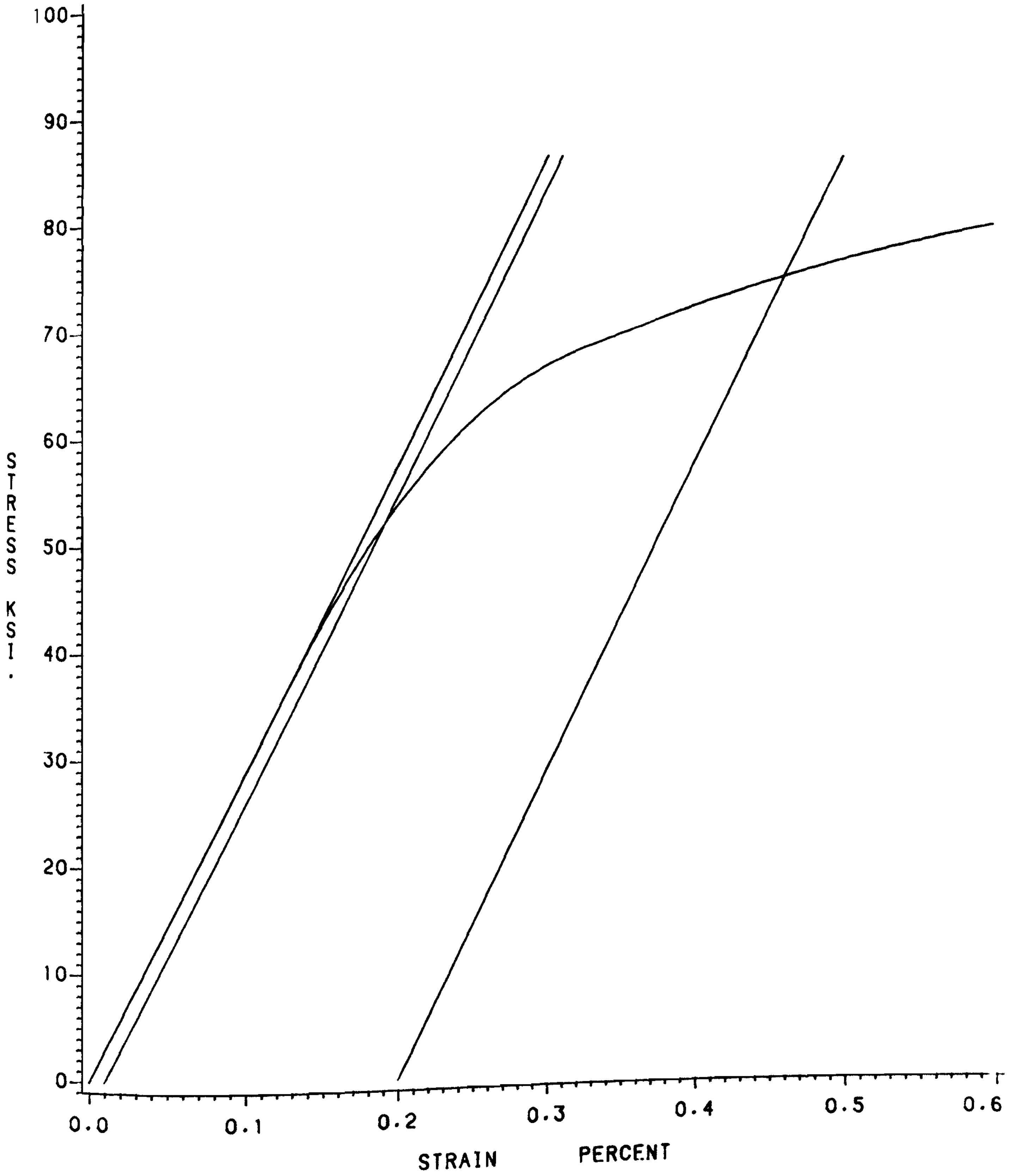


Fig. 4.21

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80SK-LC

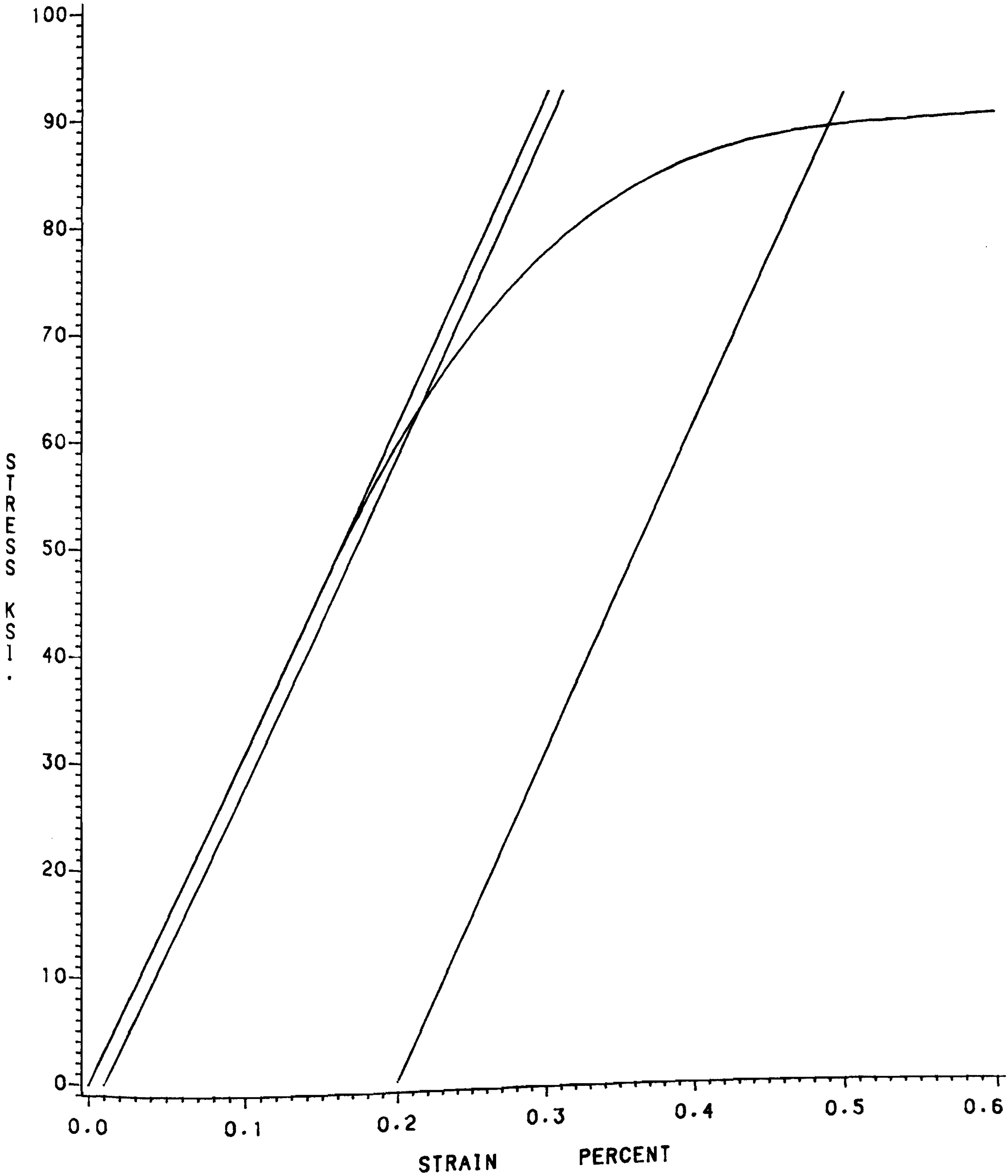


Fig. 4.22

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80SK-TC

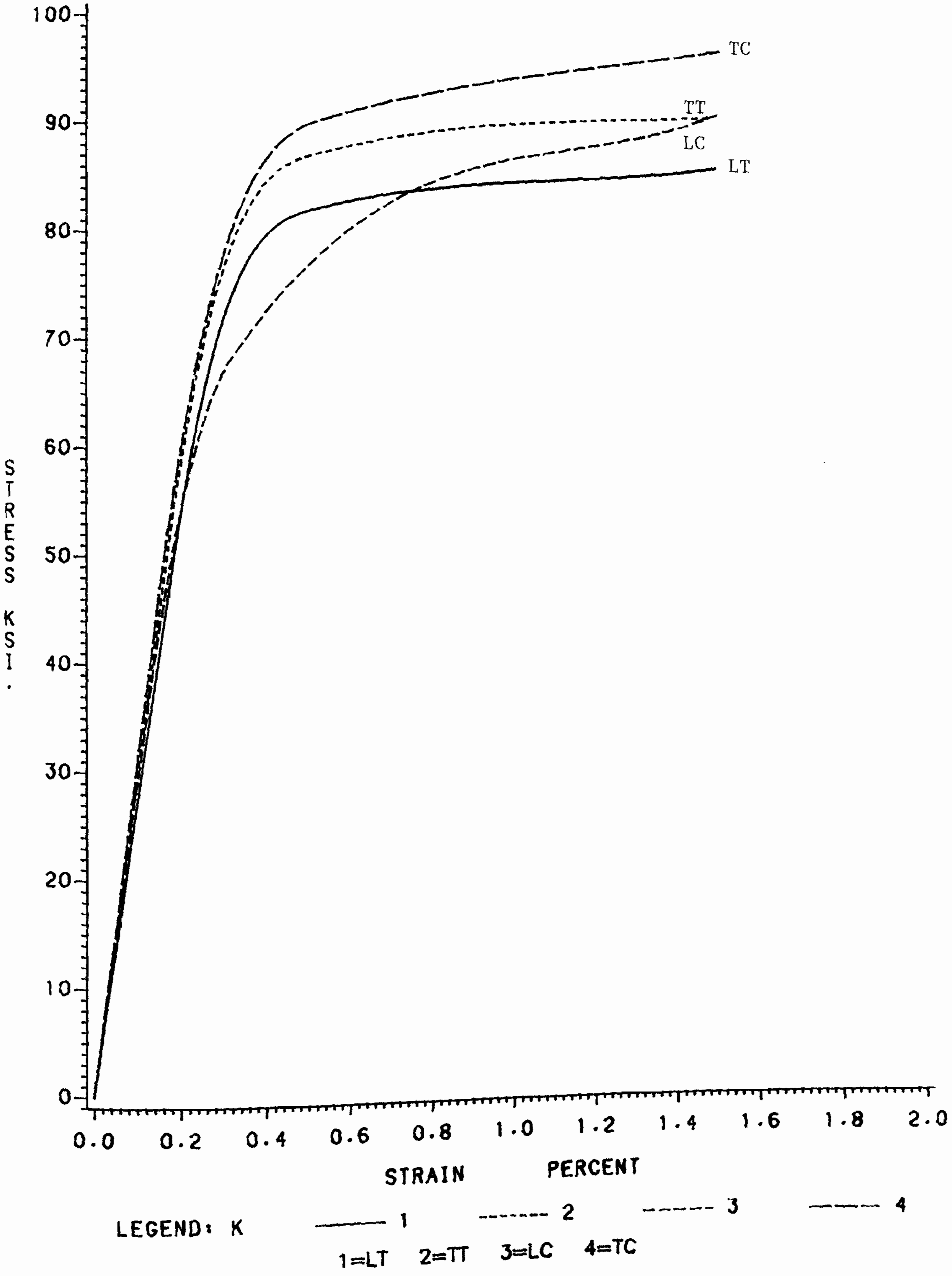


Fig. 4.23

COMPARISON OF VARIOUS TESTS FOR 80SK

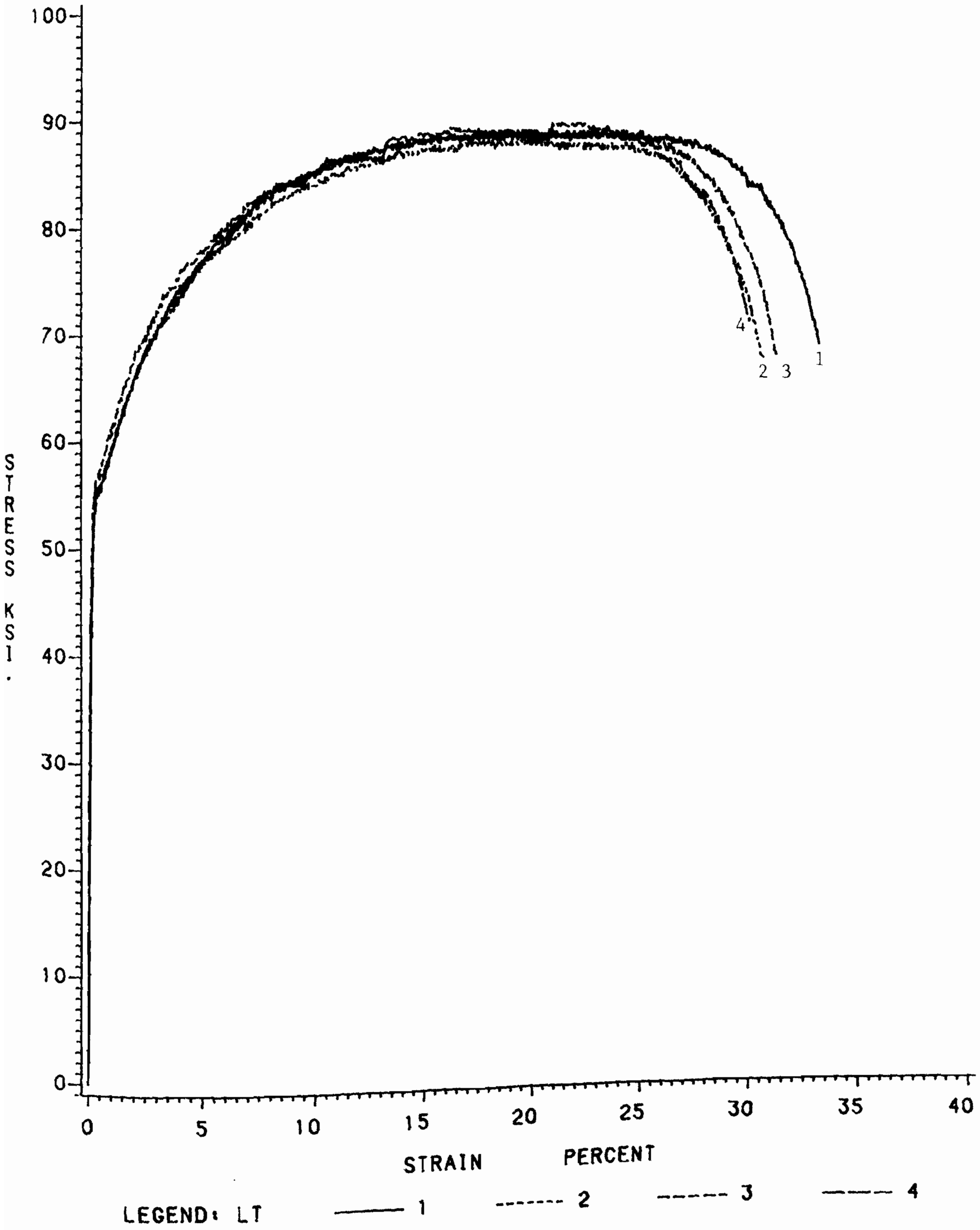


Fig. 4.24

INDIVIDUAL STRESS-STRAIN CURVE FOR 80-DF-LT

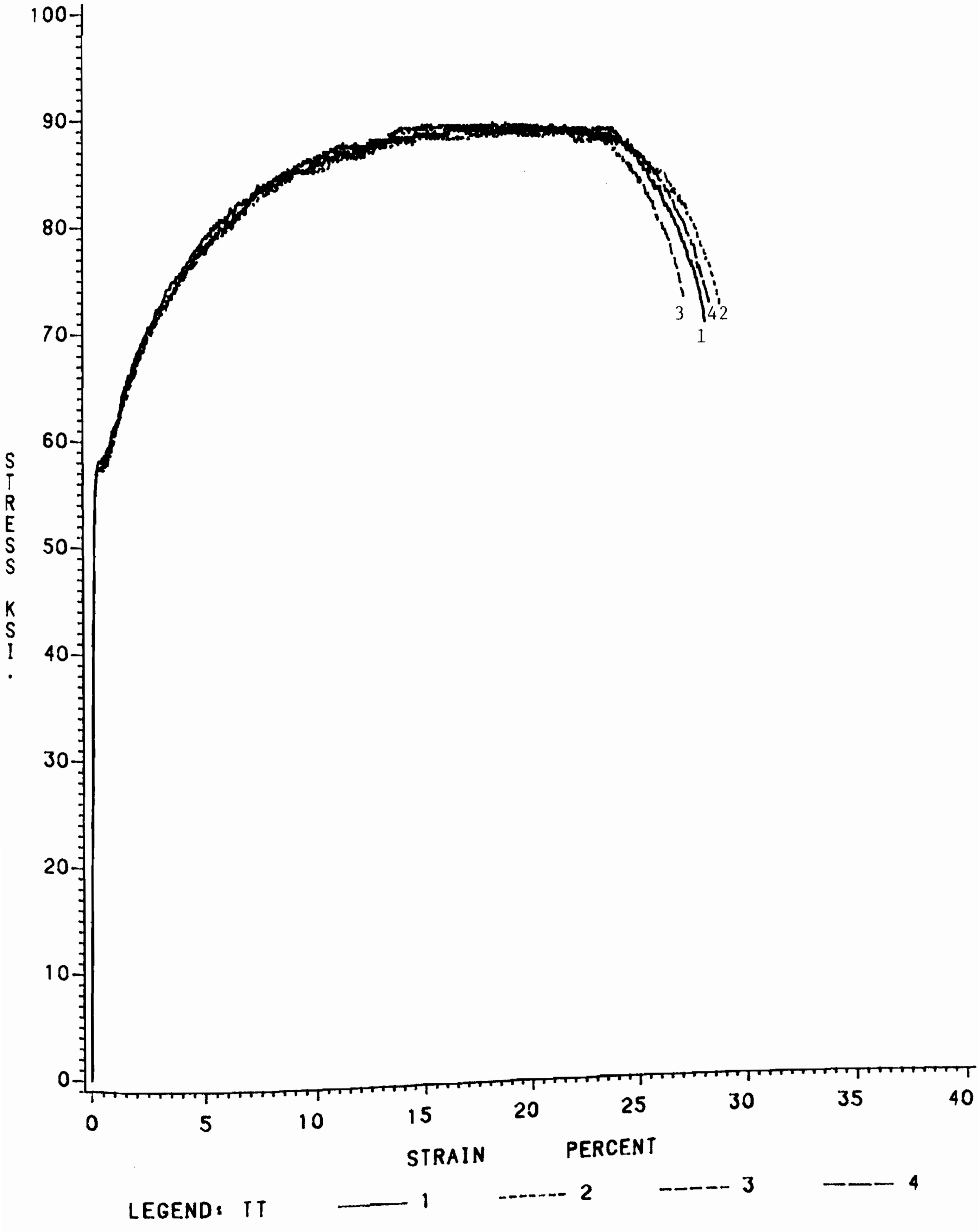


Fig. 4.25

INDIVIDUAL STRESS-STRAIN CURVE FOR 80-DF-TT

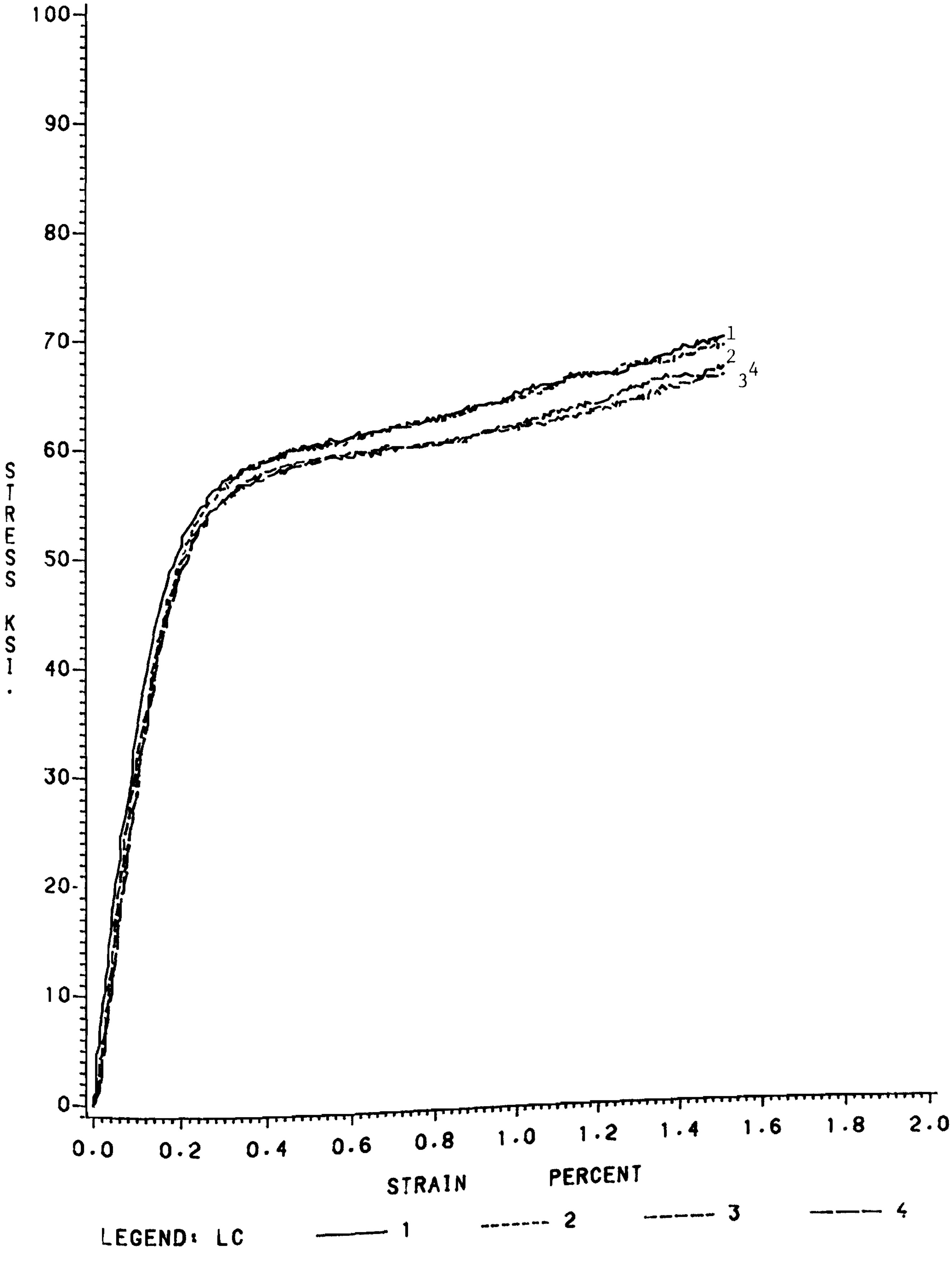


Fig. 4.26

INDIVIDUAL STRESS—STRAIN CURVE FOR 80DF—LC

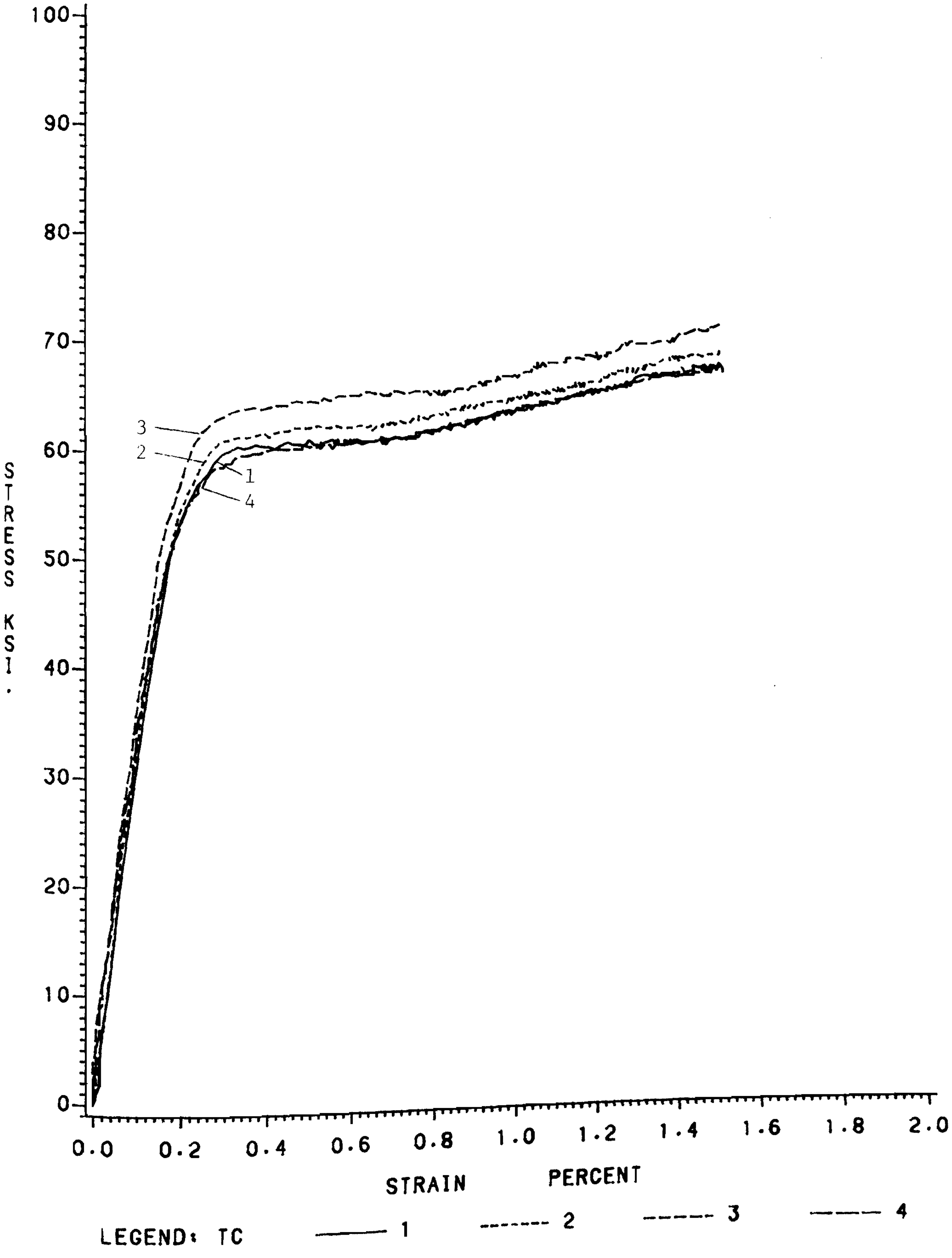


Fig. 4.27

INDIVIDUAL STRESS–STRAIN CURVE FOR 80DF–TC

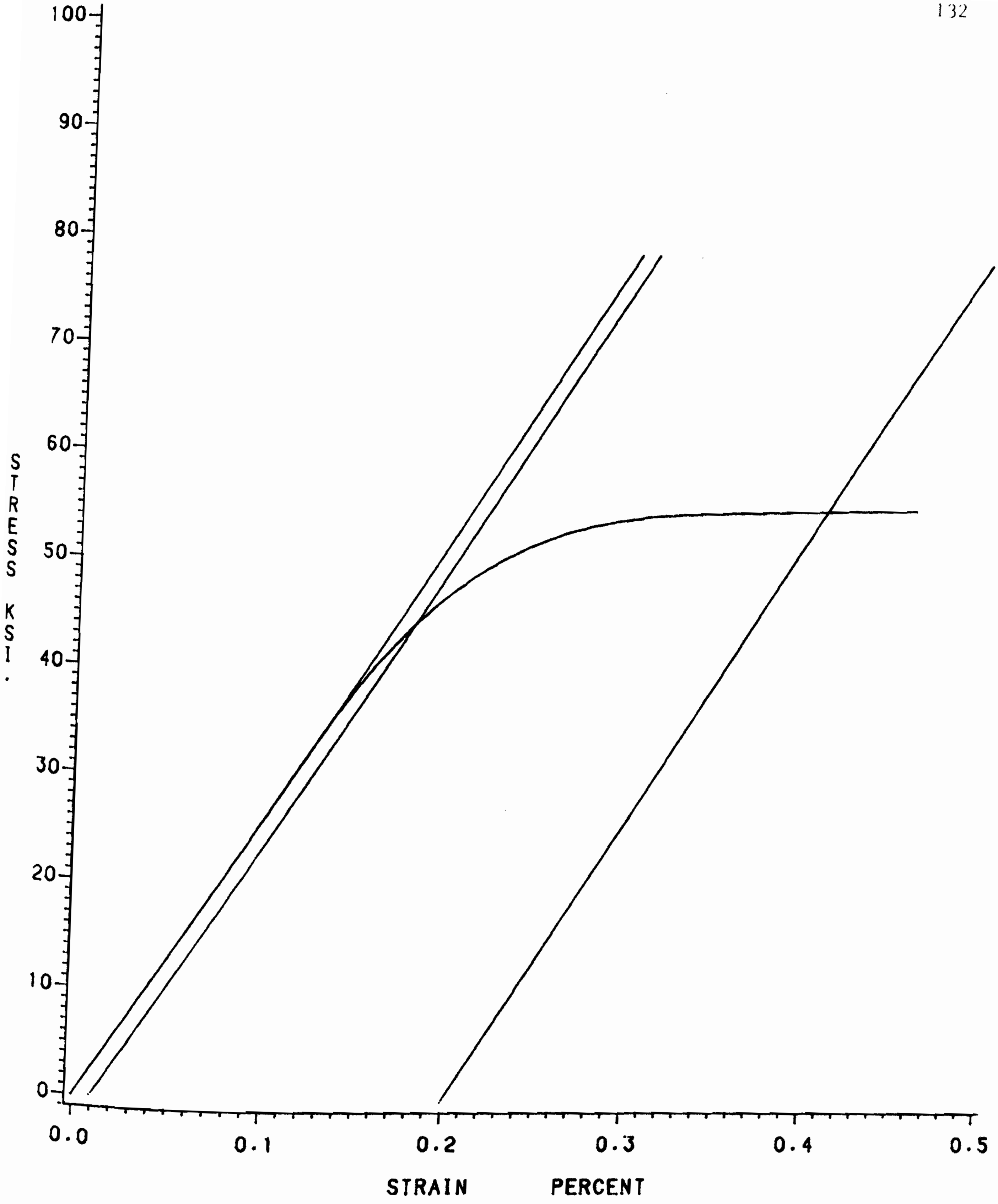


Fig. 4.28

REPRESENTATIVE STRESS--STRAIN CURVE FOR 80DF-LT

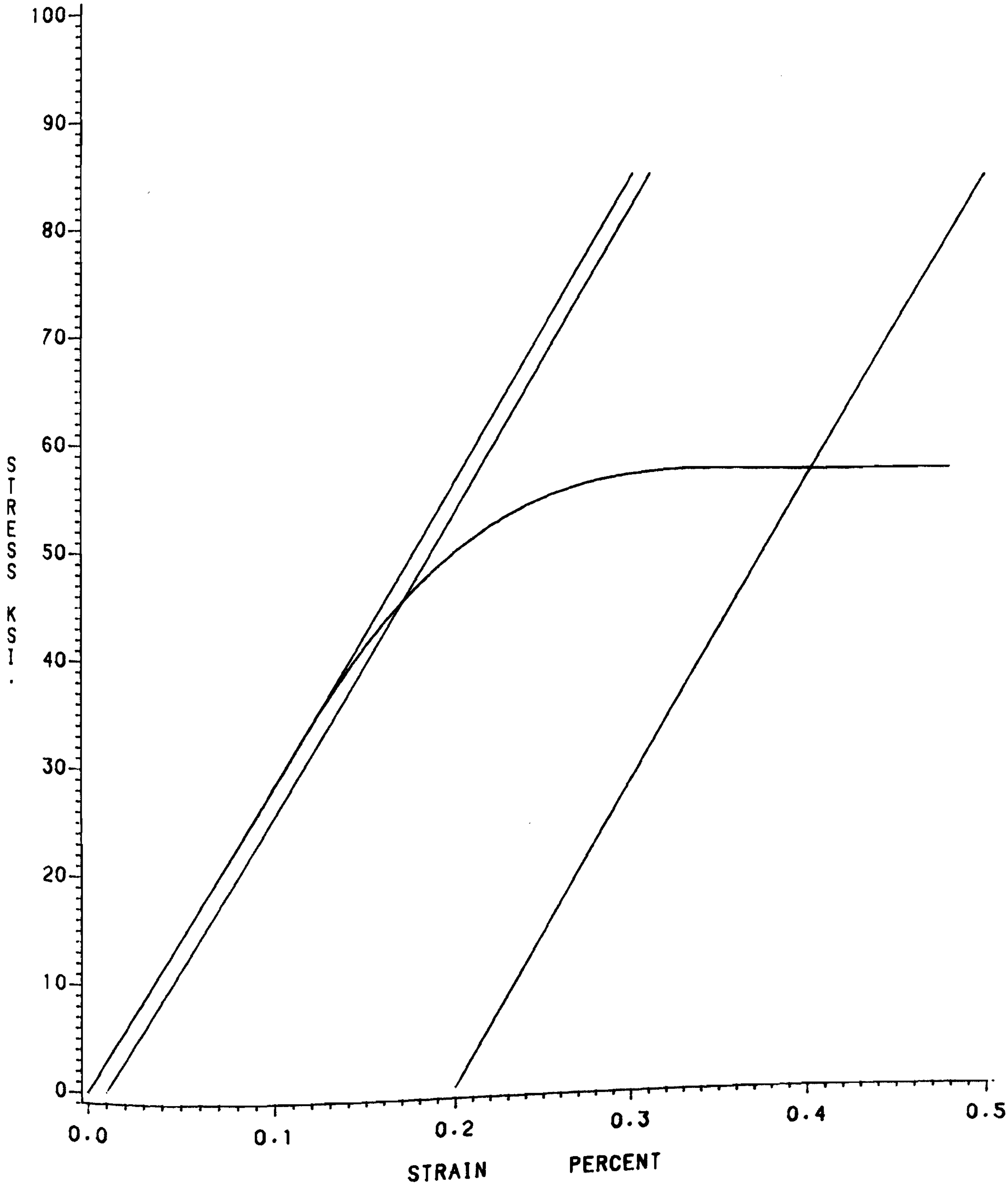


Fig. 4.29

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80DF-TT

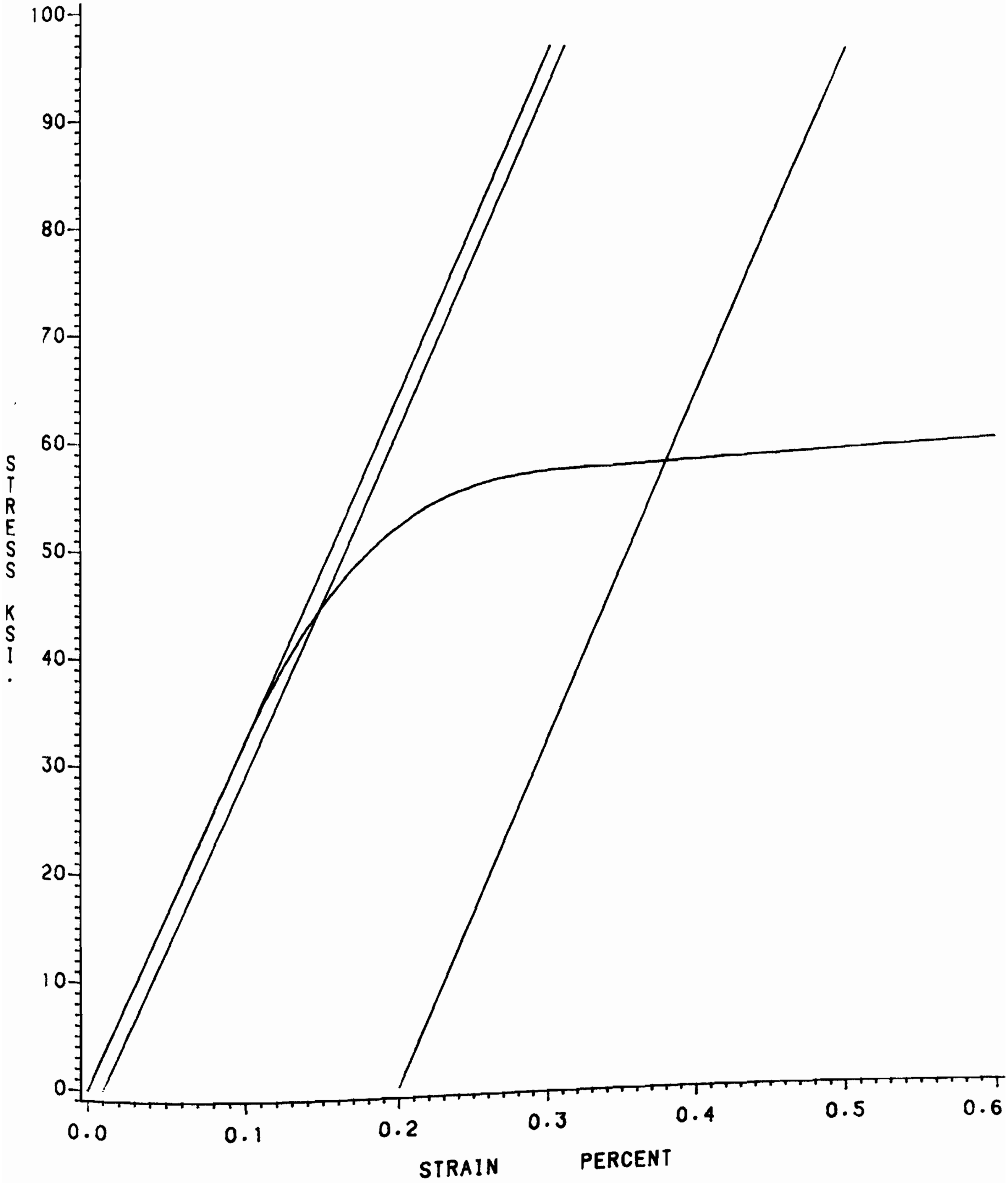


Fig. 4.30
REPRESENTATIVE STRESS-STRAIN CURVE FOR 80DF-LC

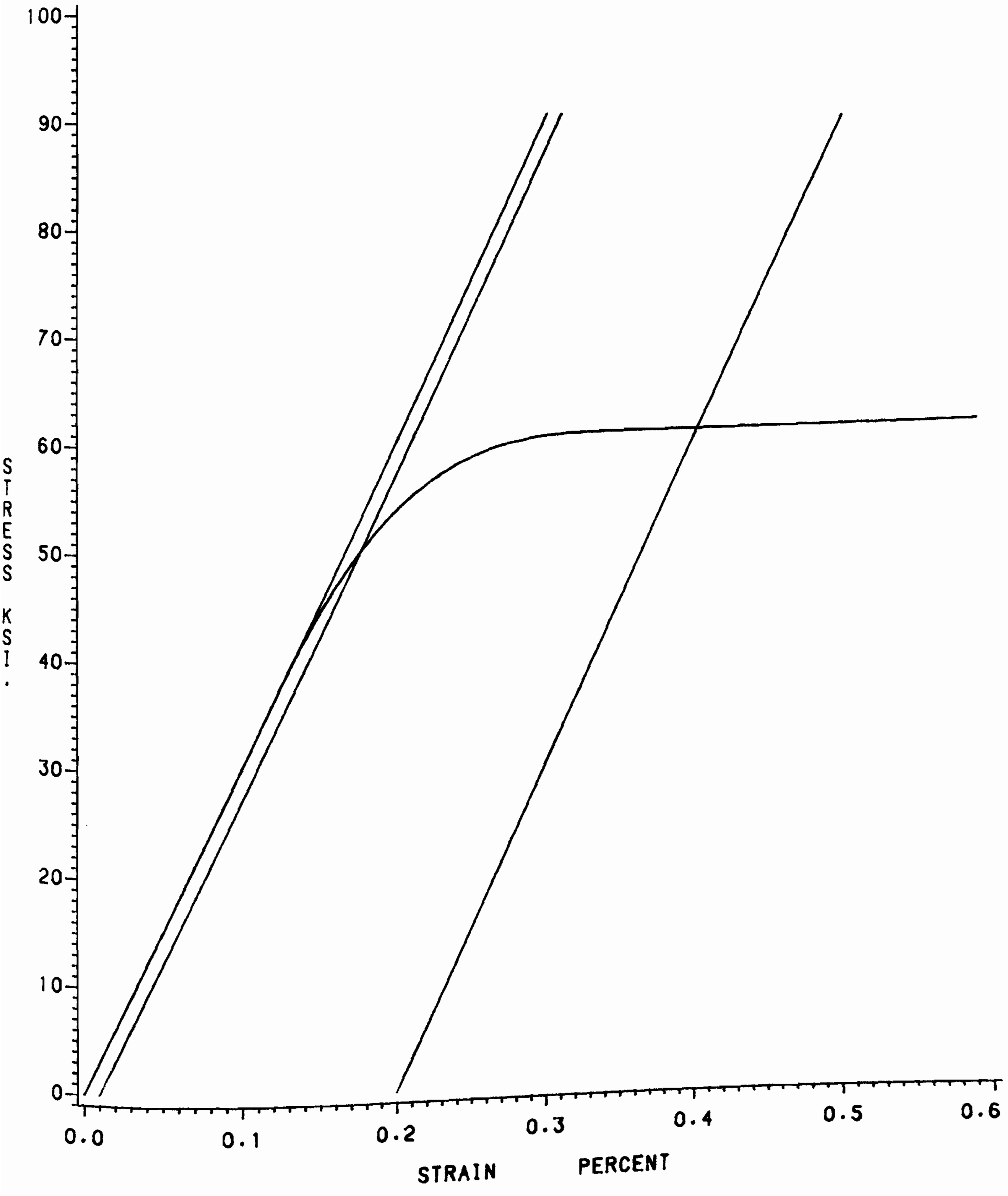


Fig. 4.31

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80DF-TC

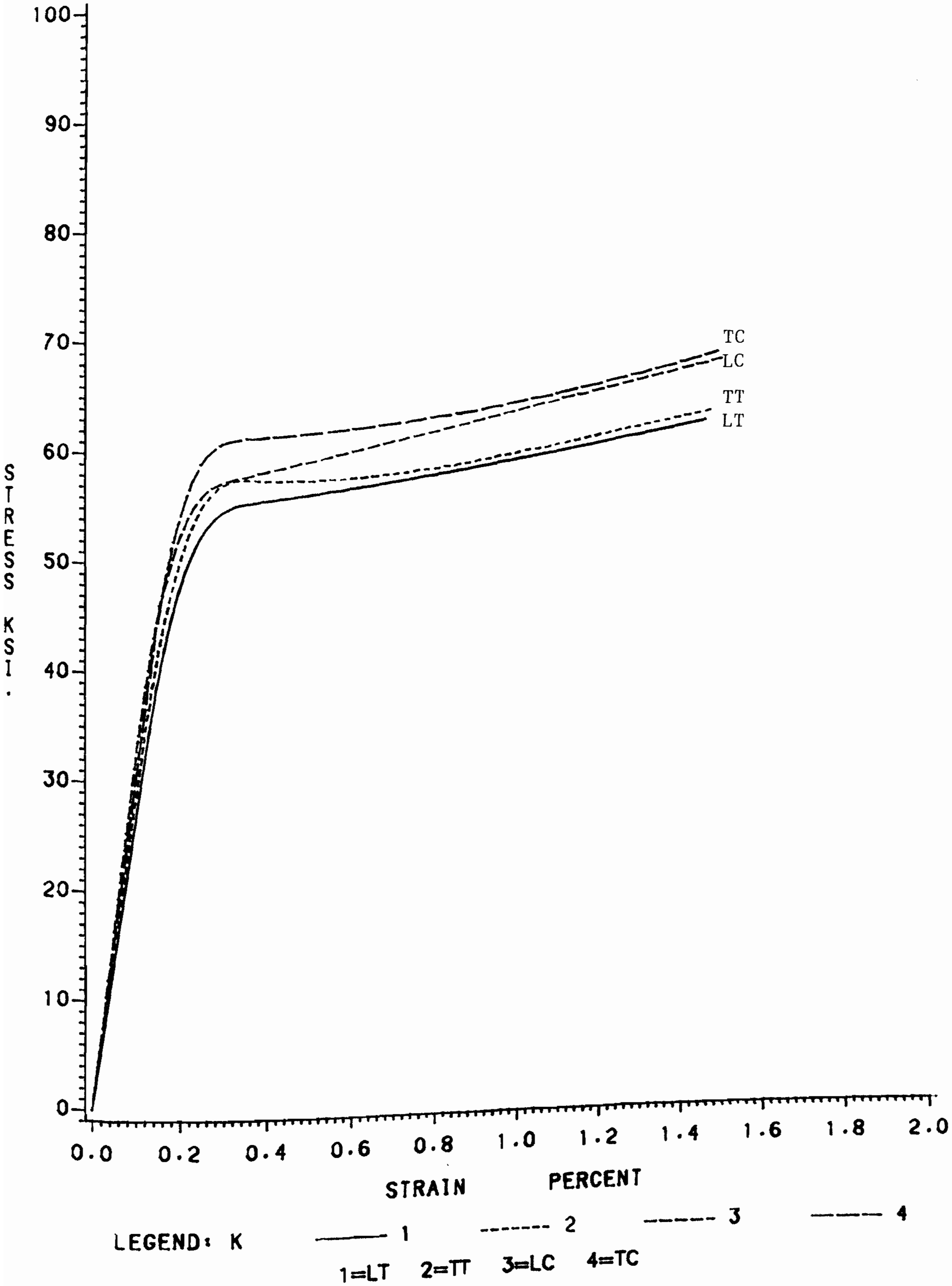


Fig. 4.32

COMPARISON OF VARIOUS TESTS FOR 80DF

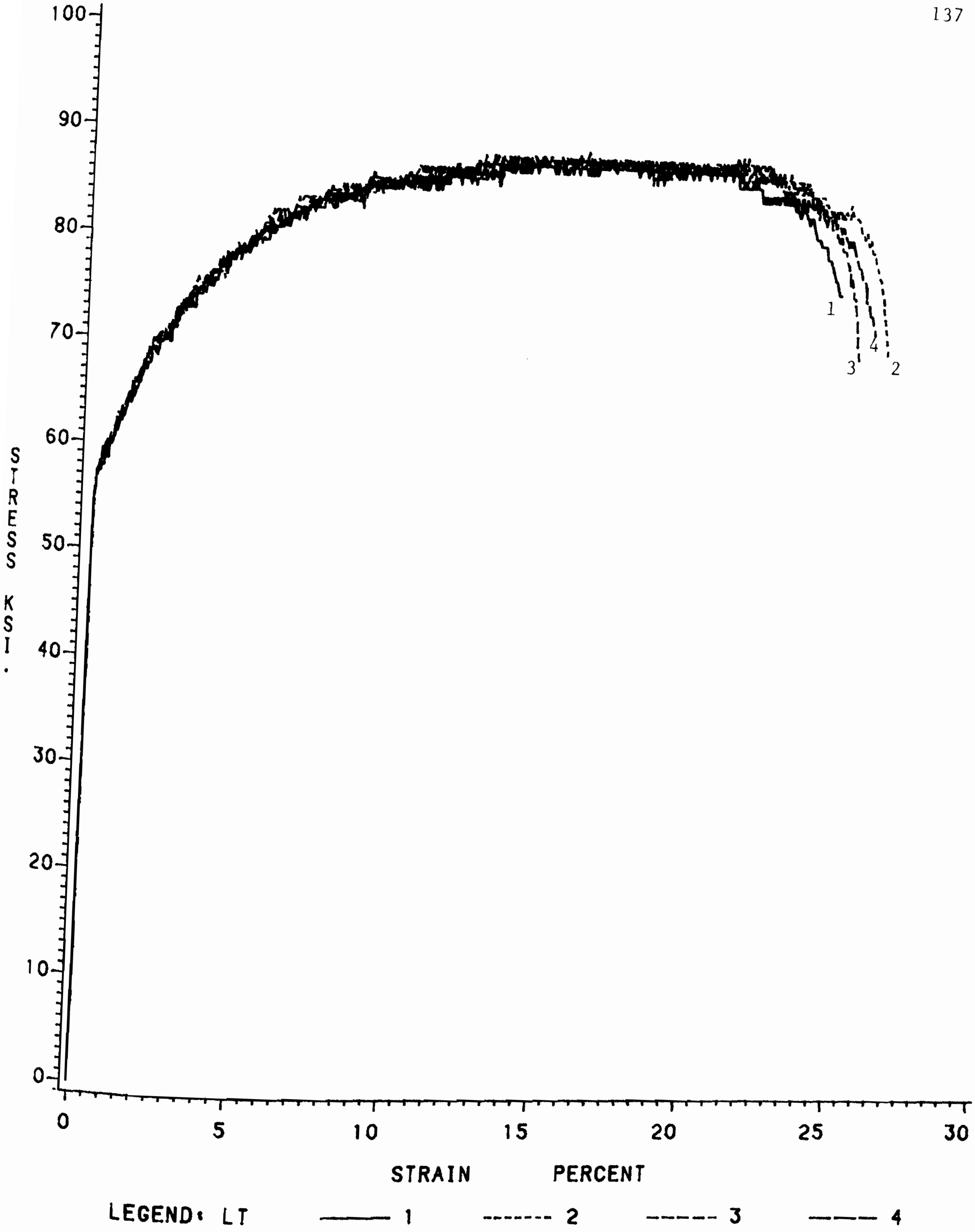


Fig. 4.33

INDIVIDUAL STRESS–STRAIN CURVE FOR 80DK–LT

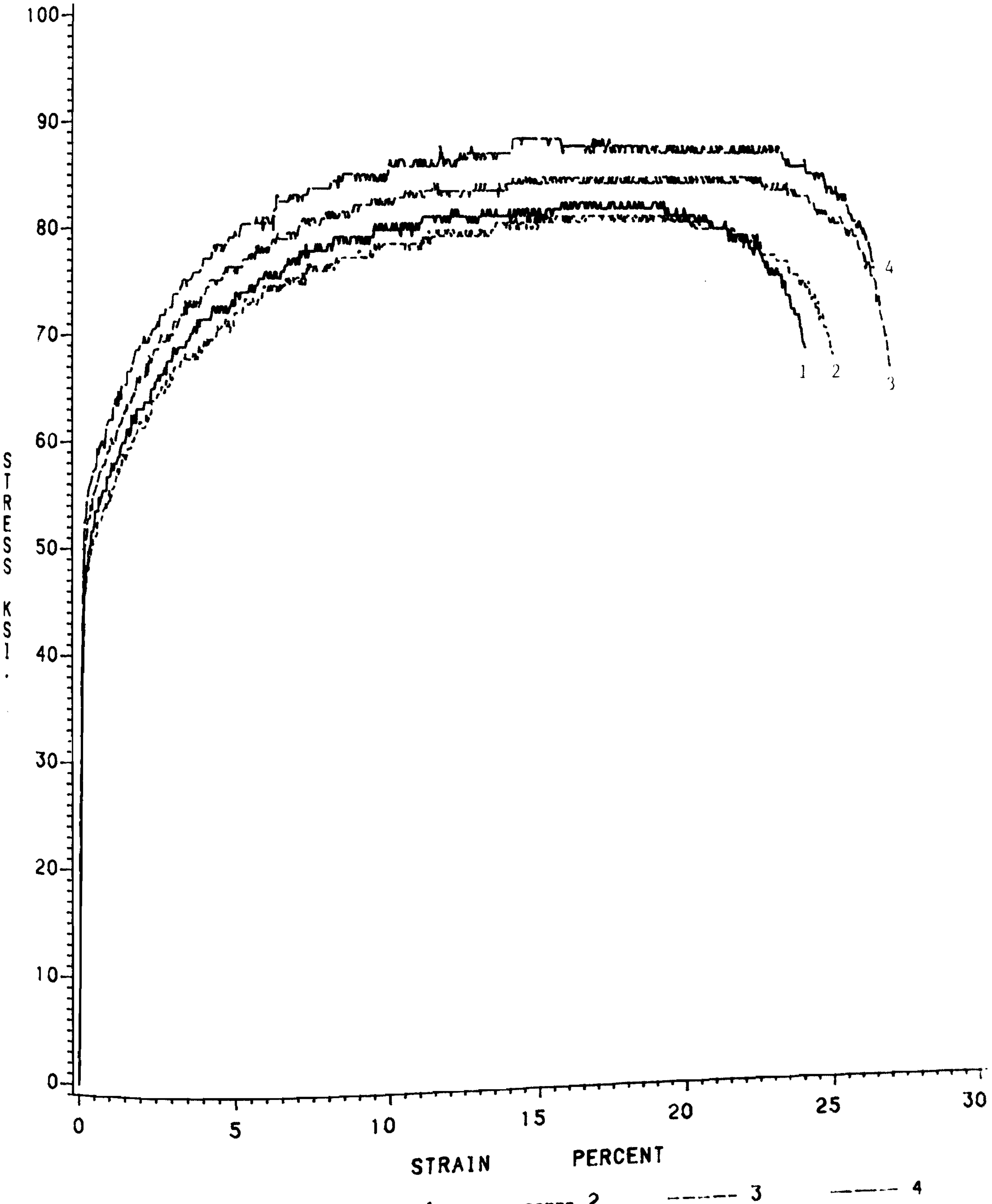


Fig. 4.34

INDIVIDUAL STRESS-STRAIN CURVE FOR 80DK-TT

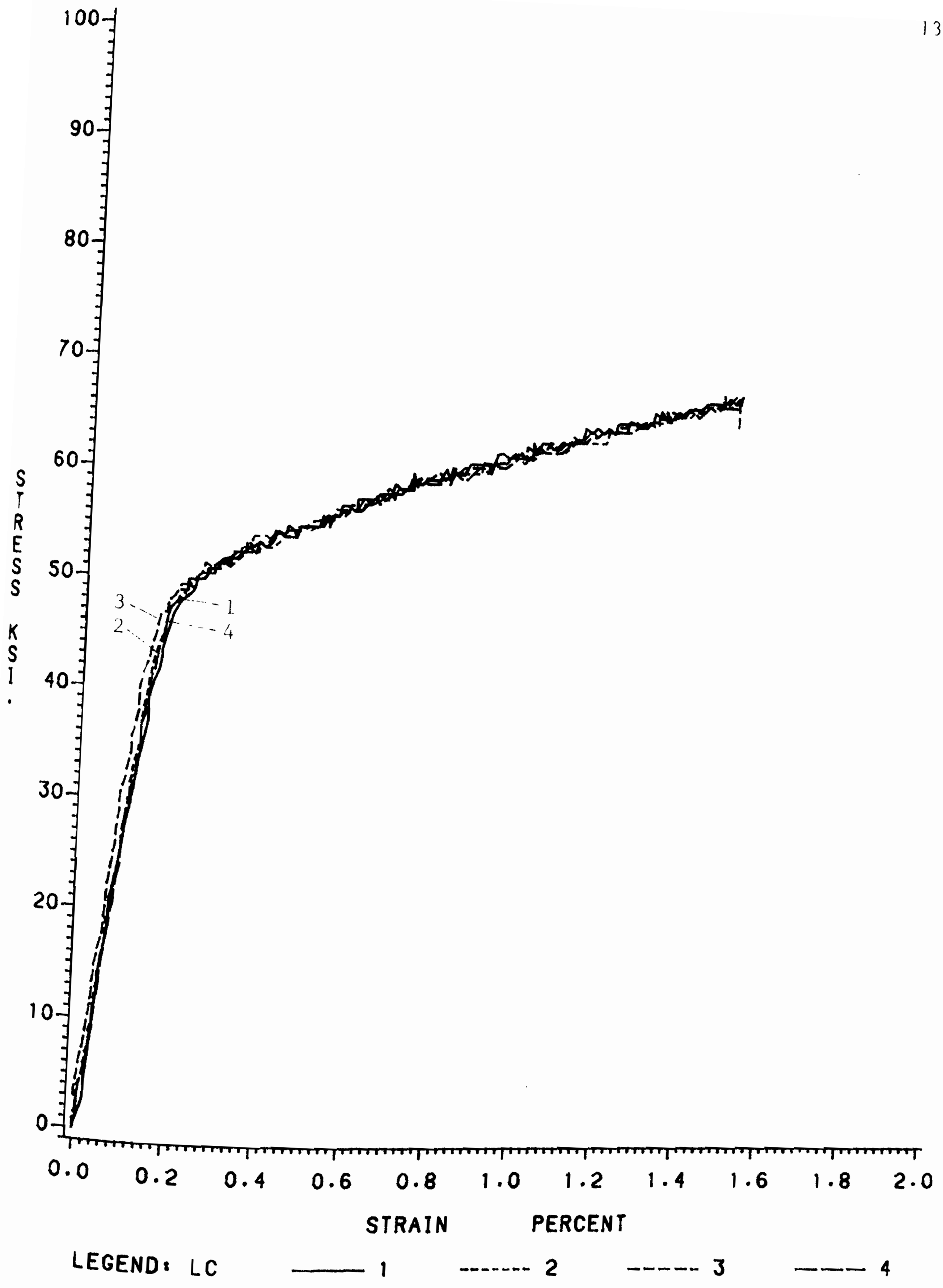


Fig. 4.35

INDIVIDUAL STRESS-STRAIN CURVE FOR 80DK-LC

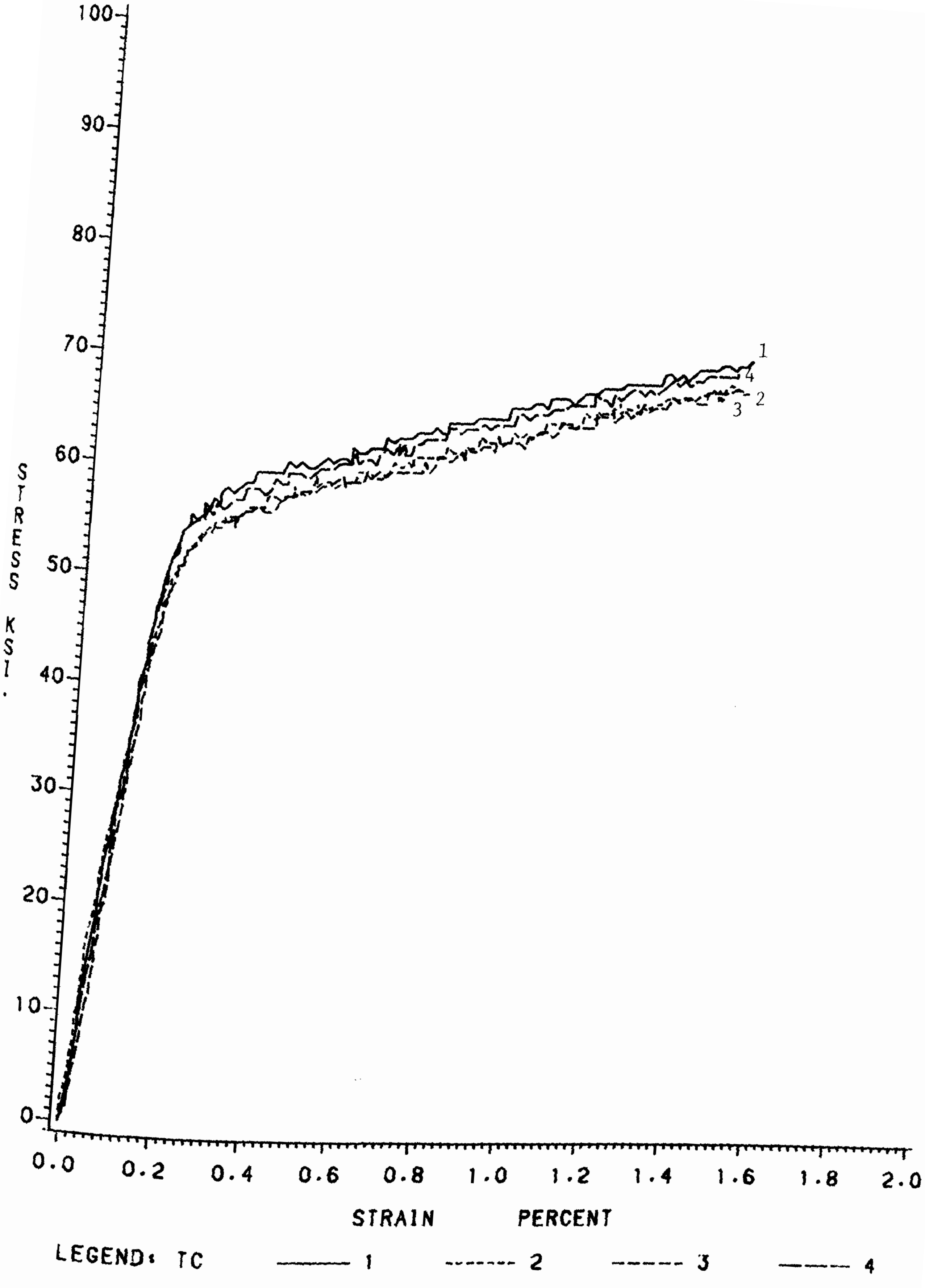


Fig. 4.36

INDIVIDUAL STRESS-STRAIN CURVE FOR 80DK-TC

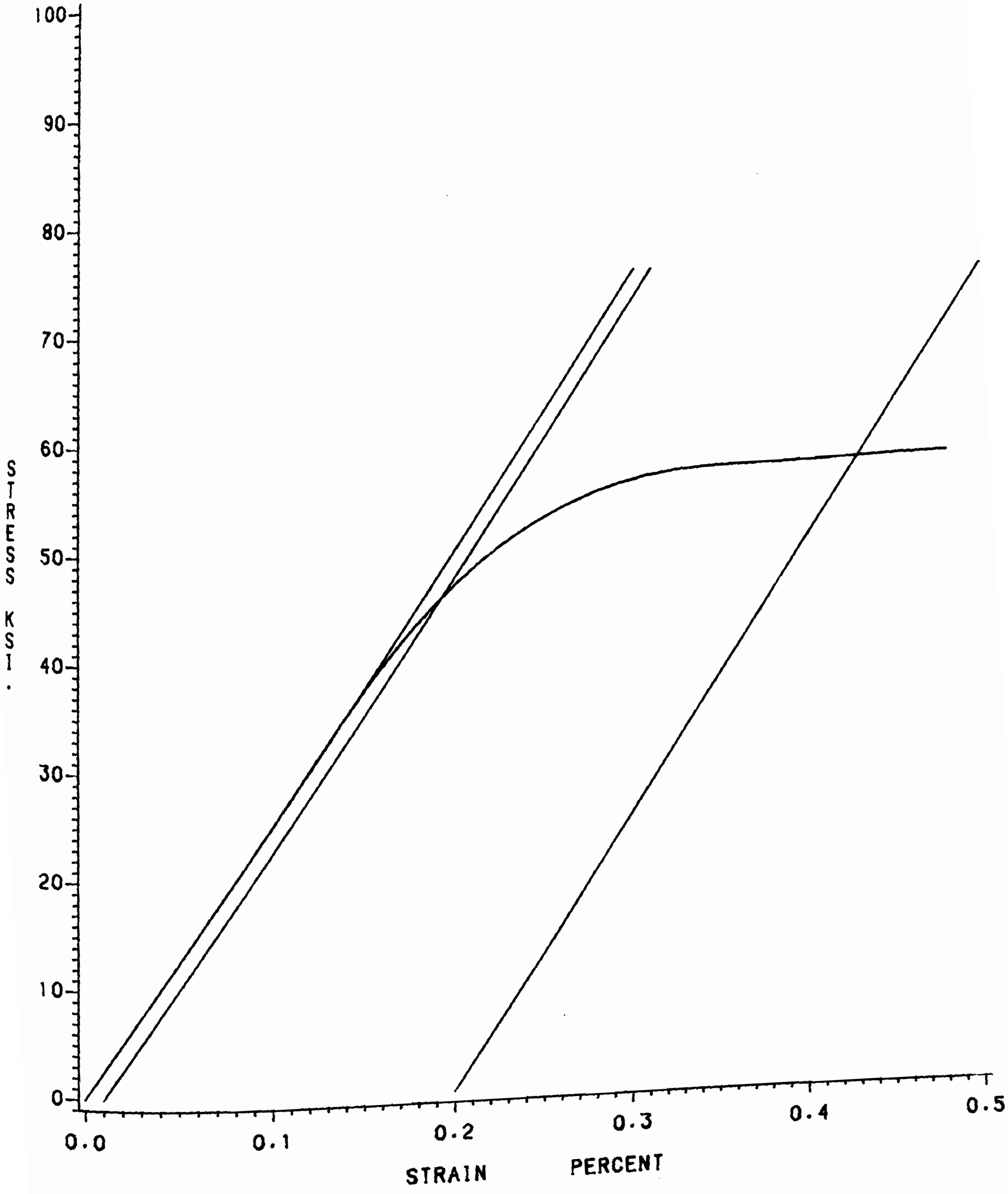


Fig. 4.37

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80DK-LT

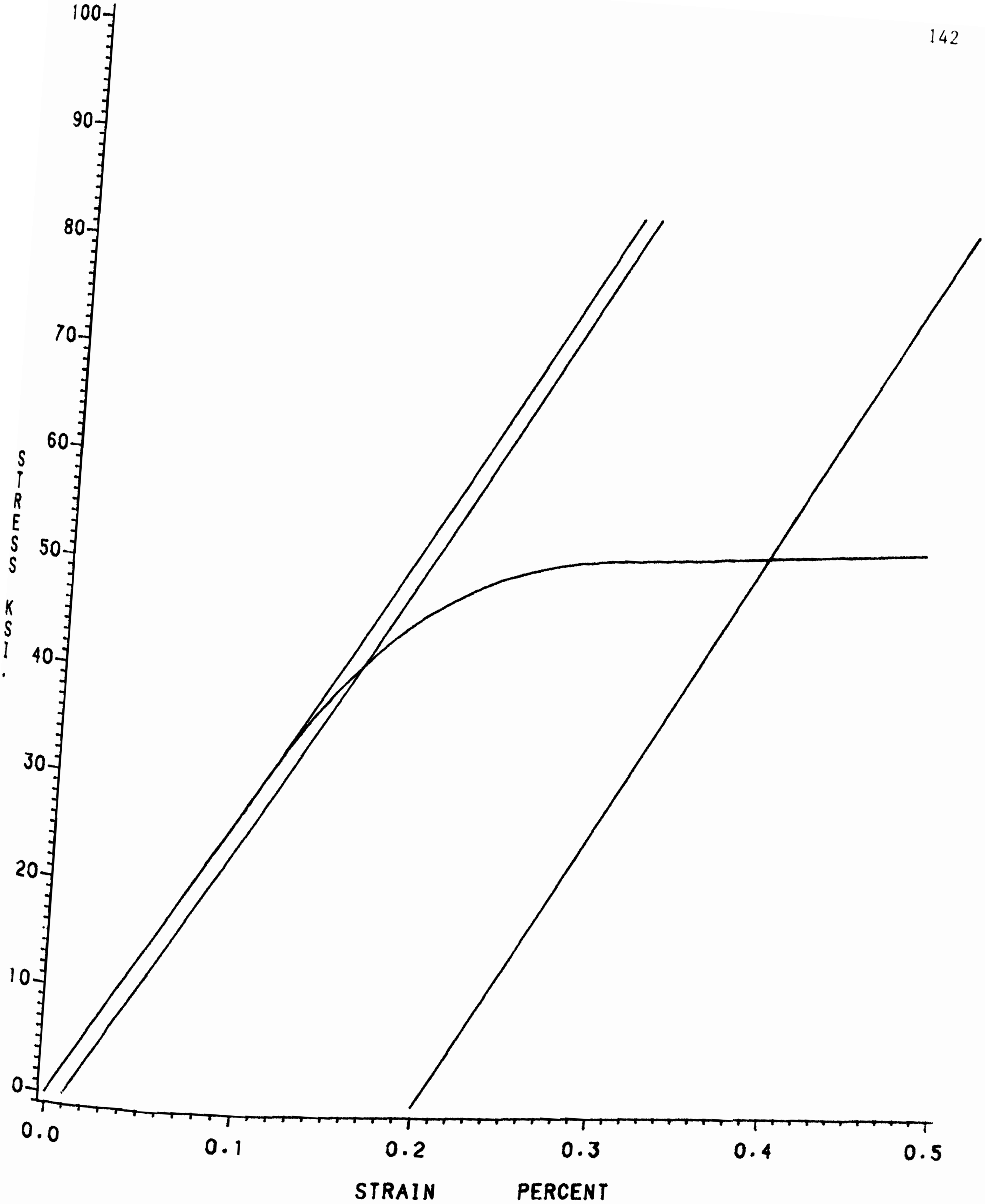


Fig. 4.38

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80DK-TT

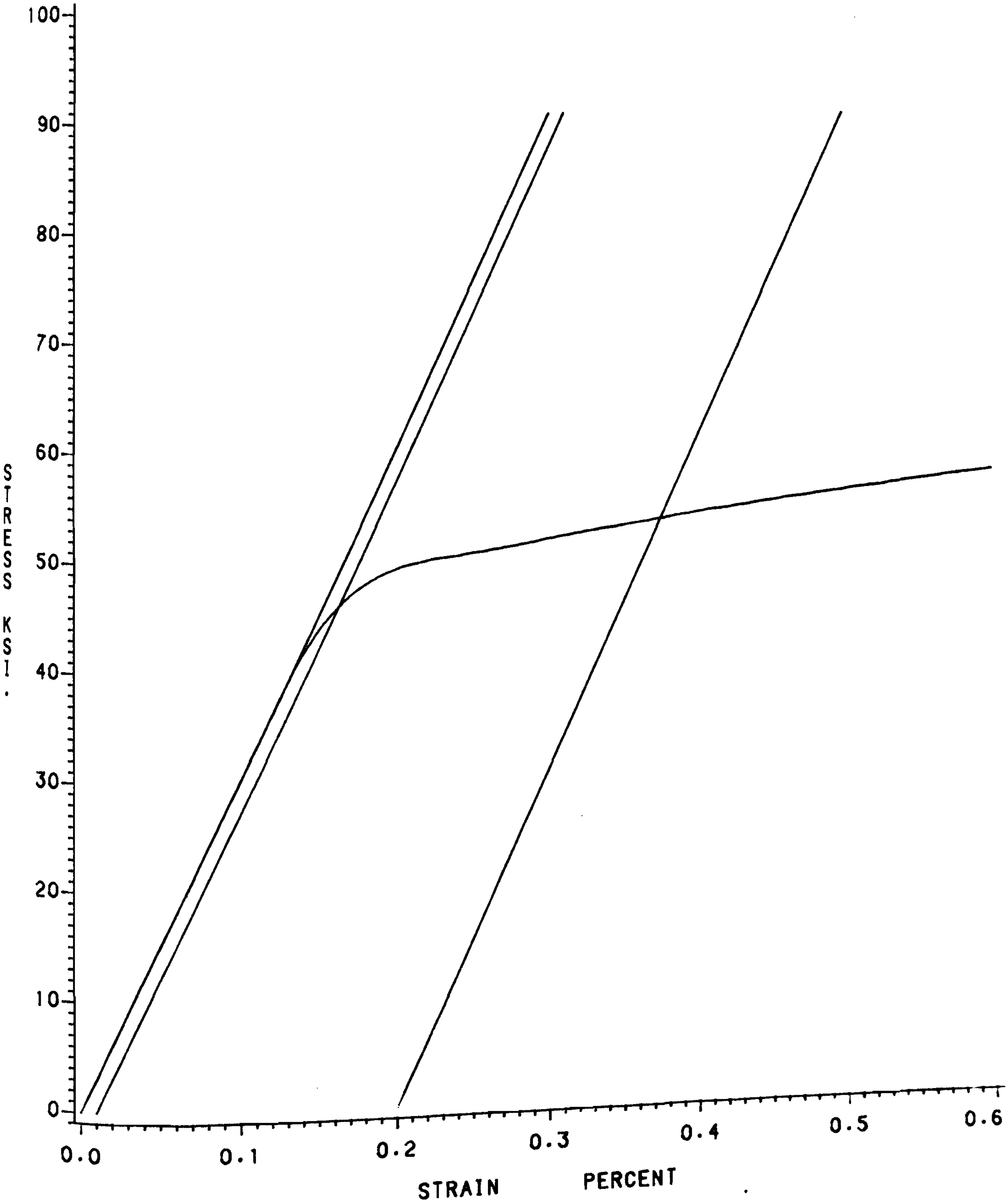


Fig. 4.39

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80DK-LC

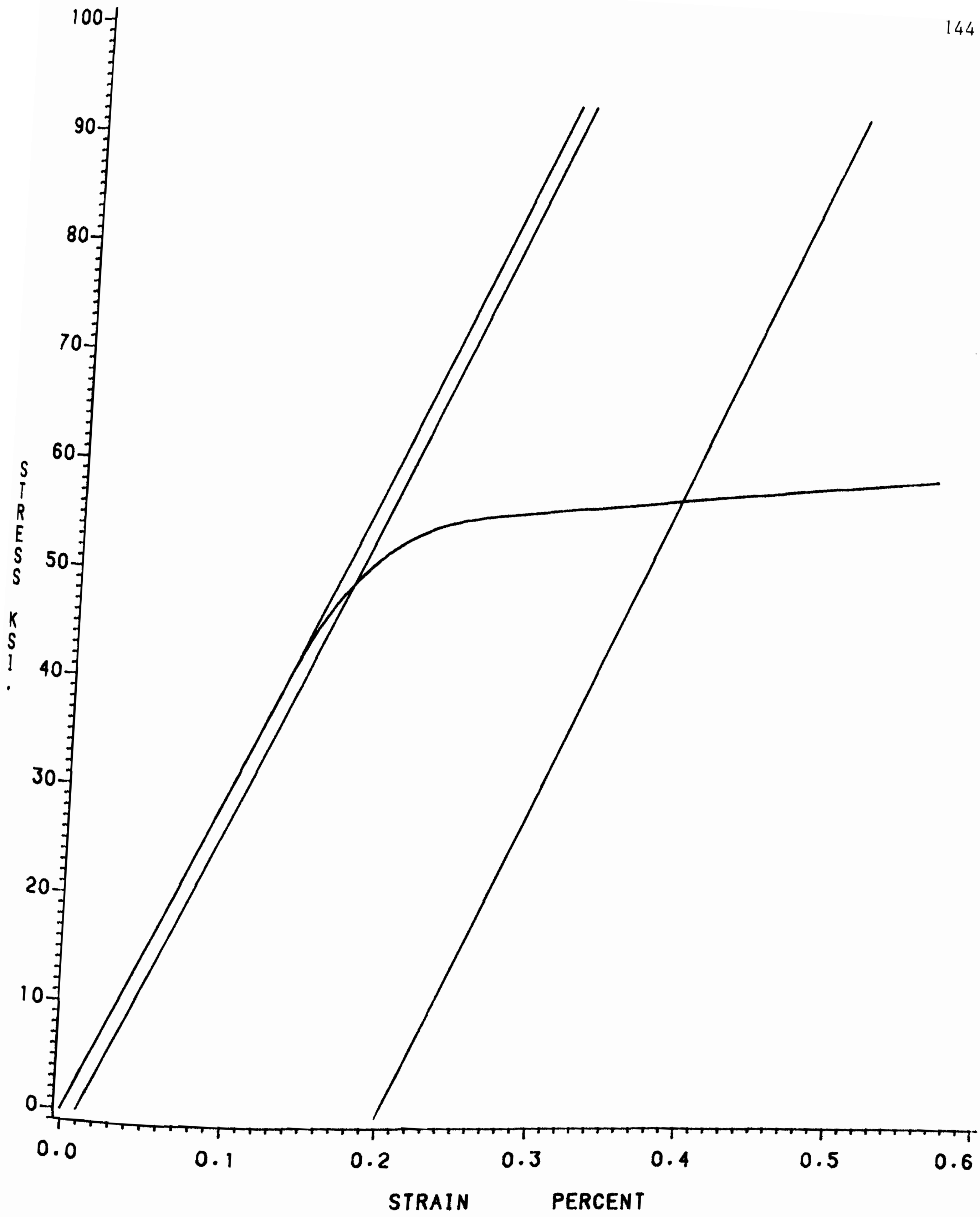


Fig. 4.40

REPRESENTATIVE STRESS—STRAIN CURVE FOR 80DK—TC

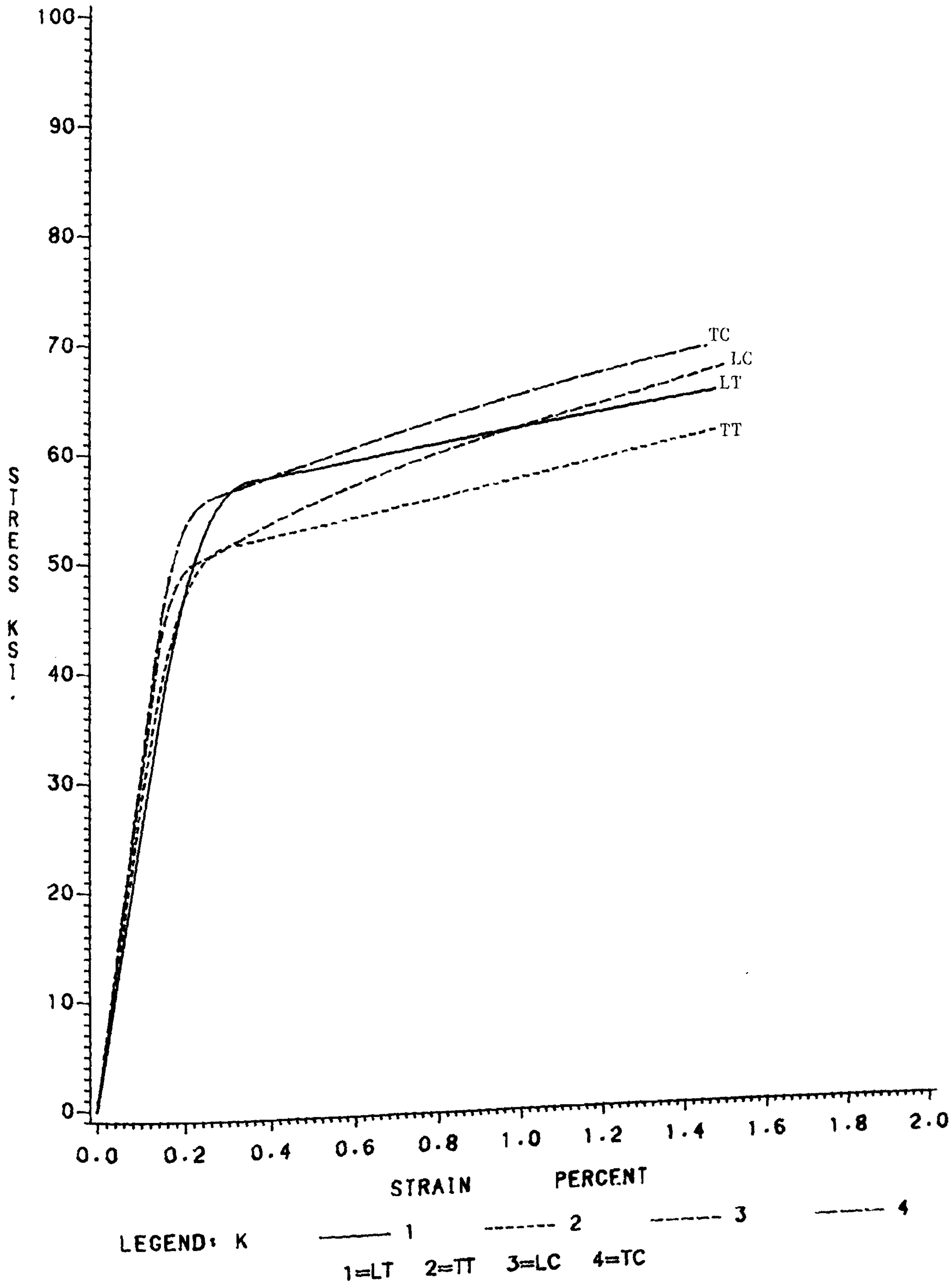


Fig. 4.41

COMPARISON OF VARIOUS TESTS FOR 80DK

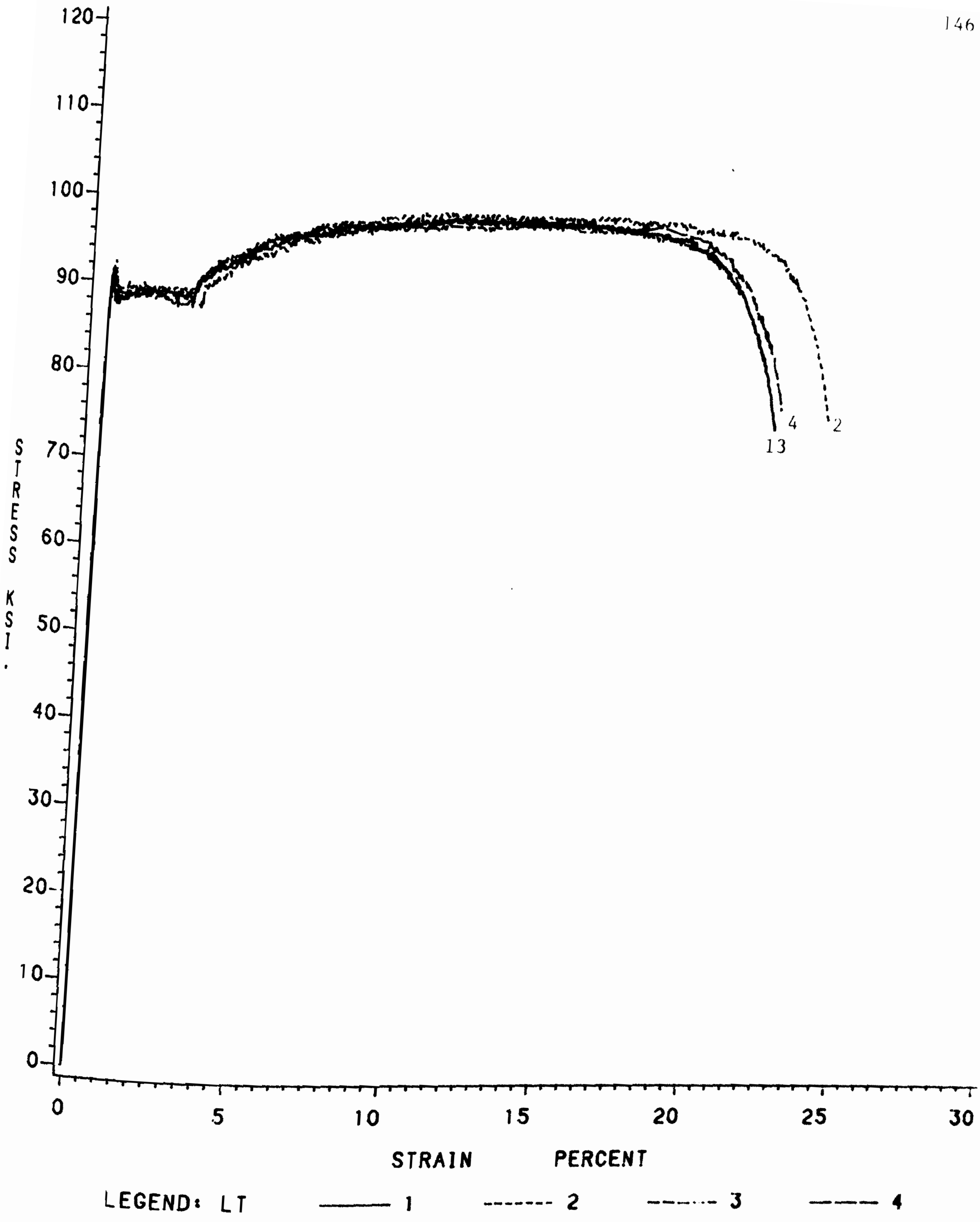


Fig. 4.42

INDIVIDUAL STRESS-STRAIN CURVE FOR 80-XF-LT

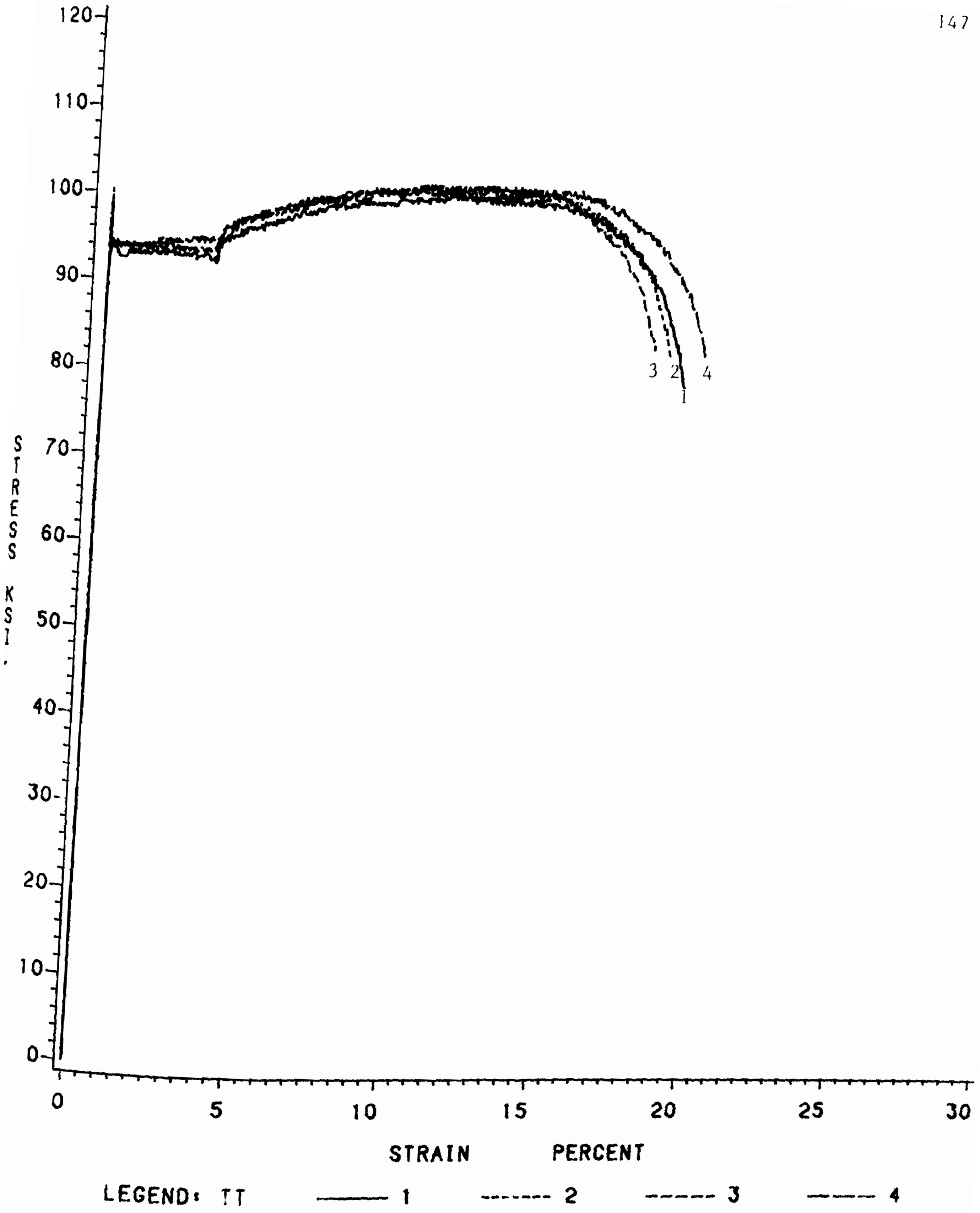


Fig. 4.43

INDIVIDUAL STRESS–STRAIN CURVE FOR 80–XF–TT

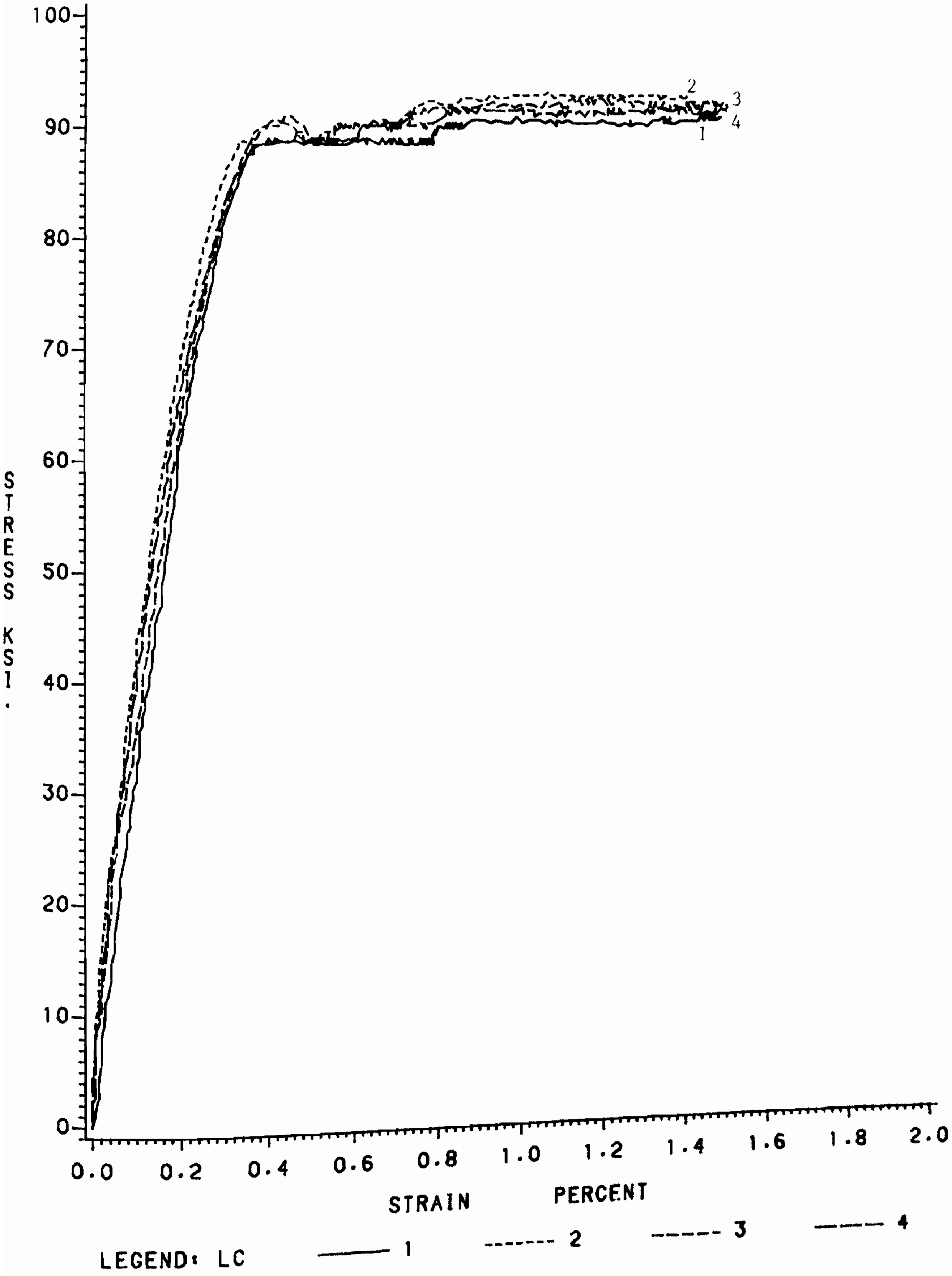


Fig. 4.44

INDIVIDUAL STRESS-STRAIN CURVE FOR 80XF-LC

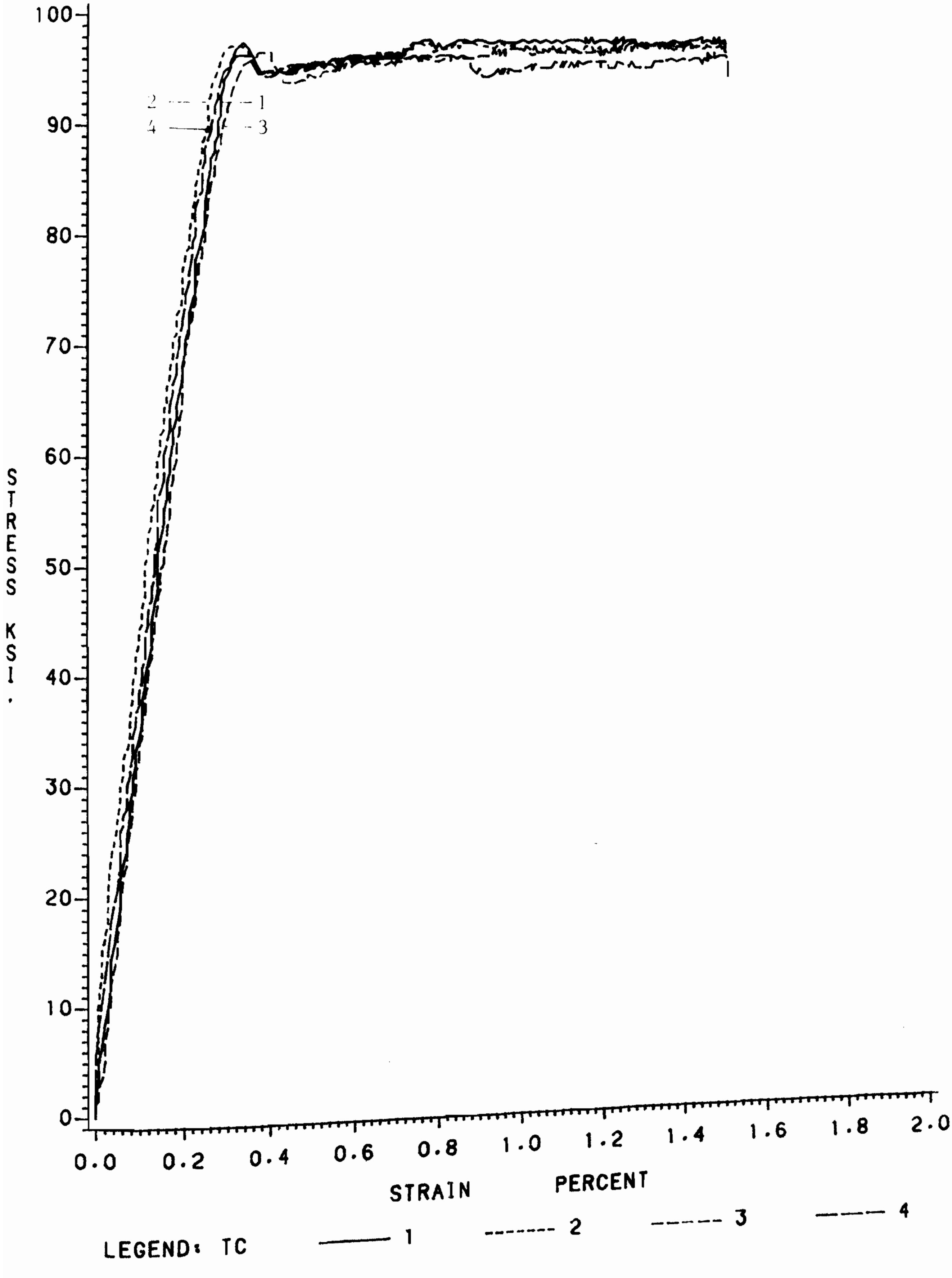


Fig. 4.45

INDIVIDUAL STRESS-STRAIN CURVE FOR 80XF-TC

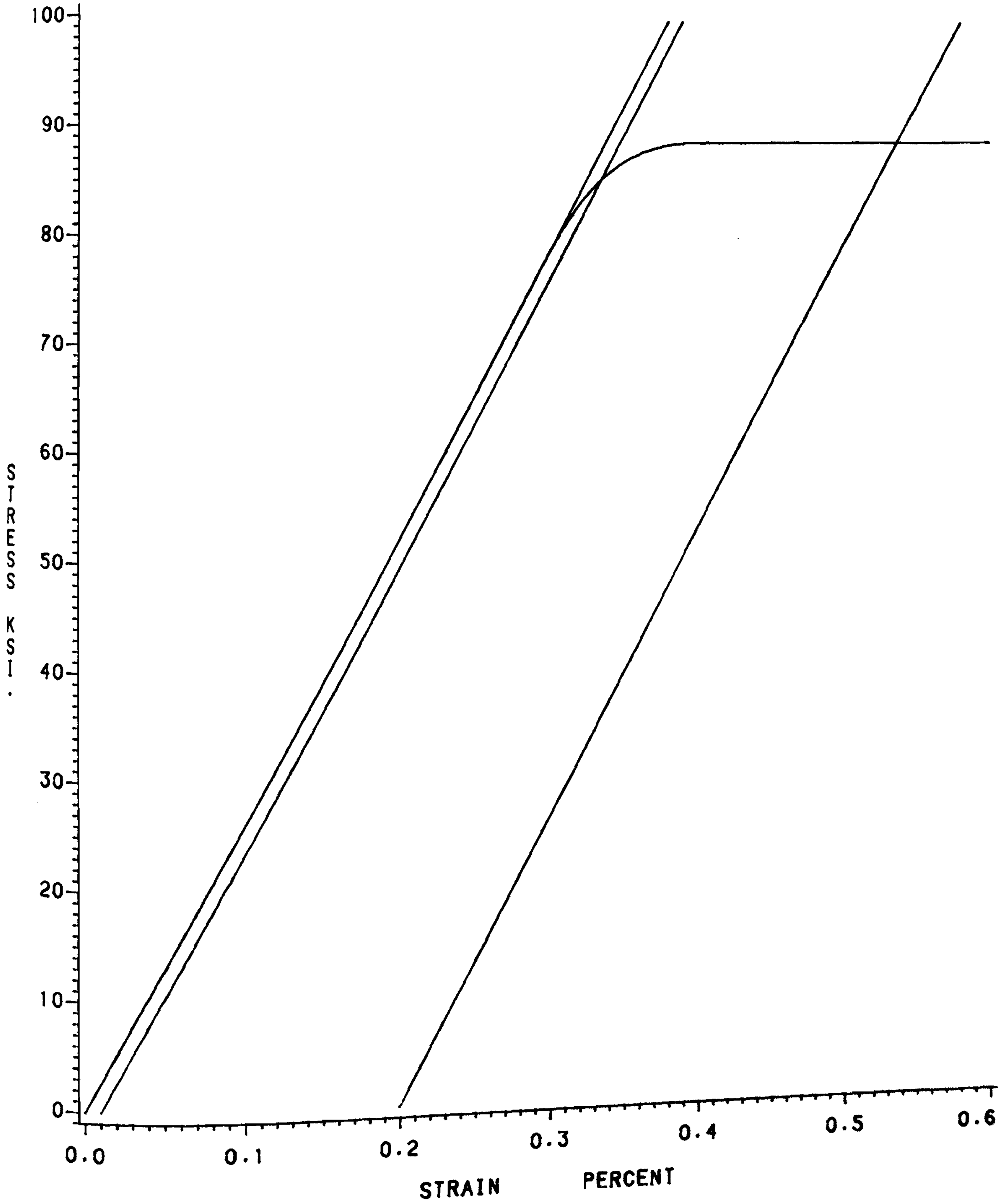


Fig. 4.46

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80XF-LT

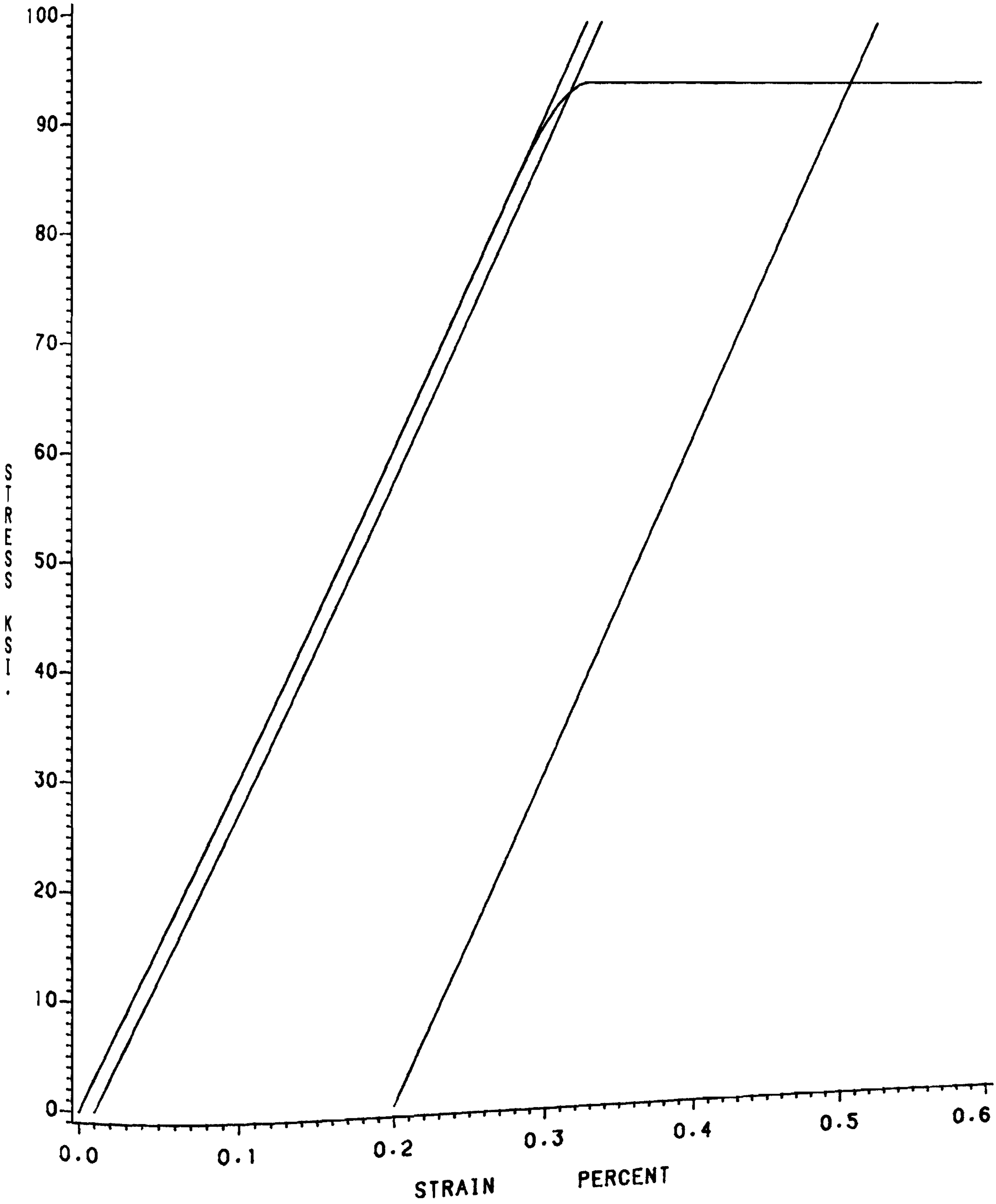


Fig. 4.47

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80XF-TT

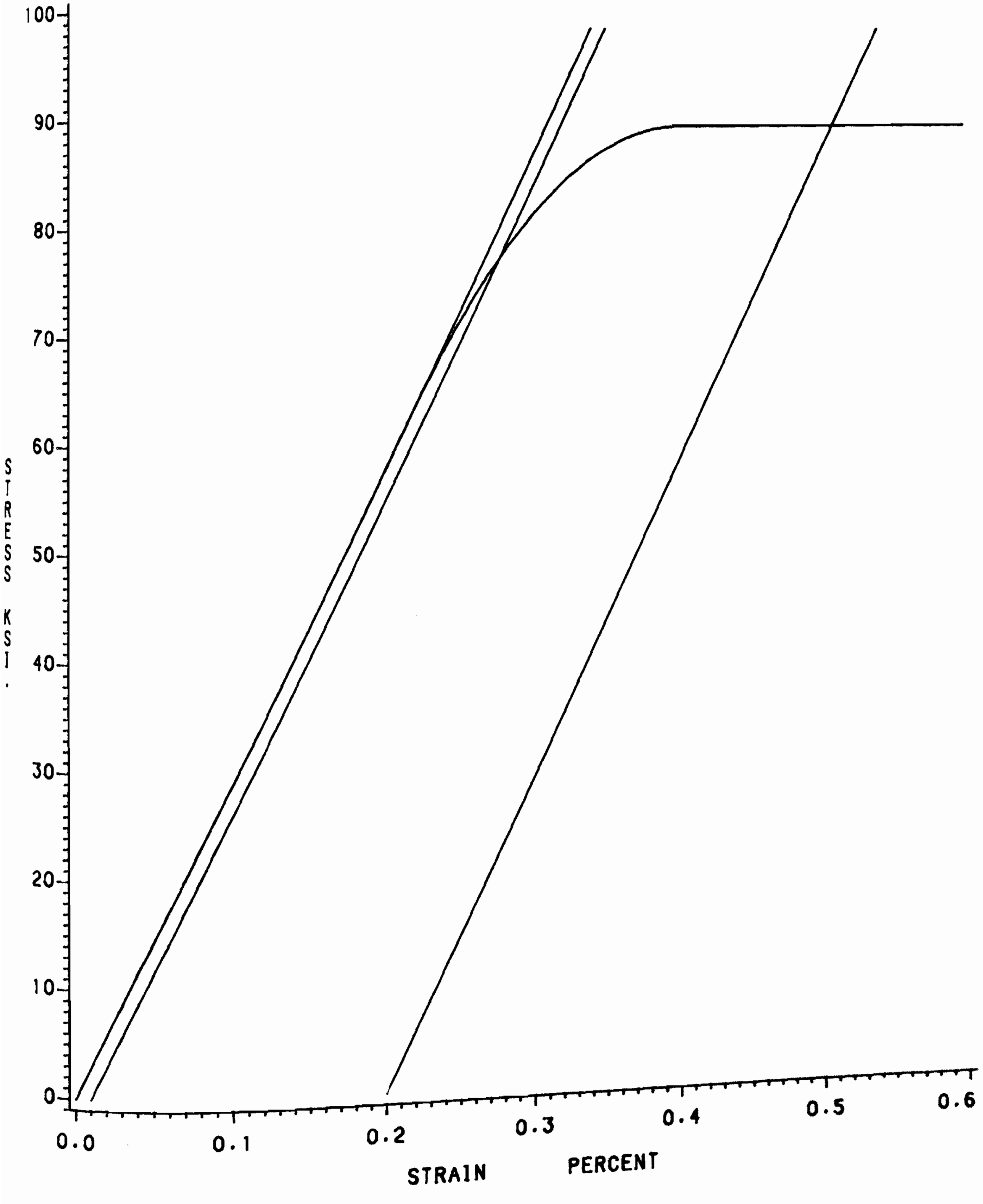


Fig. 4.48

REPRESENTATIVE STRESS–STRAIN CURVE FOR 80XF–LC

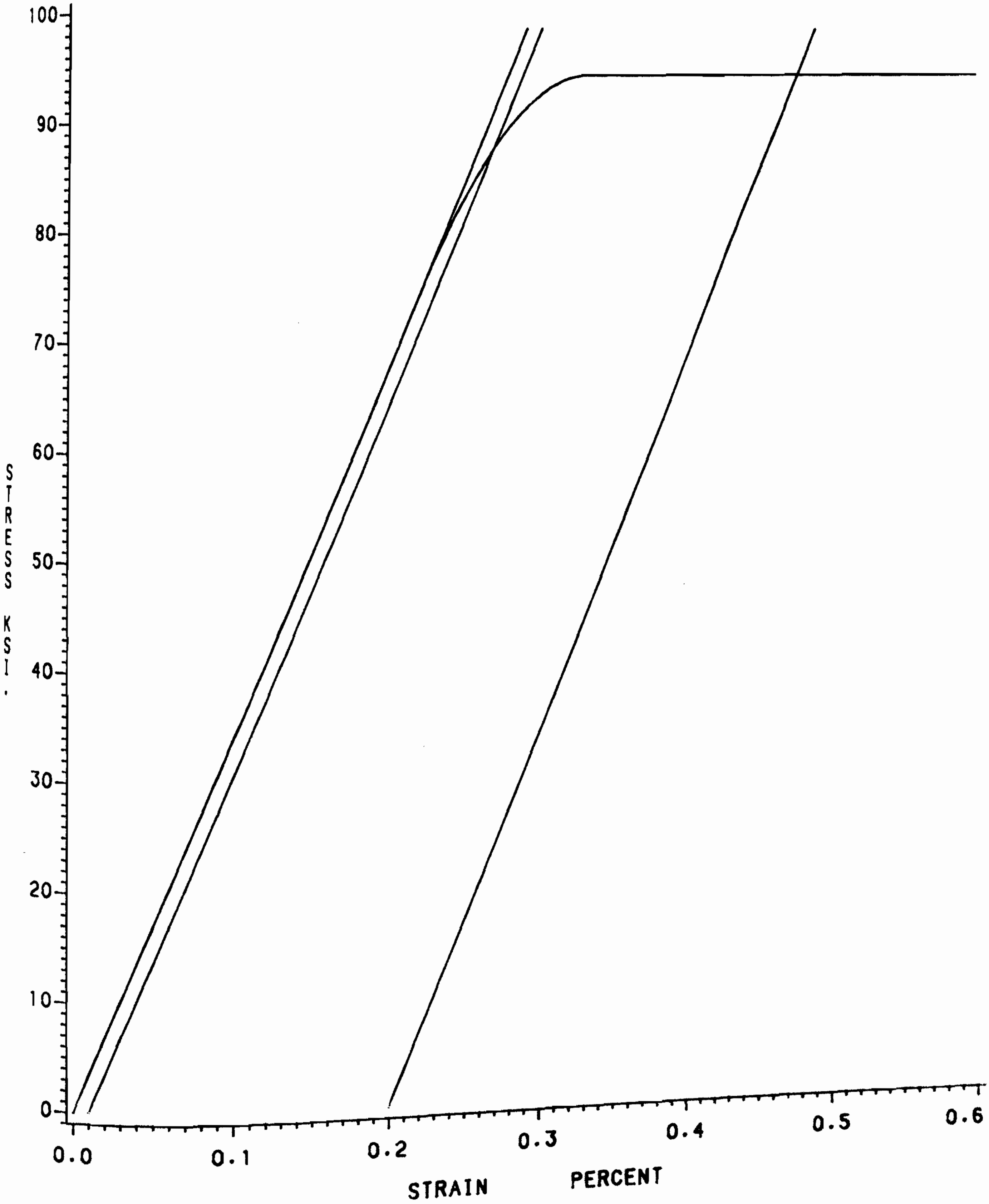


Fig. 4.49

REPRESENTATIVE STRESS-STRAIN CURVE FOR 80XF-TC

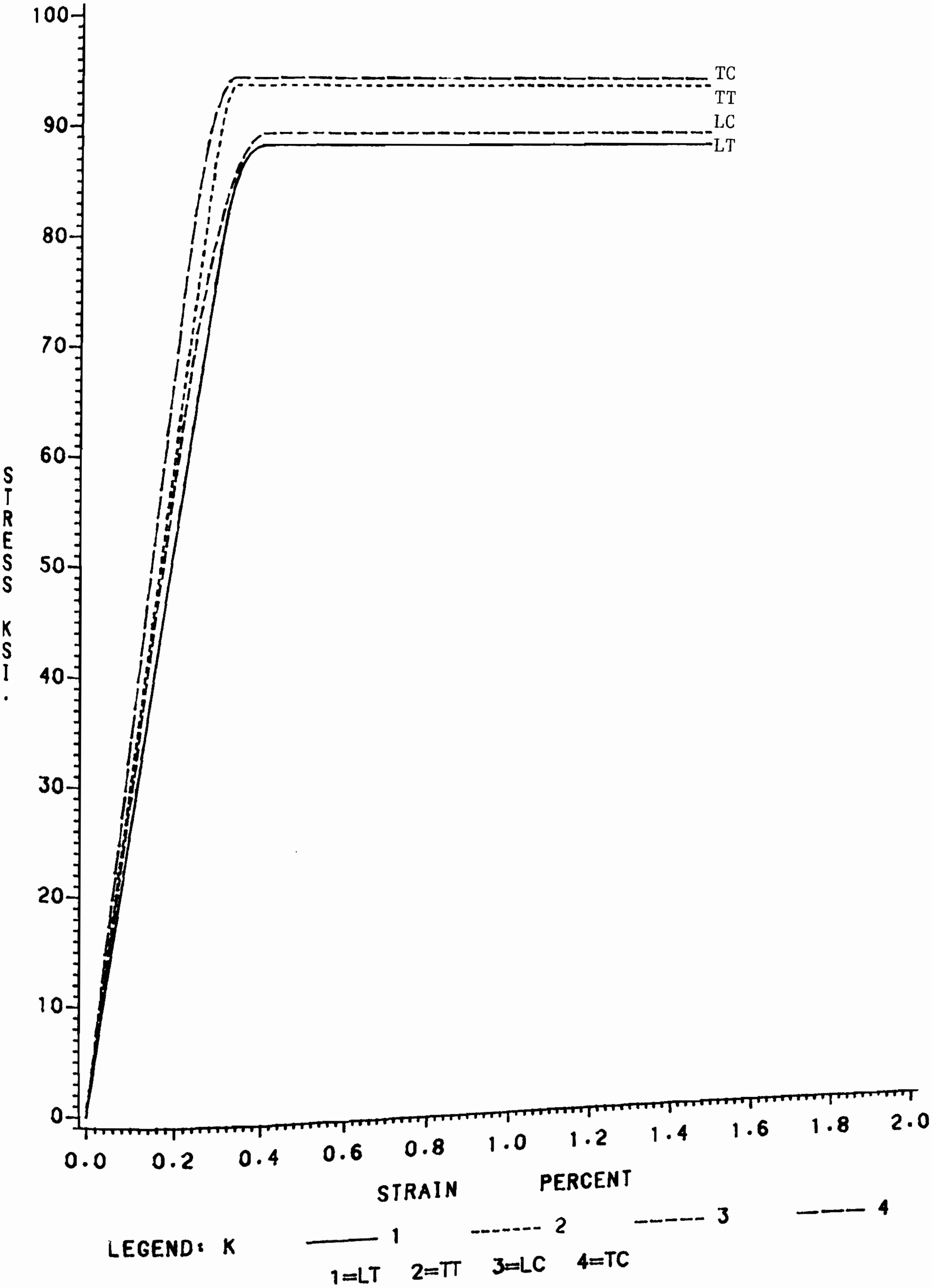


Fig. 4.50

COMPARISON OF VARIOUS TESTS FOR 80XF

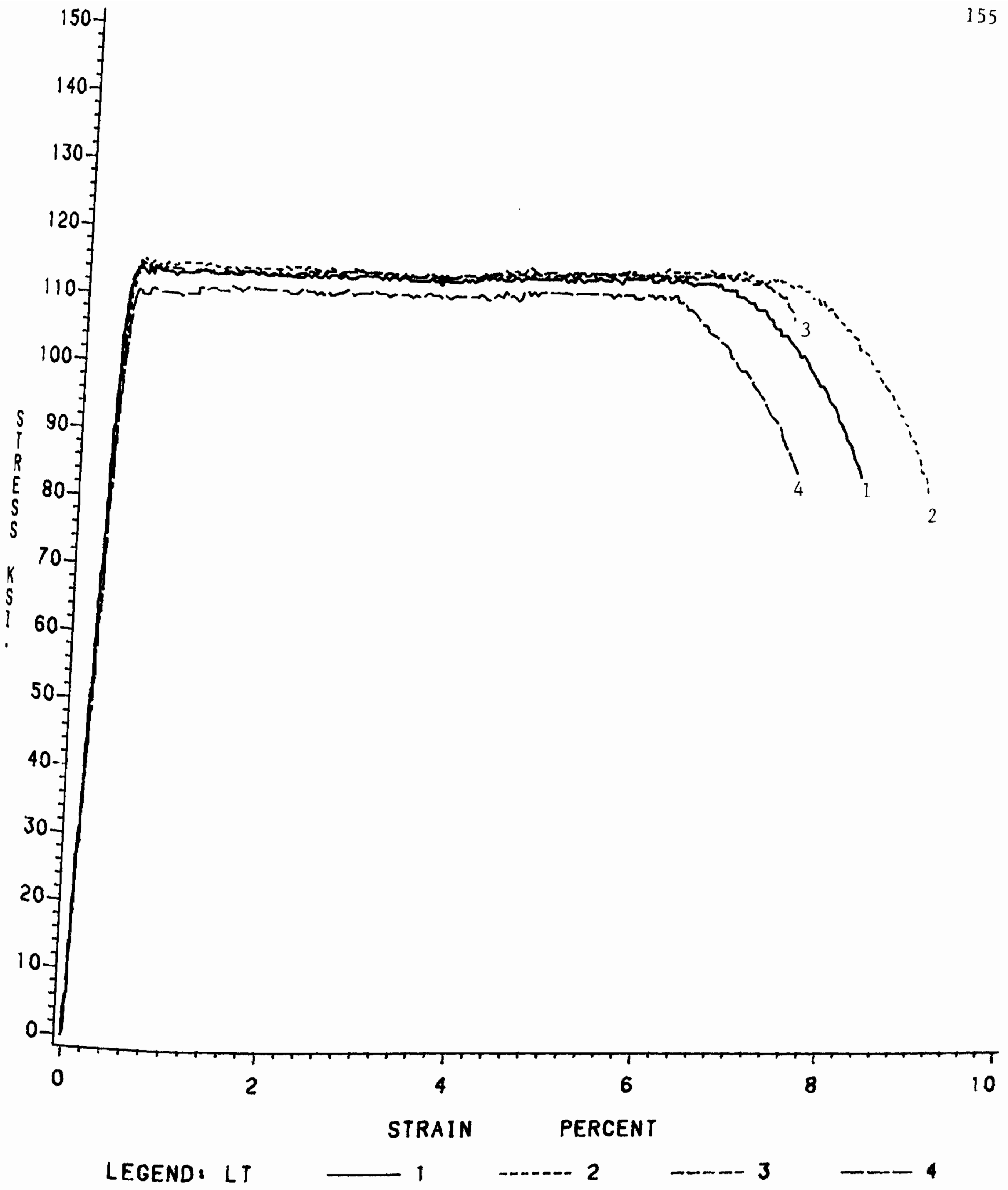


Fig. 4.51

INDIVIDUAL STRESS-STRAIN CURVE FOR 100XF-LT

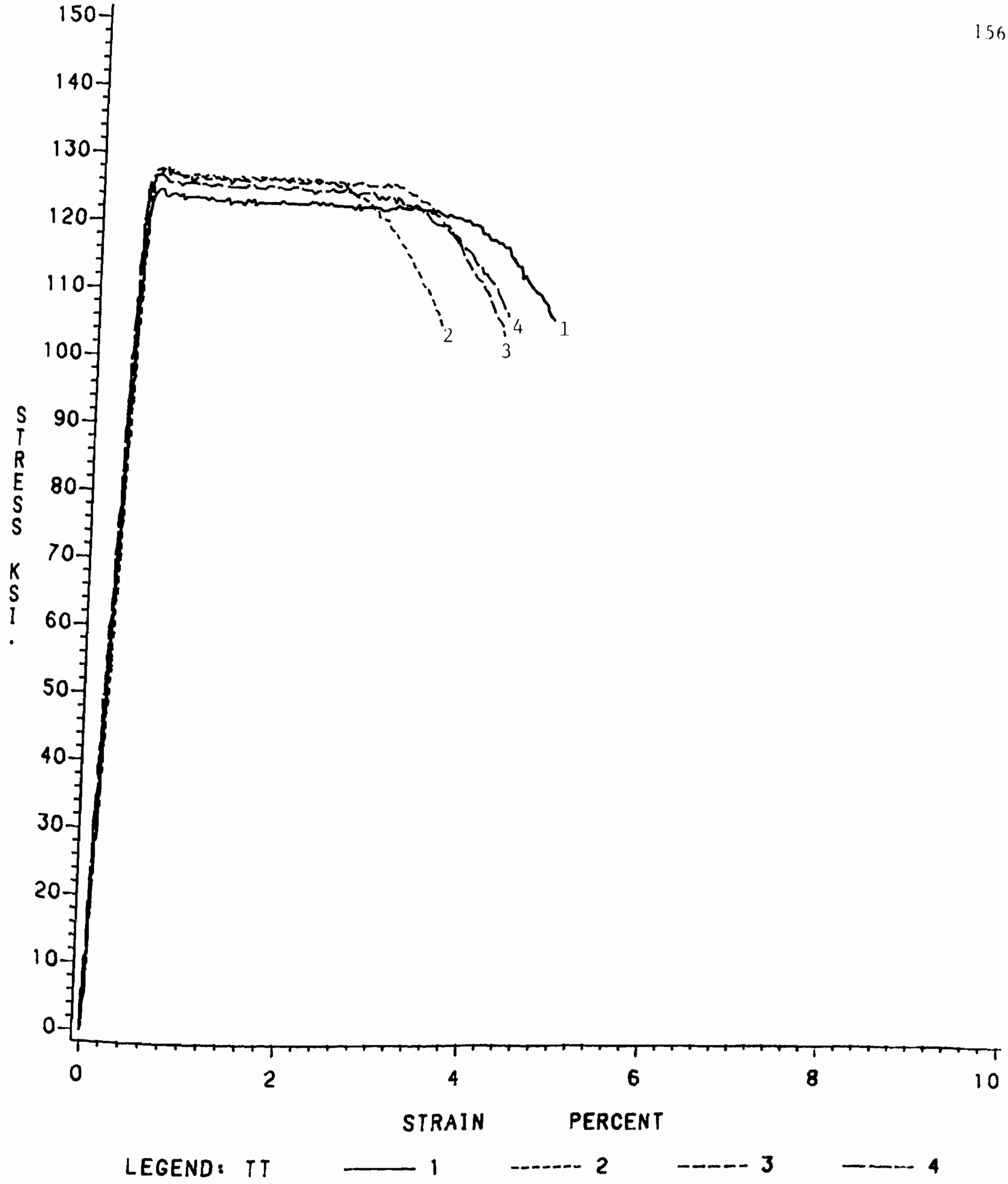


Fig. 4.52

INDIVIDUAL STRESS-STRAIN CURVE FOR 100XF-TT

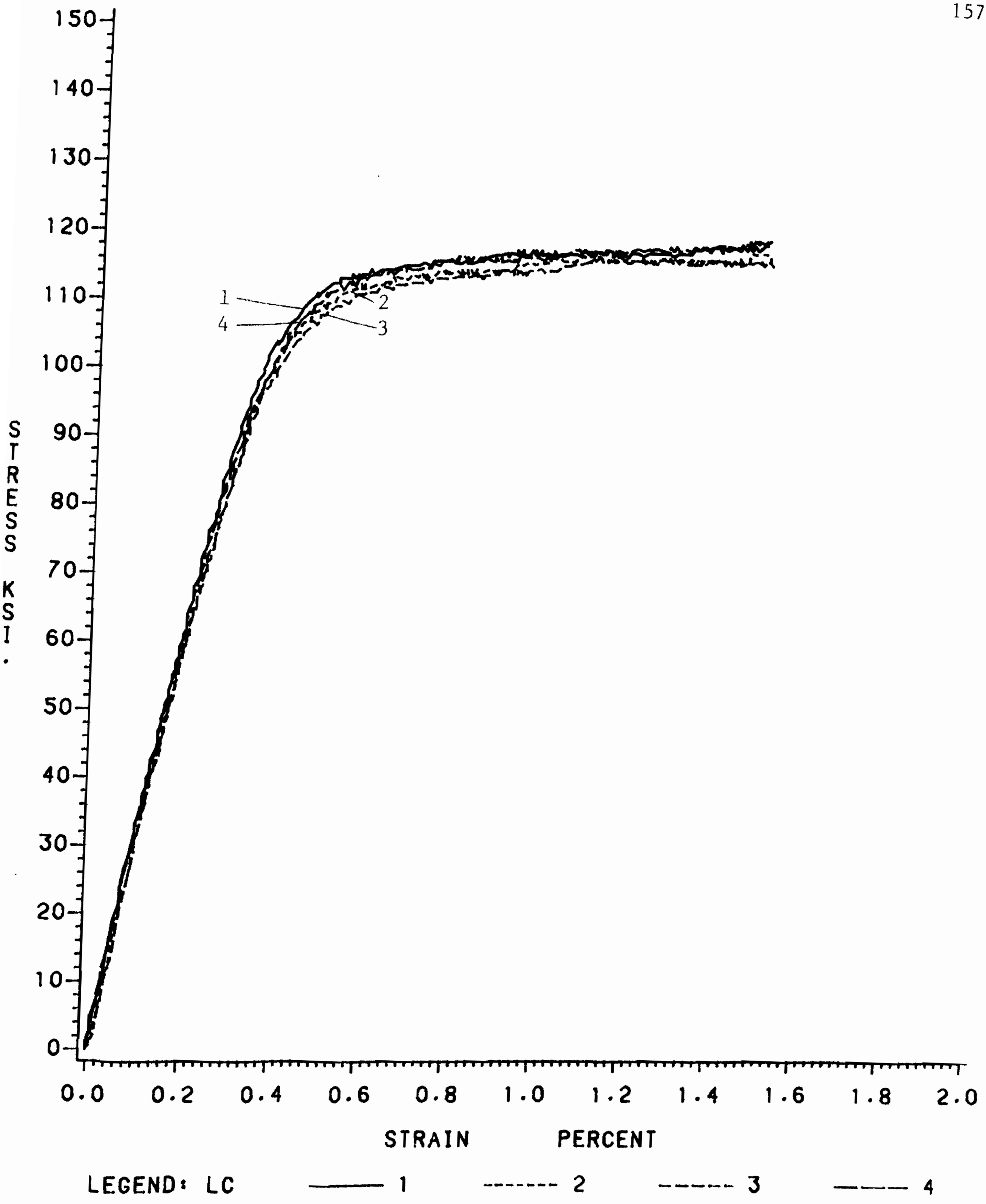


Fig. 4.53

INDIVIDUAL STRESS–STRAIN CURVE FOR 100XF–LC

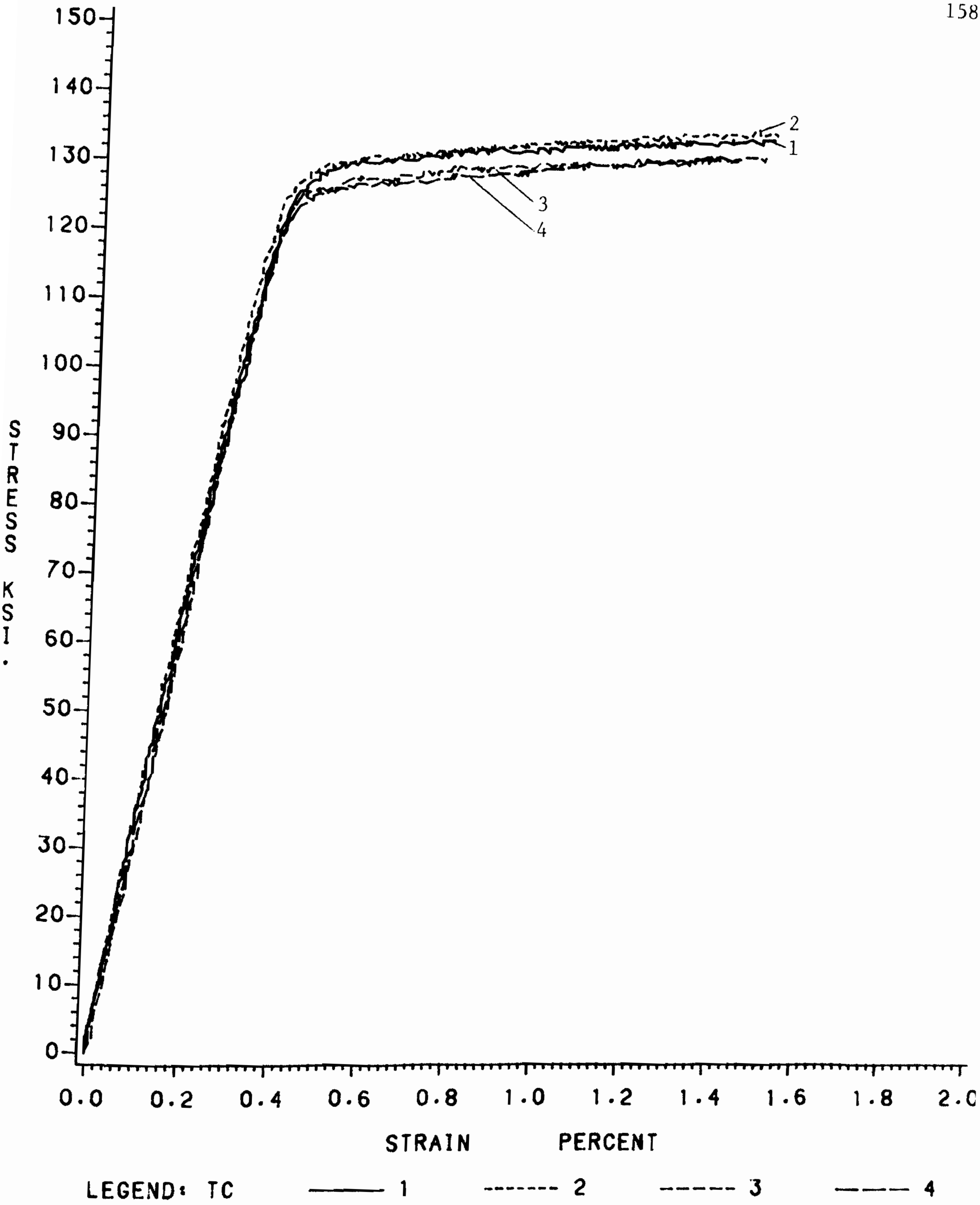


Fig. 4.54

INDIVIDUAL STRESS-STRAIN CURVE FOR 100XF-TC

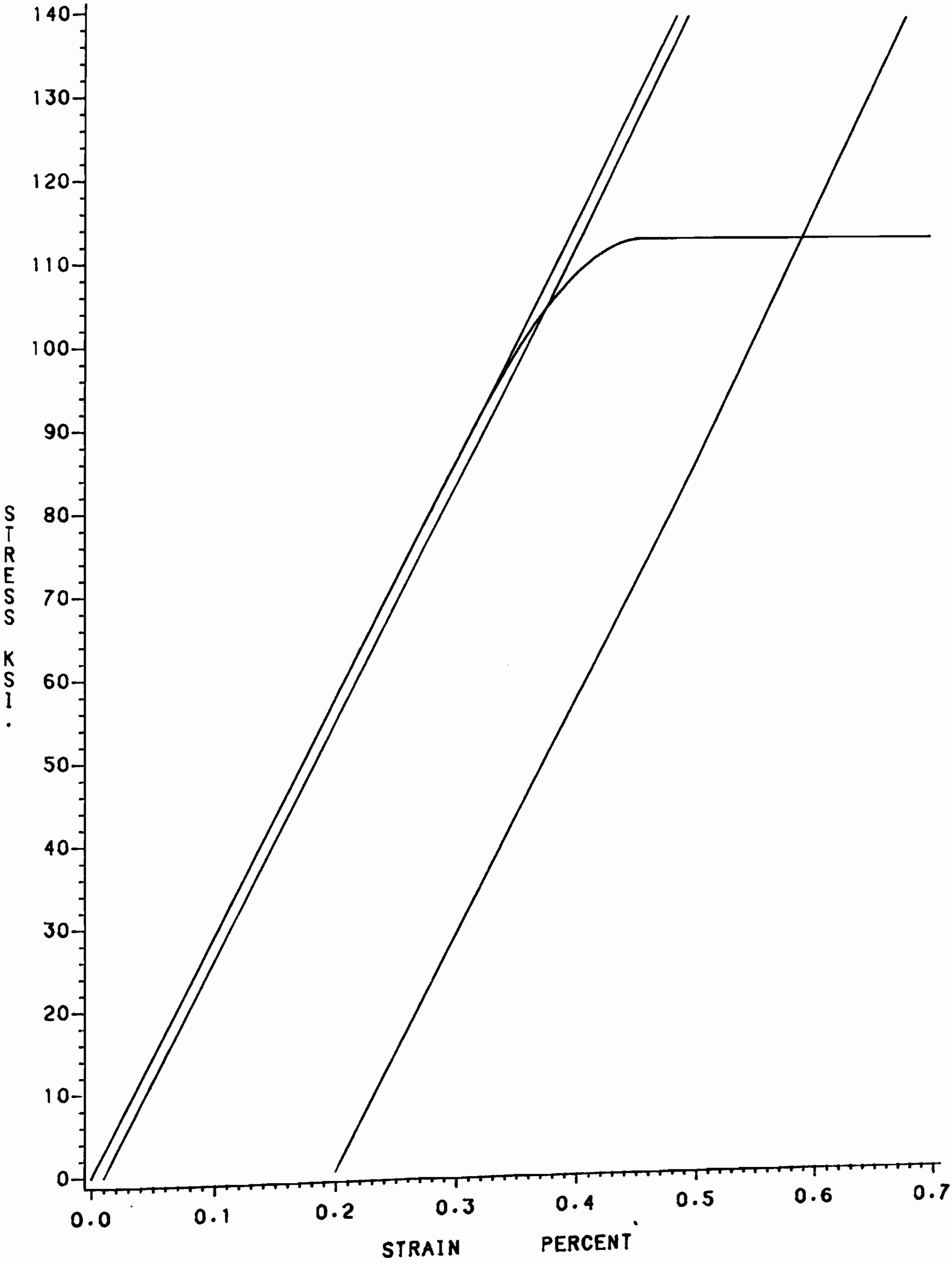


Fig. 4.55

REPRESENTATIVE STRESS--STRAIN CURVE FOR 100XF-LT

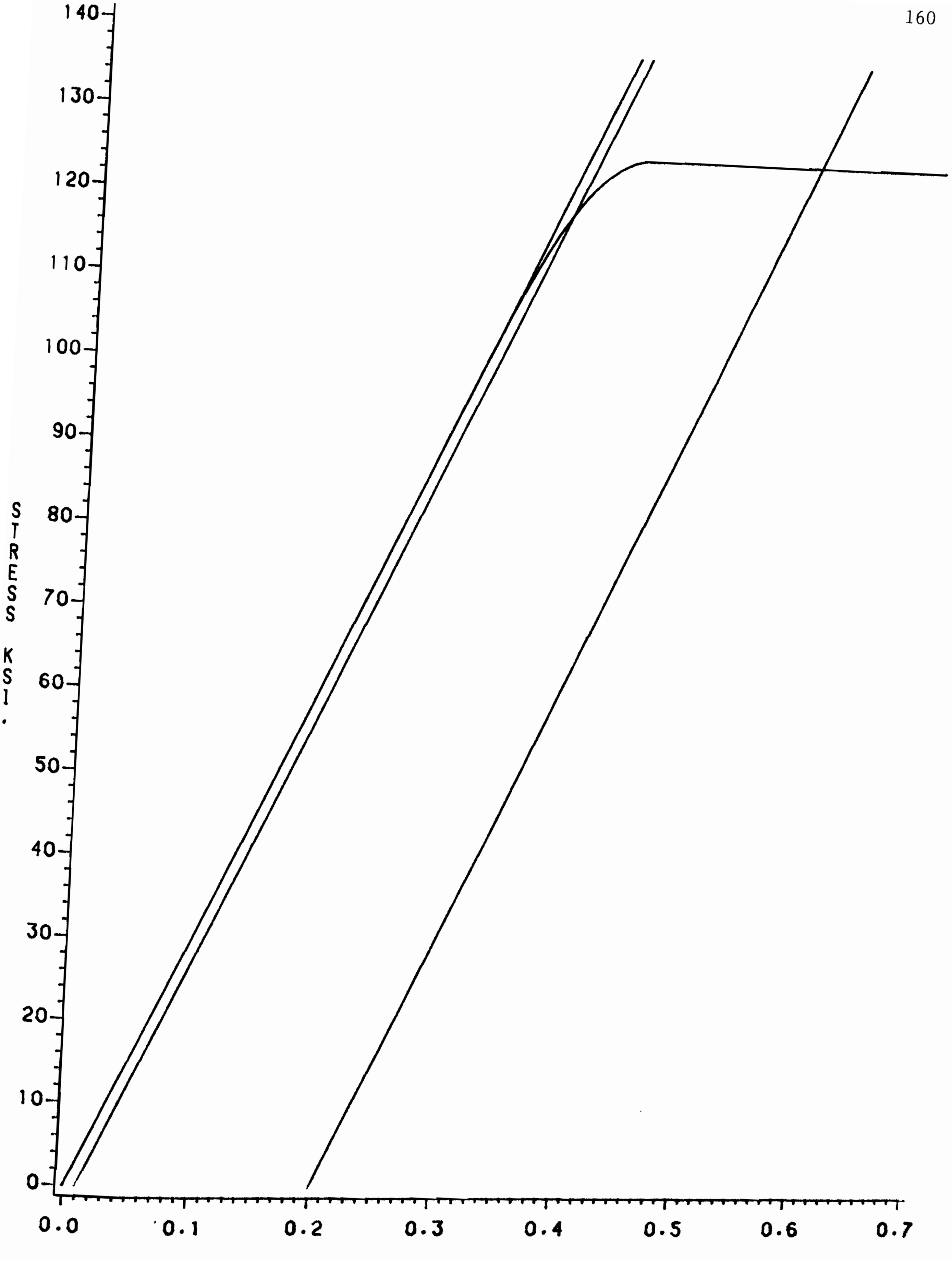


Fig. 4.56

REPRESENTATIVE STRESS-STRAIN CURVE FOR 100XF-TT

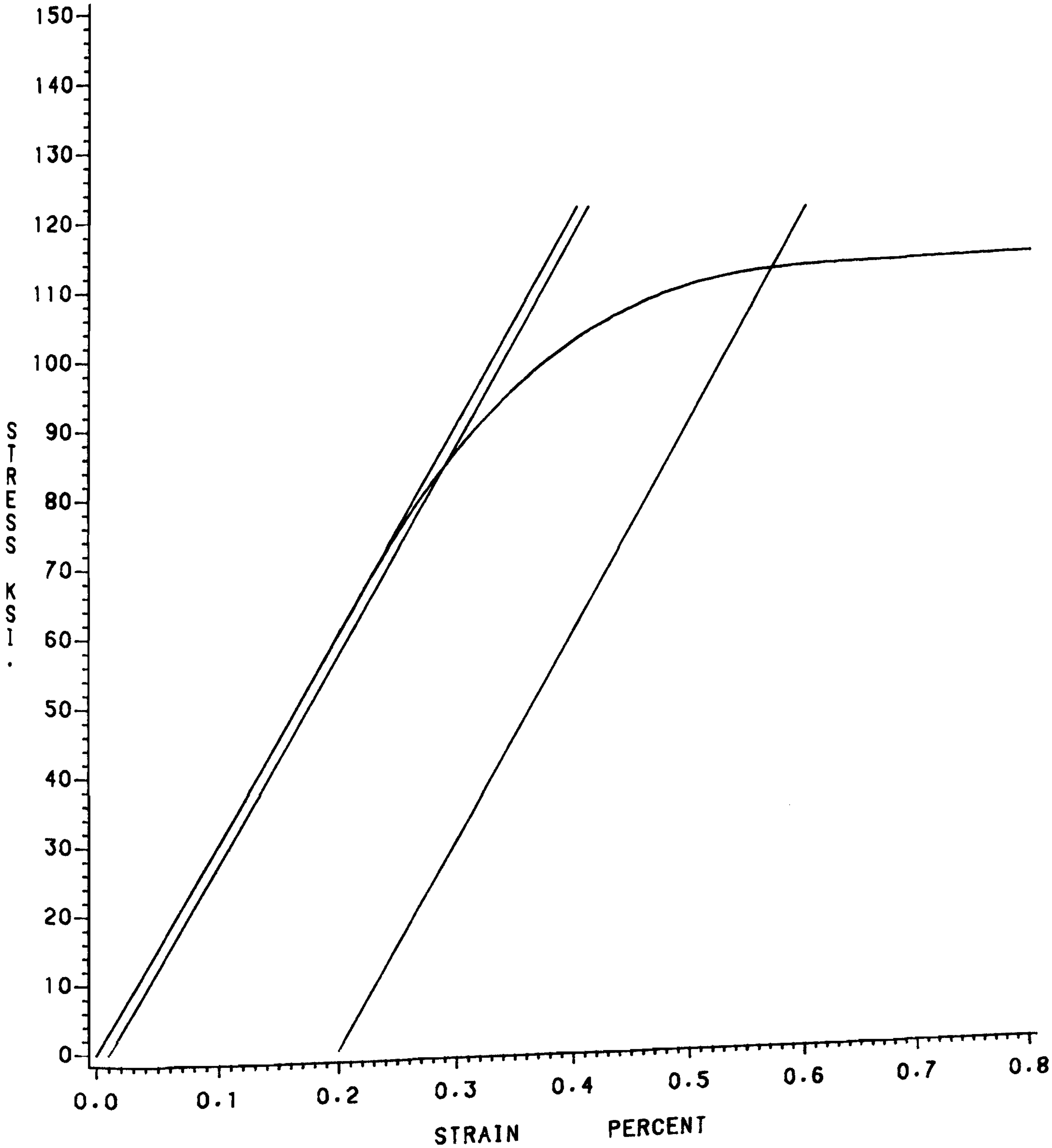


Fig. 4.57

REPRESENTATIVE STRESS-STRAIN CURVE FOR 100XF-LC

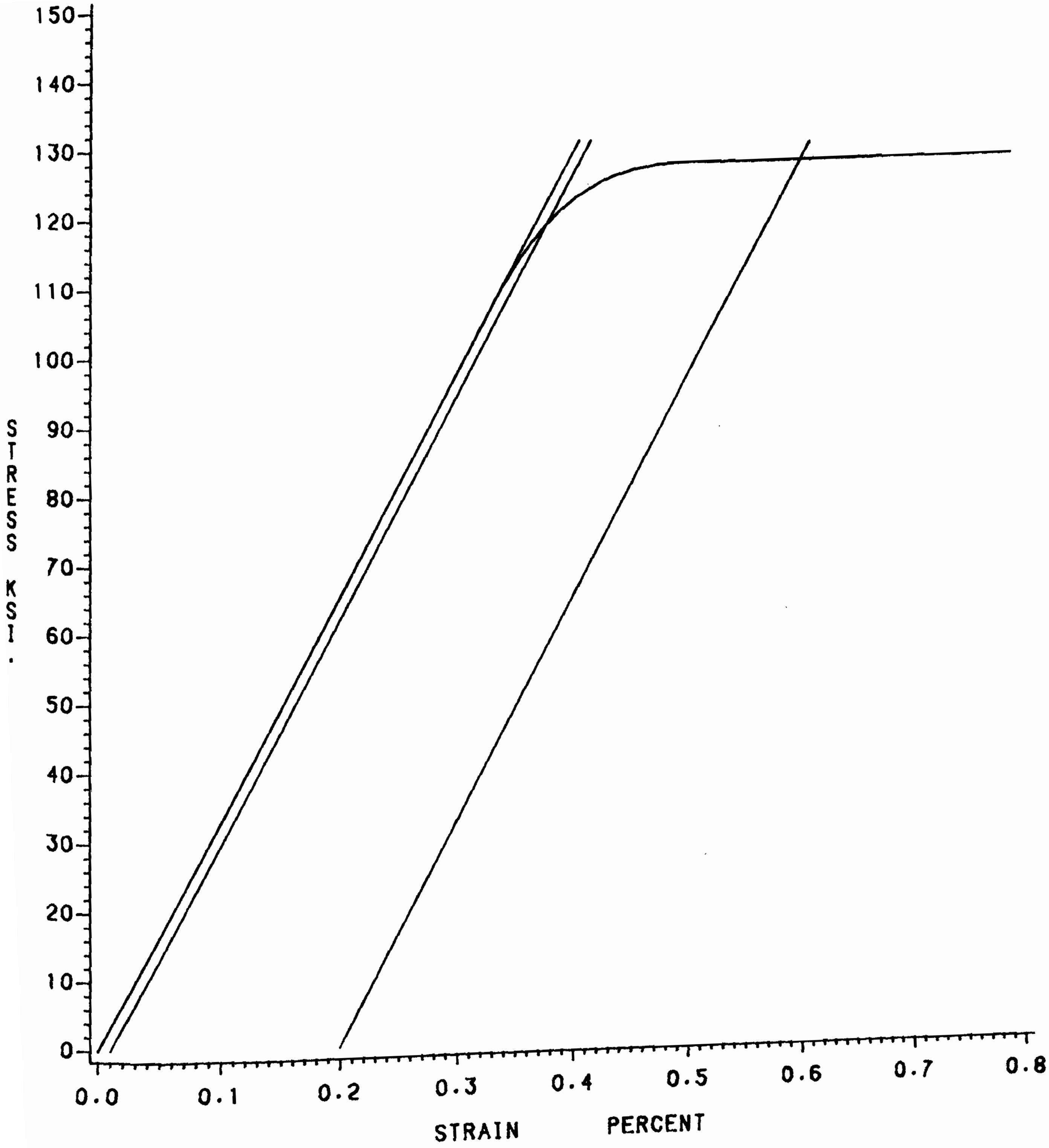
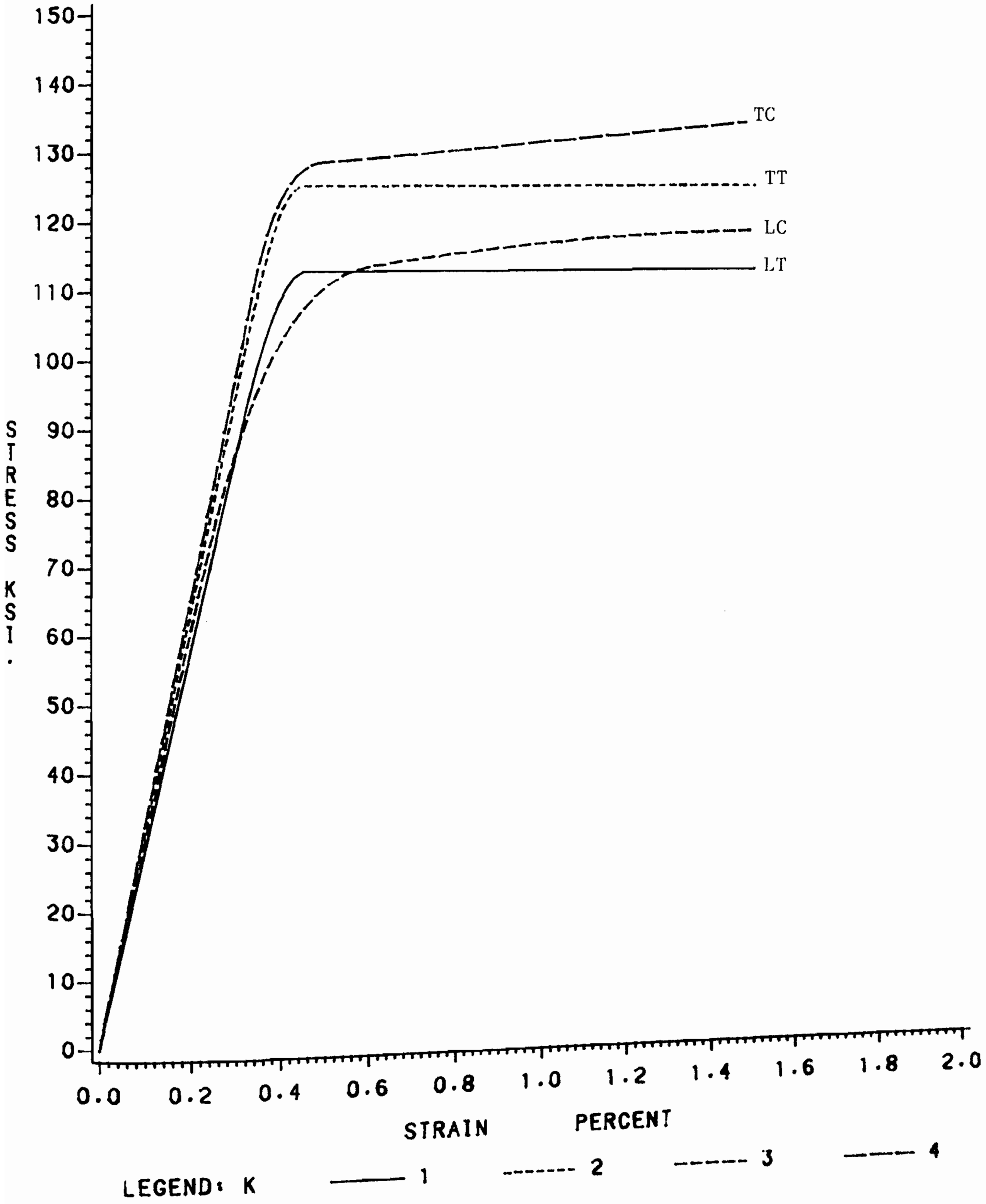


Fig. 4.58

REPRESENTATIVE STRESS-STRAIN CURVE FOR 100XF-TC



1=LT 2=TT 3=LC 4=TC

Fig. 4.59

COMPARISON OF VARIOUS TESTS FOR 100XF

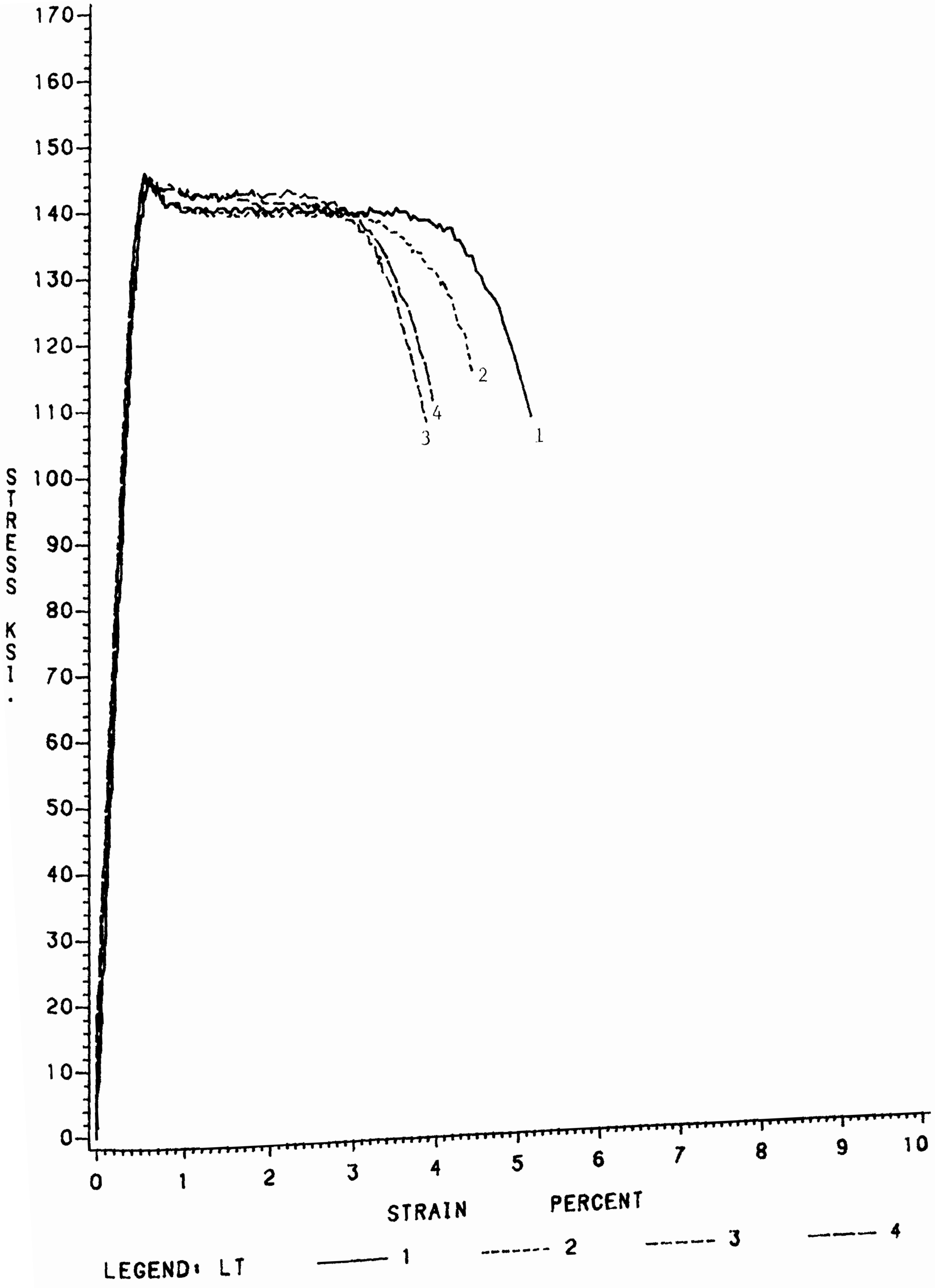


Fig. 4.60

INDIVIDUAL STRESS-STRAIN CURVE FOR 140XF-LT

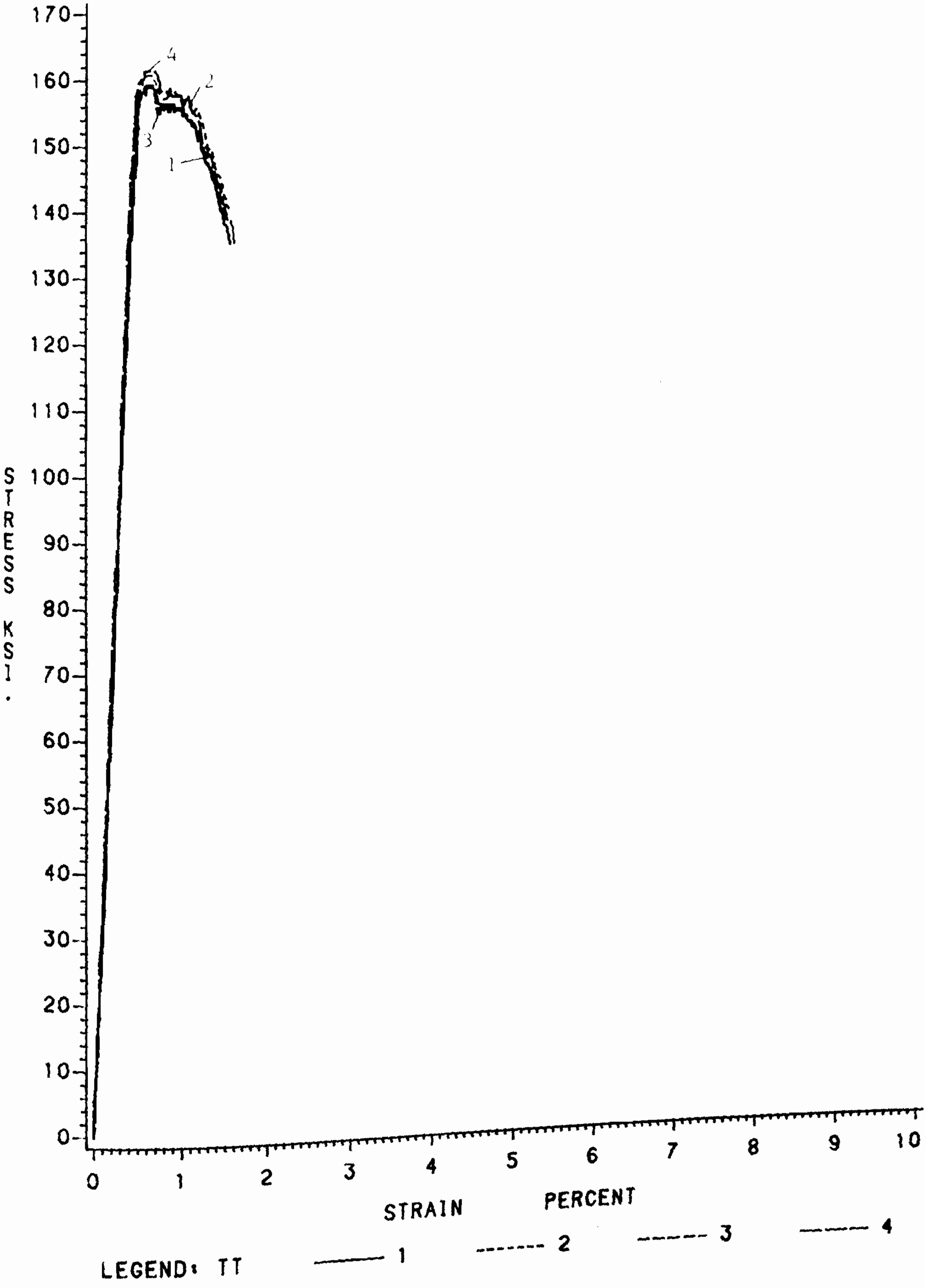


Fig. 4.61

INDIVIDUAL STRESS-STRAIN CURVE FOR 140XF-TT

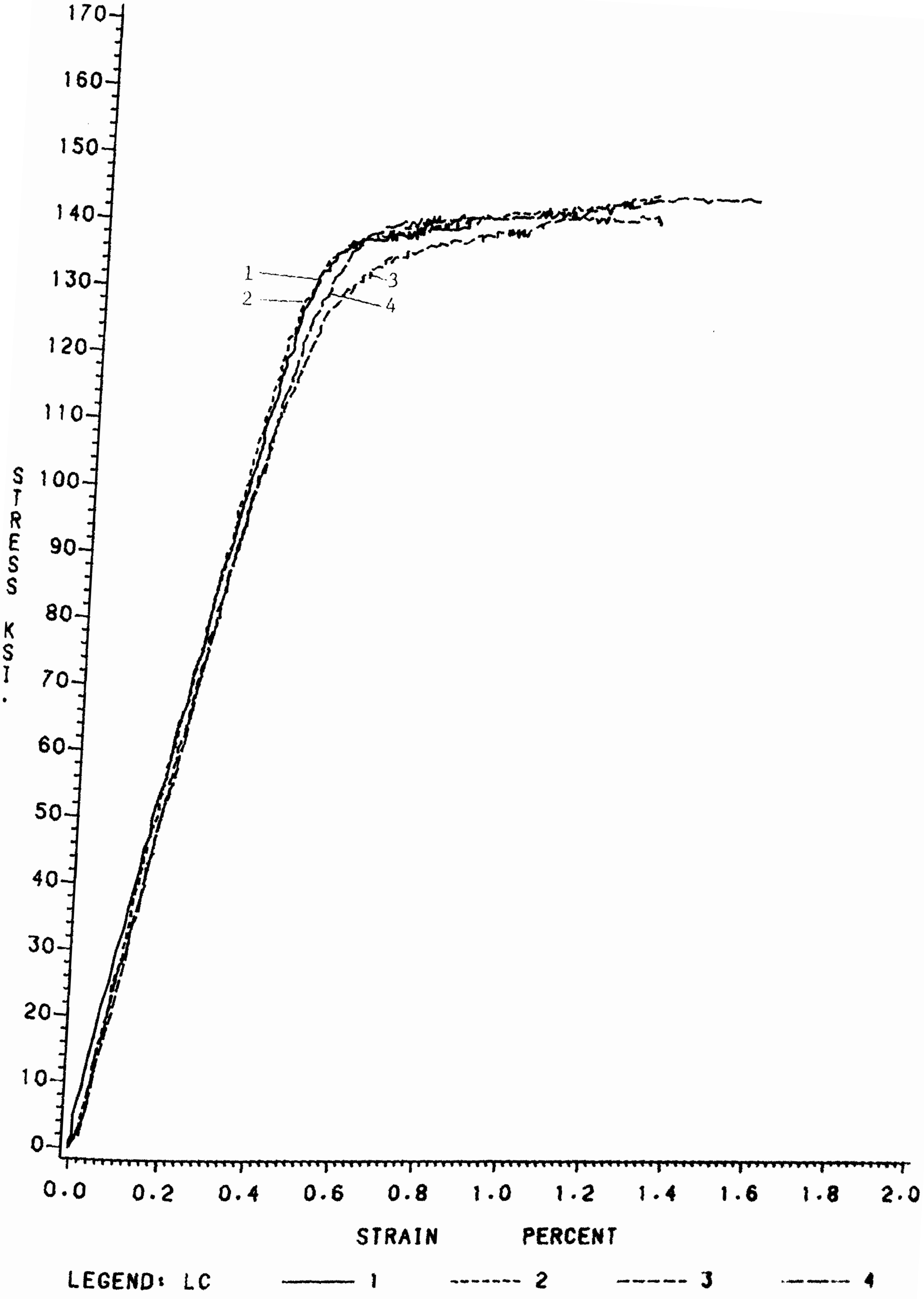


Fig. 4.62

INDIVIDUAL STRESS-STRAIN CURVE FOR 140XF-LC

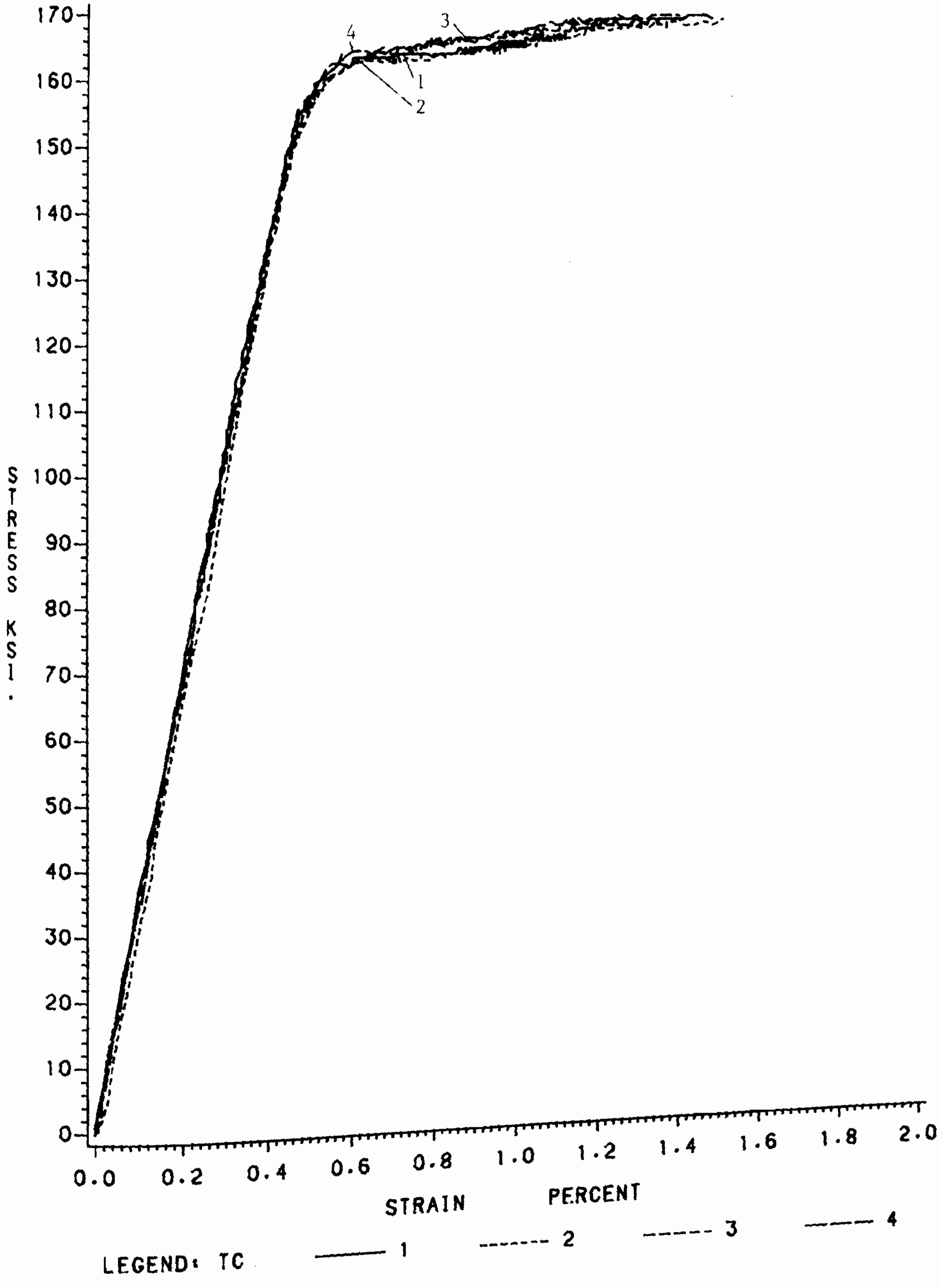


Fig. 4.63

INDIVIDUAL STRESS-STRAIN CURVE FOR 140XF-TC

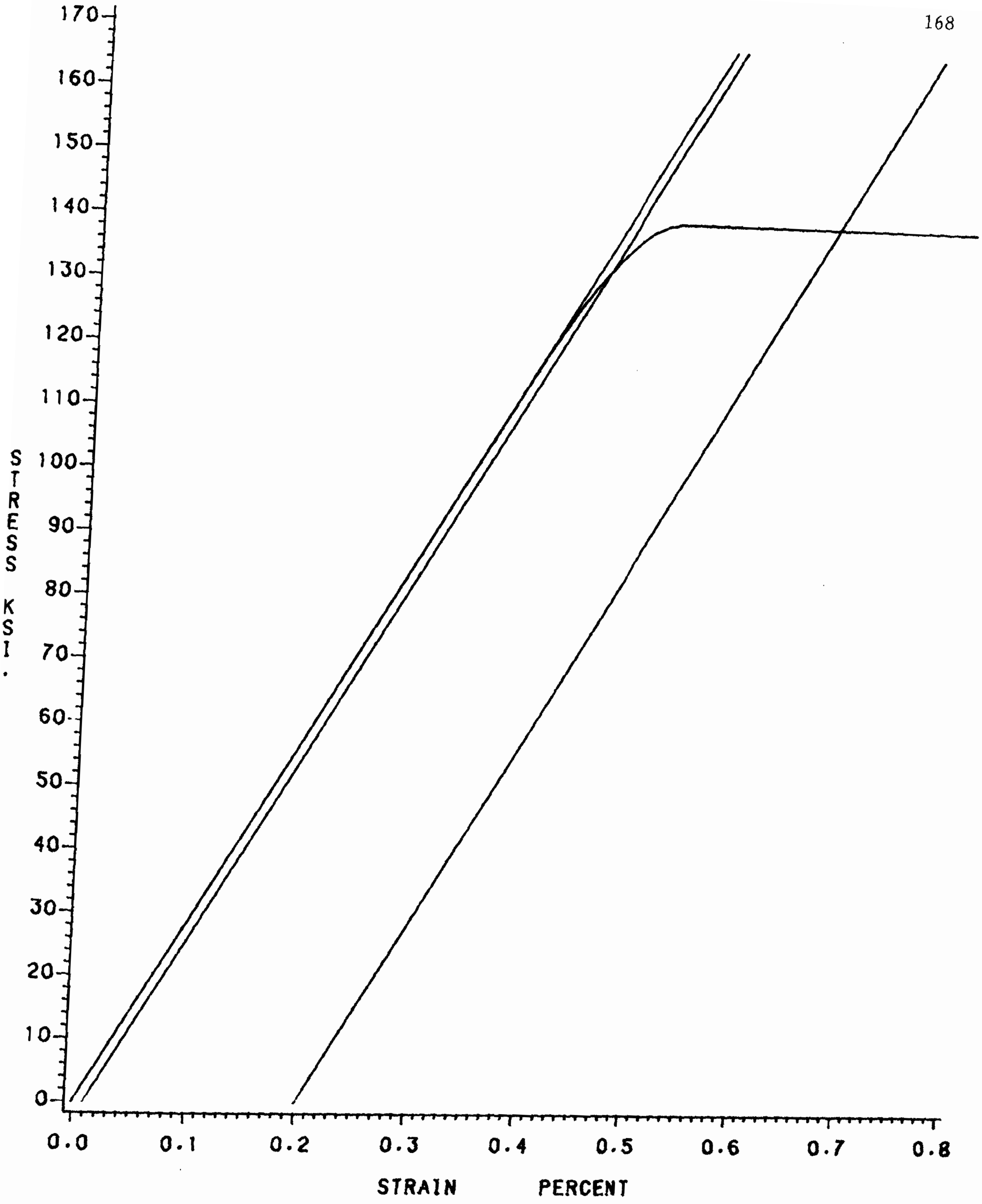


Fig. 4.64

REPRESENTATIVE STRESS–STRAIN CURVE FOR 140XF–LT

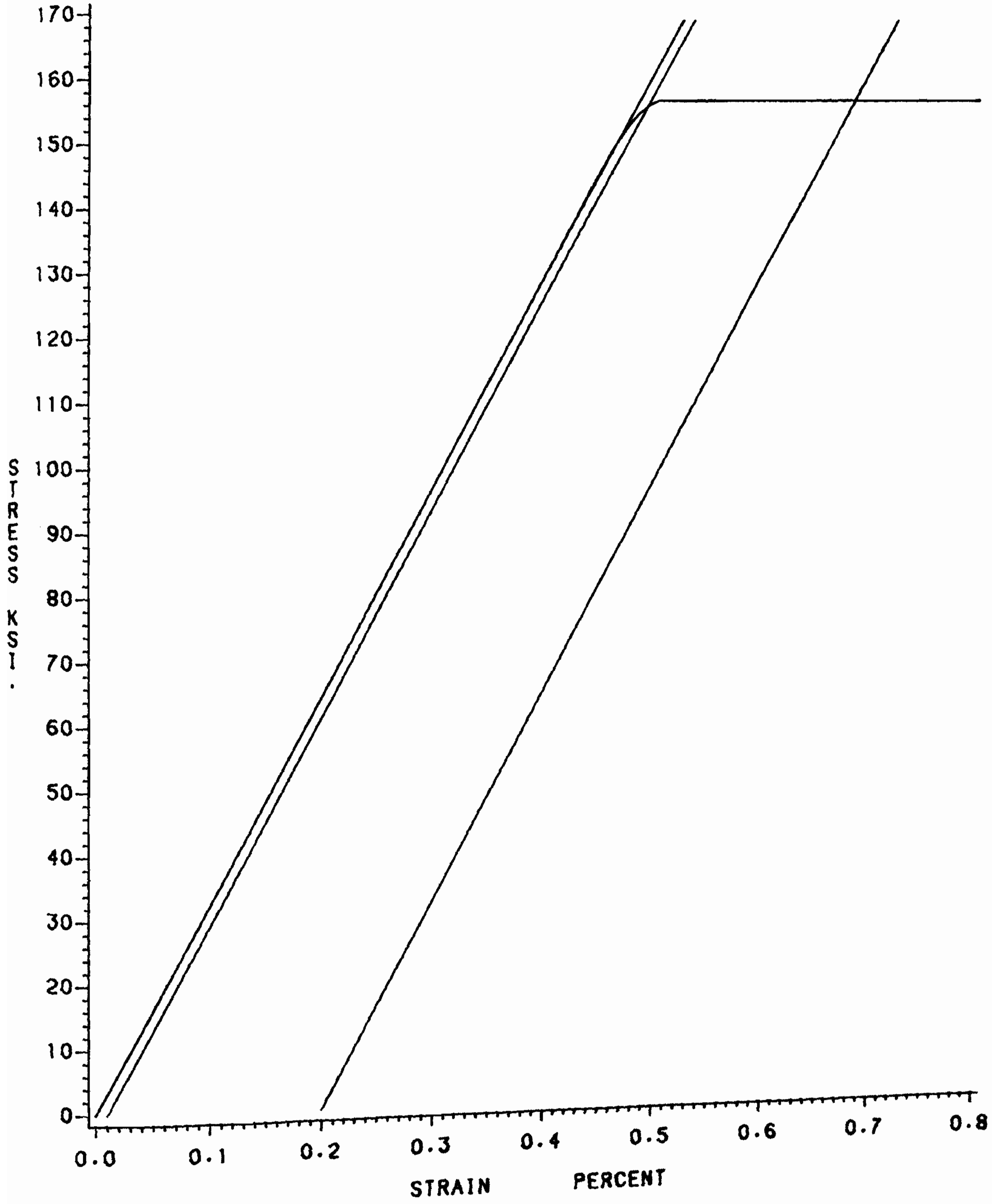


Fig. 4.65

REPRESENTATIVE STRESS-STRAIN CURVE FOR 140XF-TT

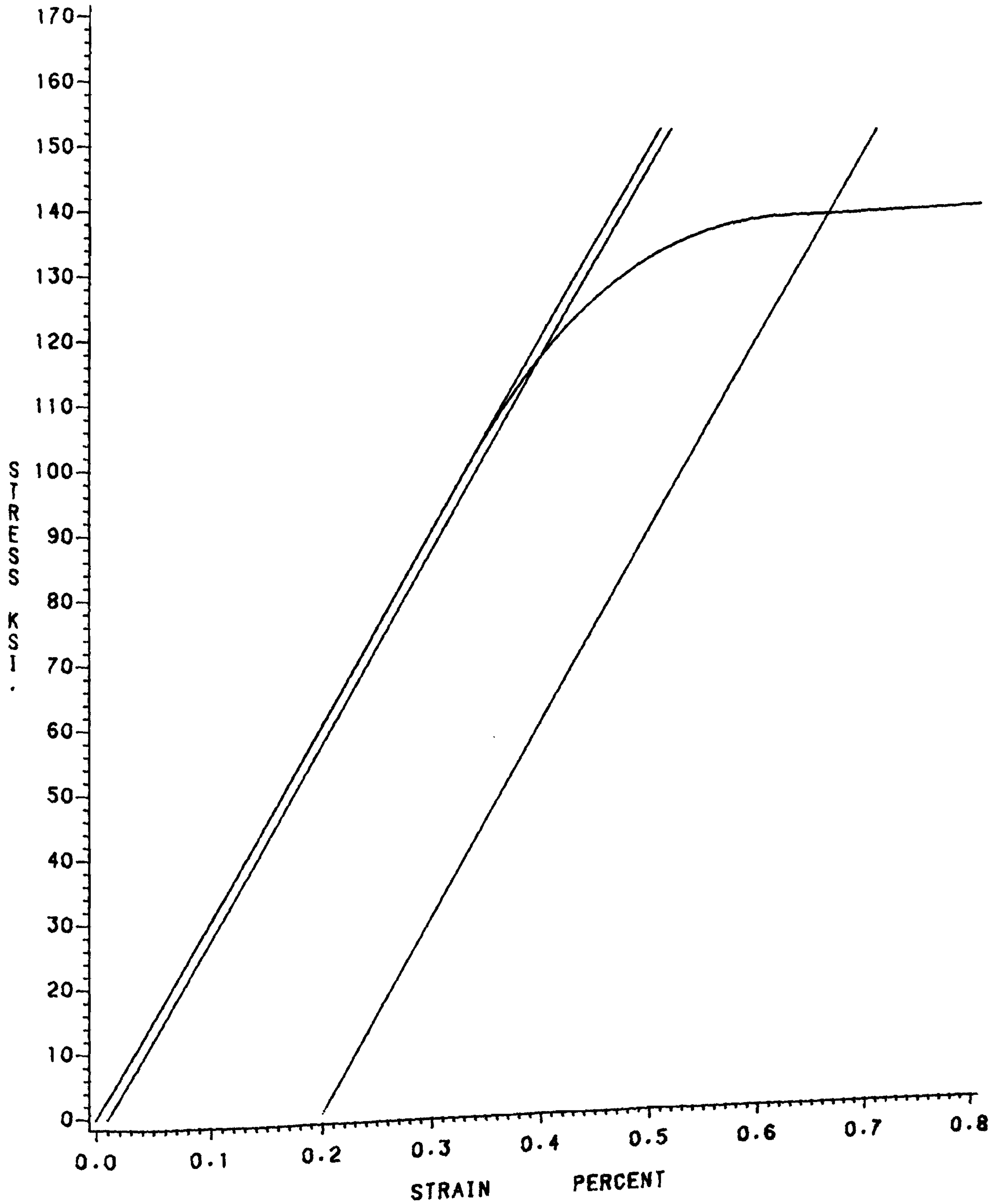


Fig. 4.66

REPRESENTATIVE STRESS—STRAIN CURVE FOR 140XF—LC

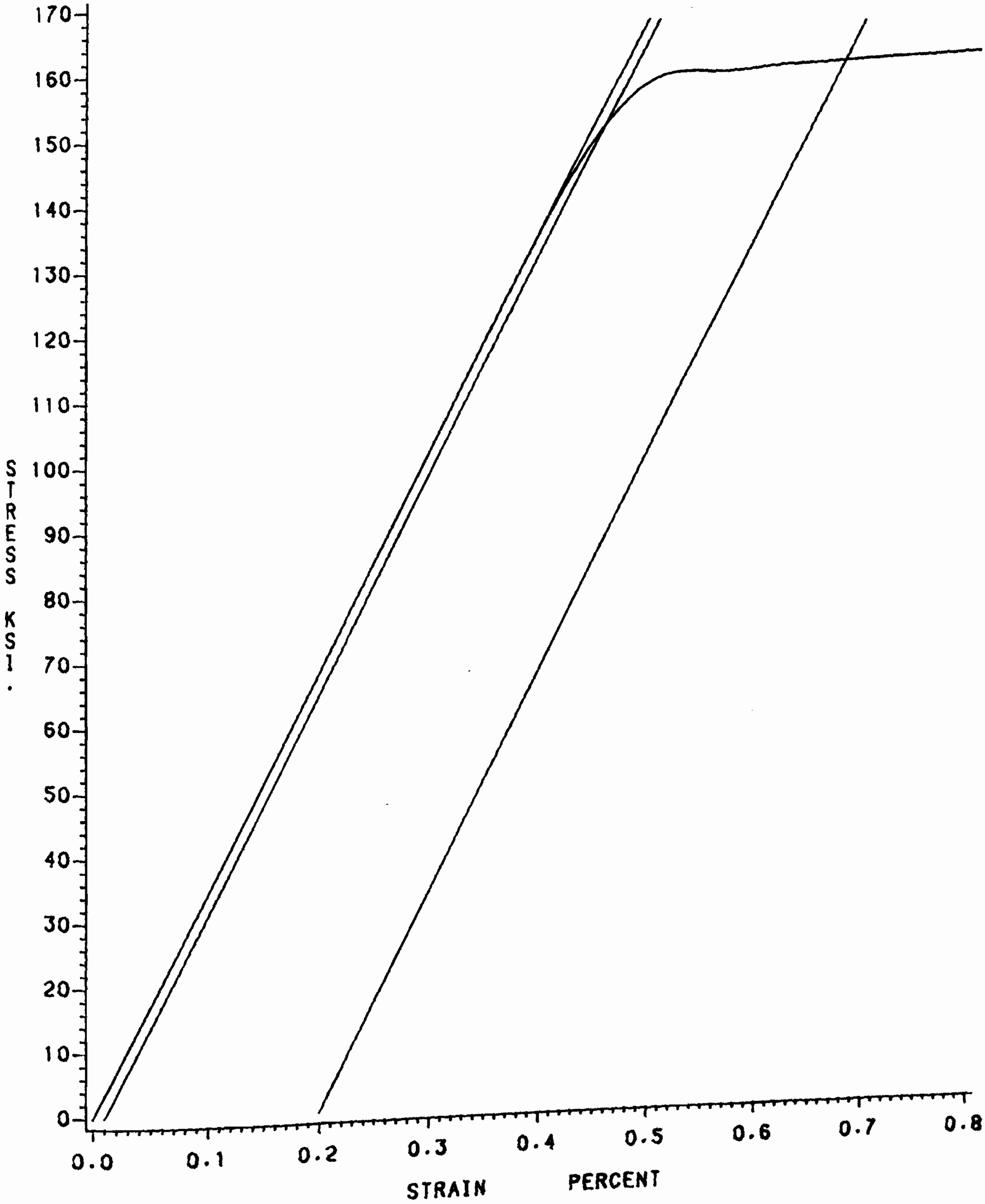
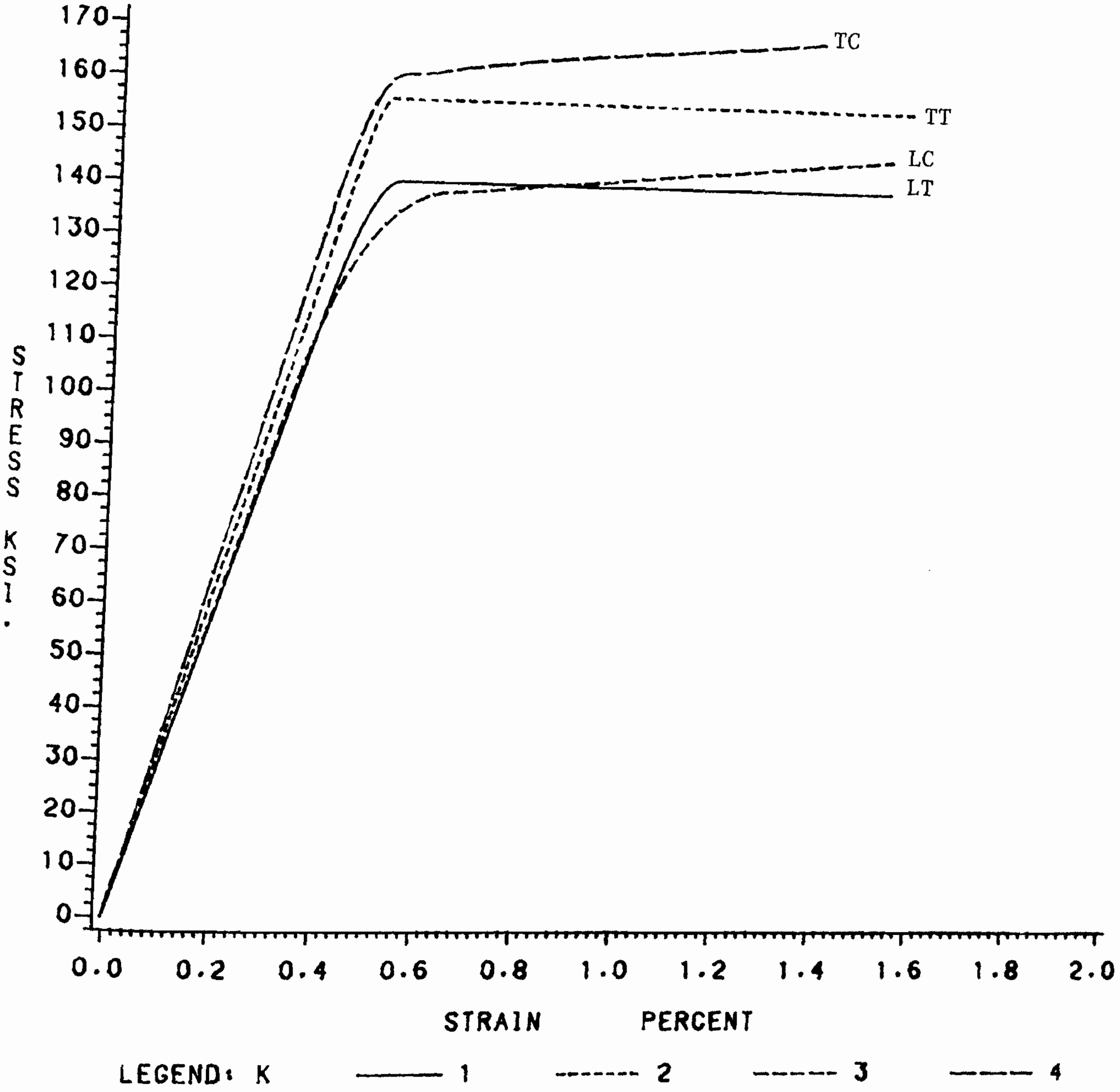


Fig. 4.67

REPRESENTATIVE STRESS-STRAIN CURVE FOR 140XF-TC



1=LT 2=TT 3=LC 4=TC

Fig. 4.68

COMPARISON OF VARIOUS TESTS FOR 140XF

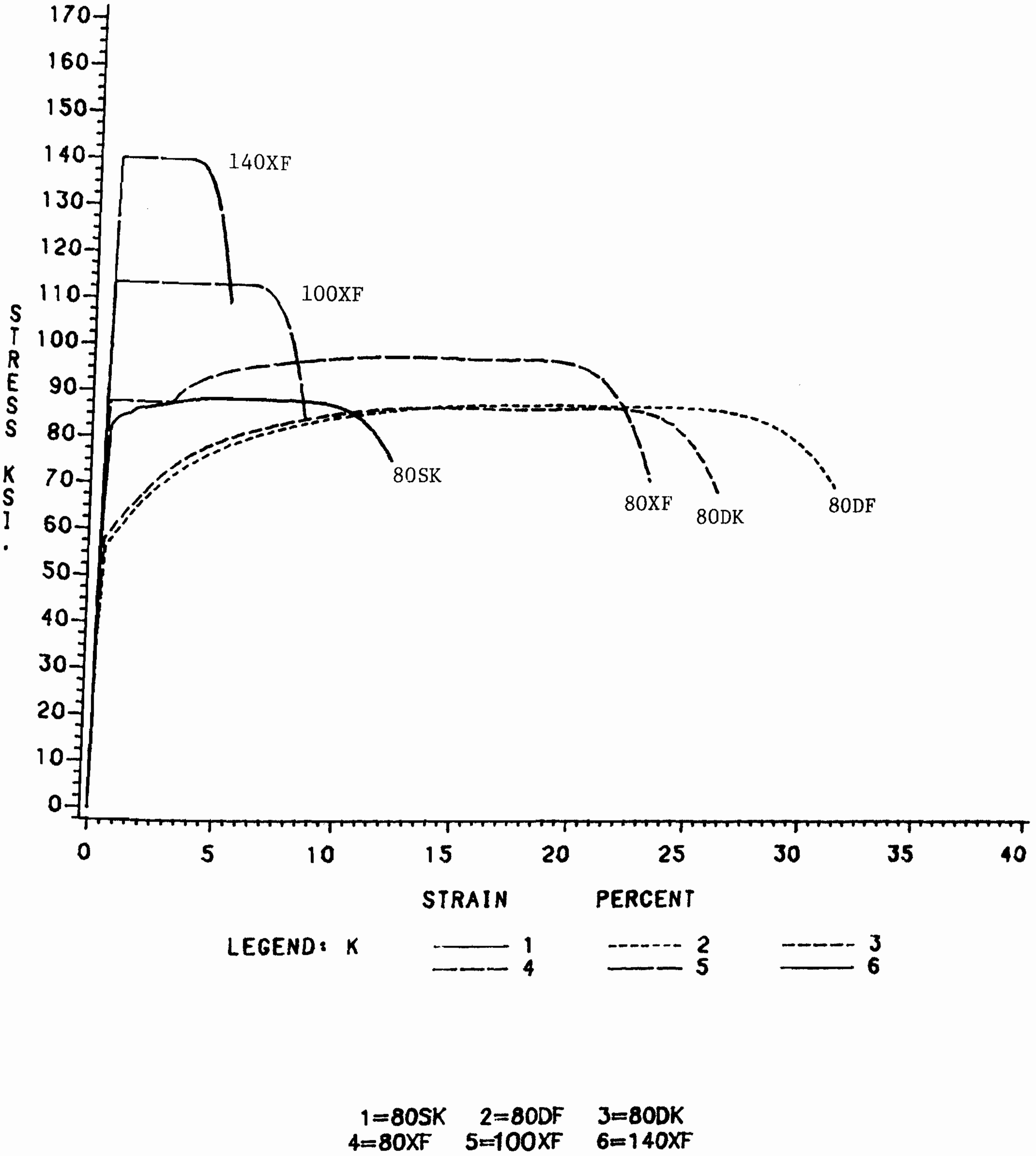
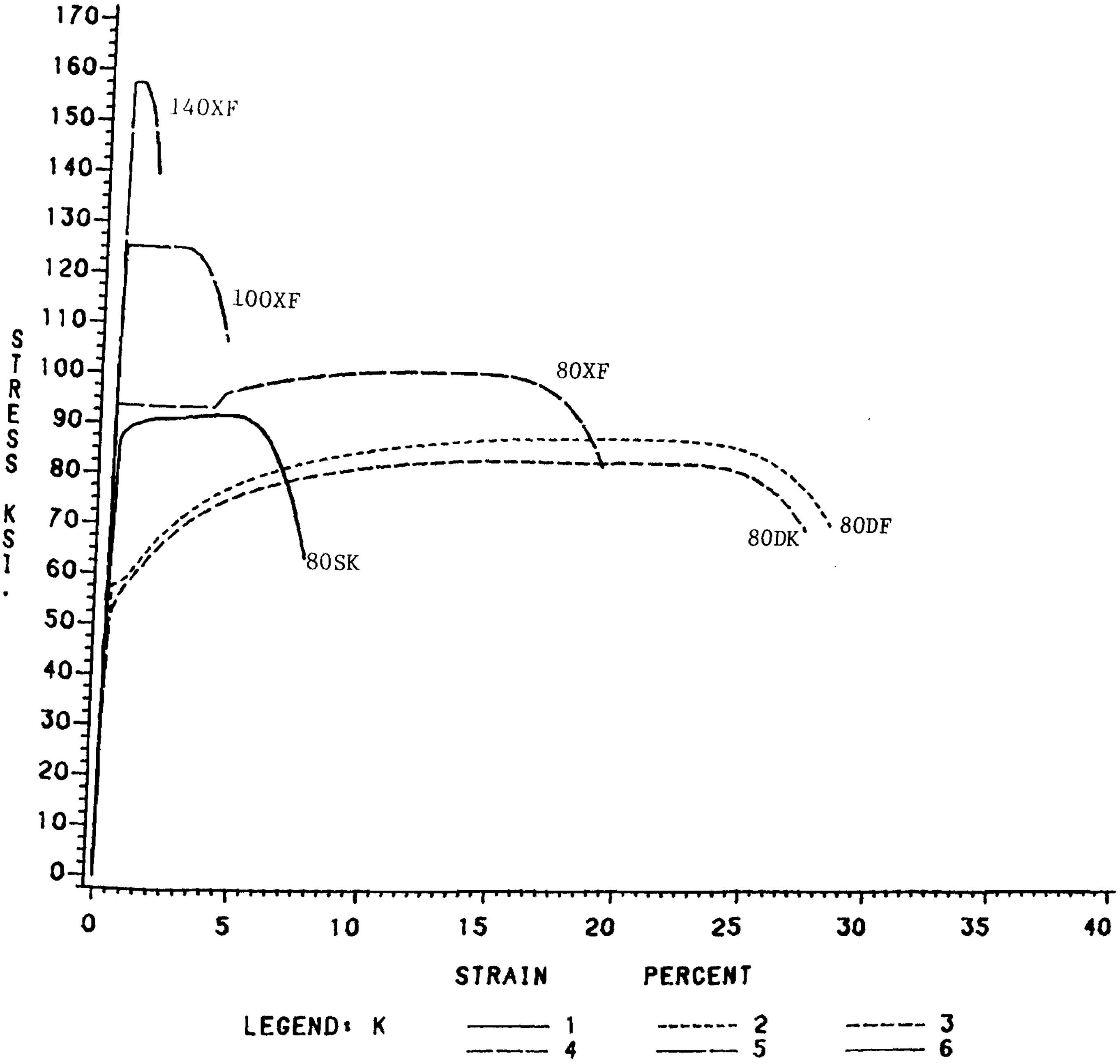


Fig. 4.69
COMPARISON OF SIX SHEET STEELS FOR LONGITUDINAL TENSION



1=80SK 2=80DF 3=80DK
4=80XF 5=100XF 6=140XF

Fig. 4.70

COMPARISON OF SIX SHEET STEELS FOR TRANSVERSE TENSION

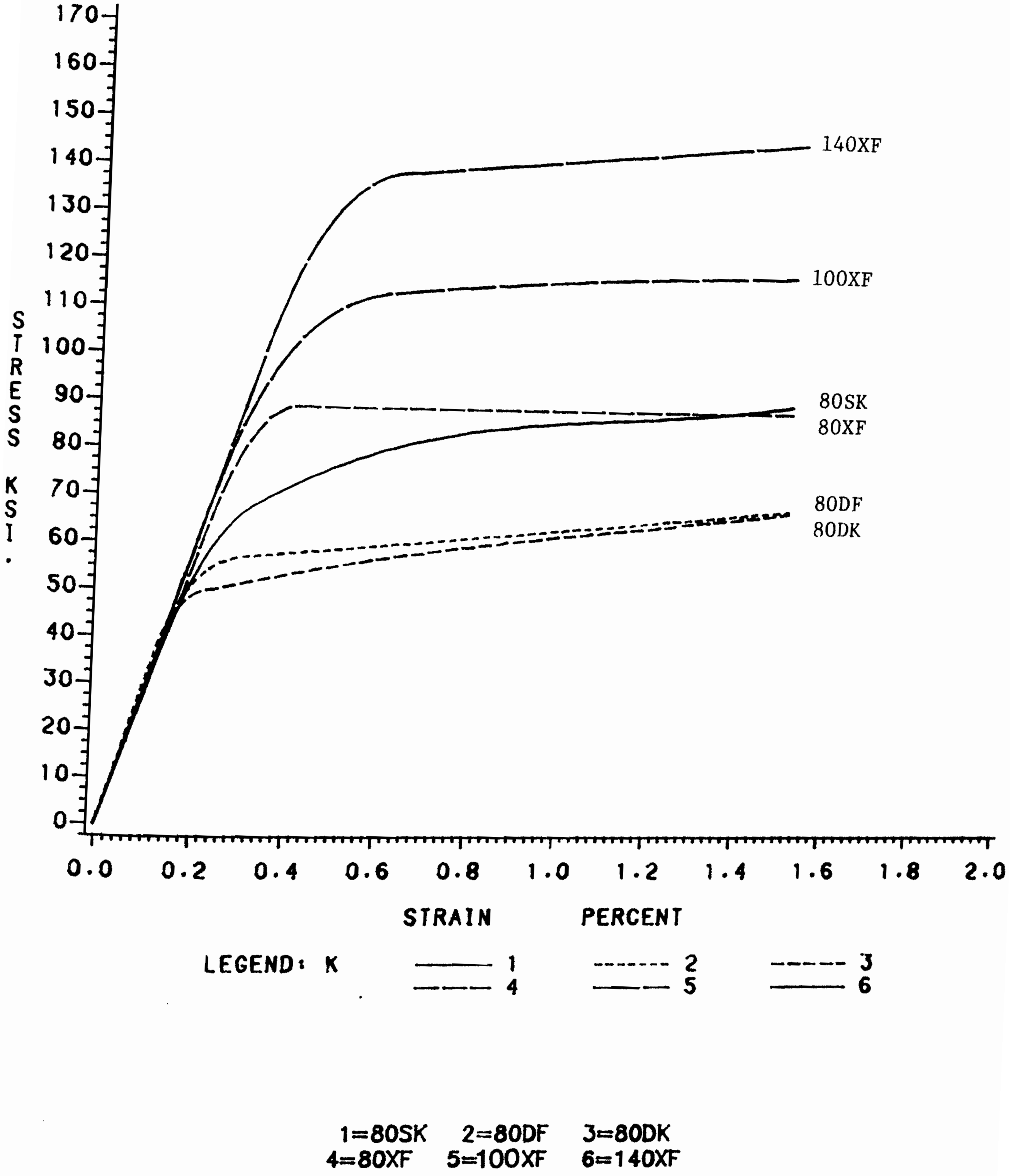


Fig. 4.71

COMPARISON OF SIX SHEET STEELS FOR LONGITUDINAL COMPRESSION

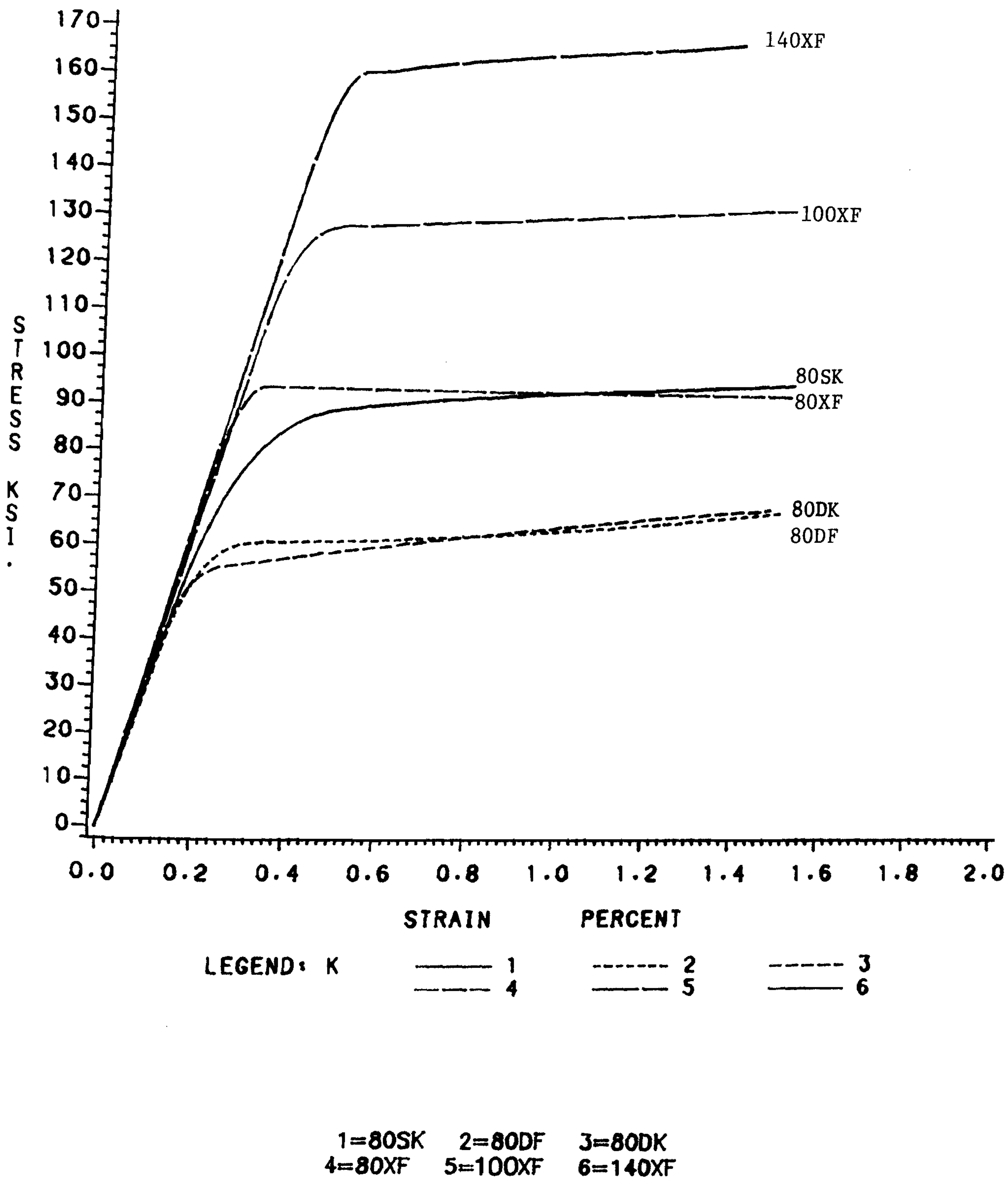


Fig. 4.72

COMPARISON OF SIX SHEET STEELS FOR TRANSVERSE COMPRESSION

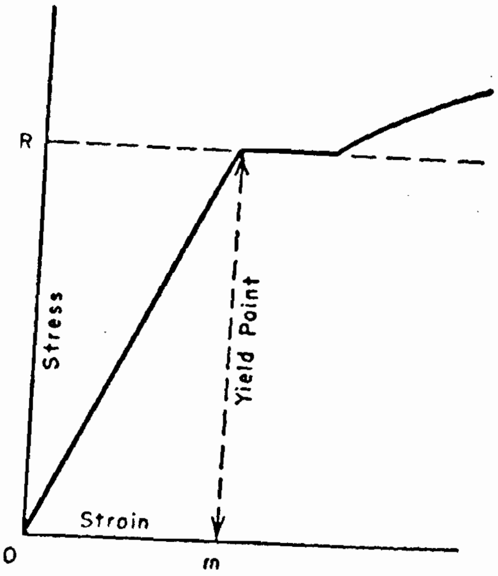
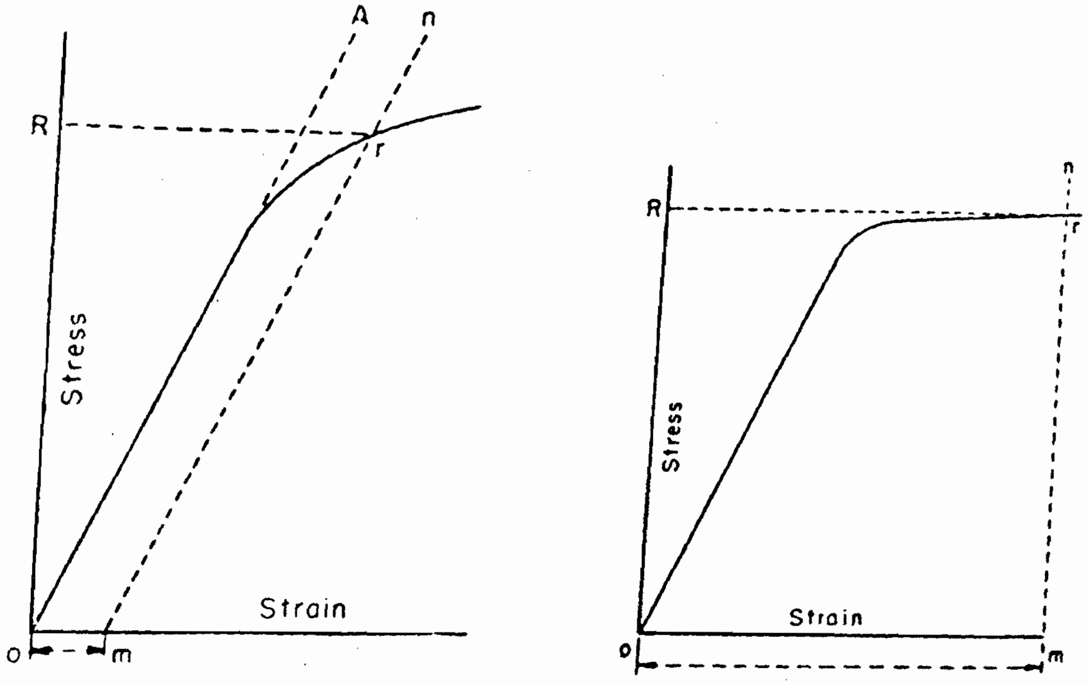


Fig. 4.73 Stress-Strain Curve of Sharp-Yielding Steel[4.1]



om = 0.2 percent

(a) Determination of Yield Strength by the Offset Method

om = 0.5 percent

(b) Determination of Yield Strength by the Extension-Under-Load Method

Fig. 4.74 Stress-Strain Curve of Gradual-Yielding Steel[4.1]

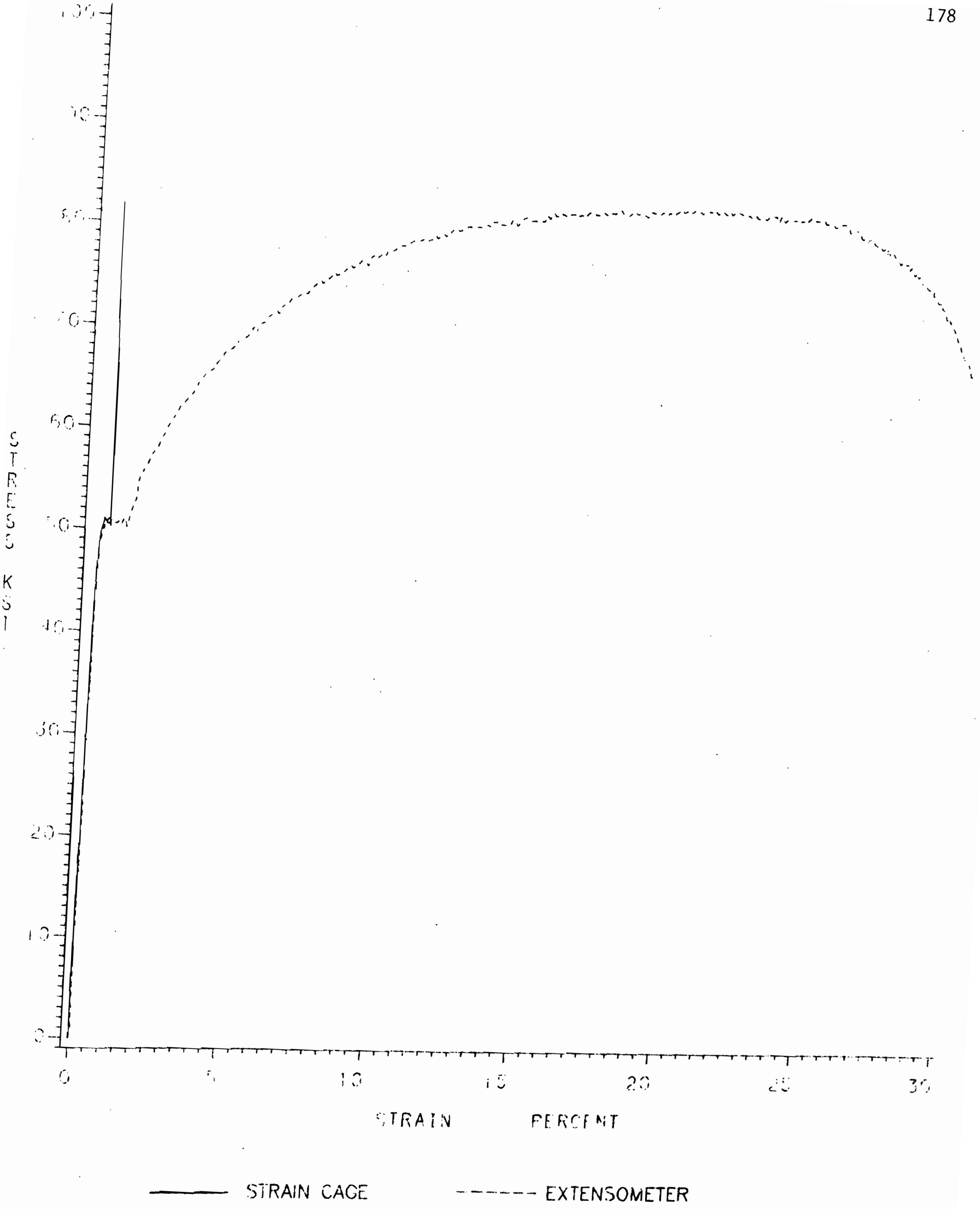


Fig. 4.75

COMPARISON OF STRESS-STRAIN CURVES FOR 80DF -LT
USING STRAIN CAGE AND EXTENSOMETER

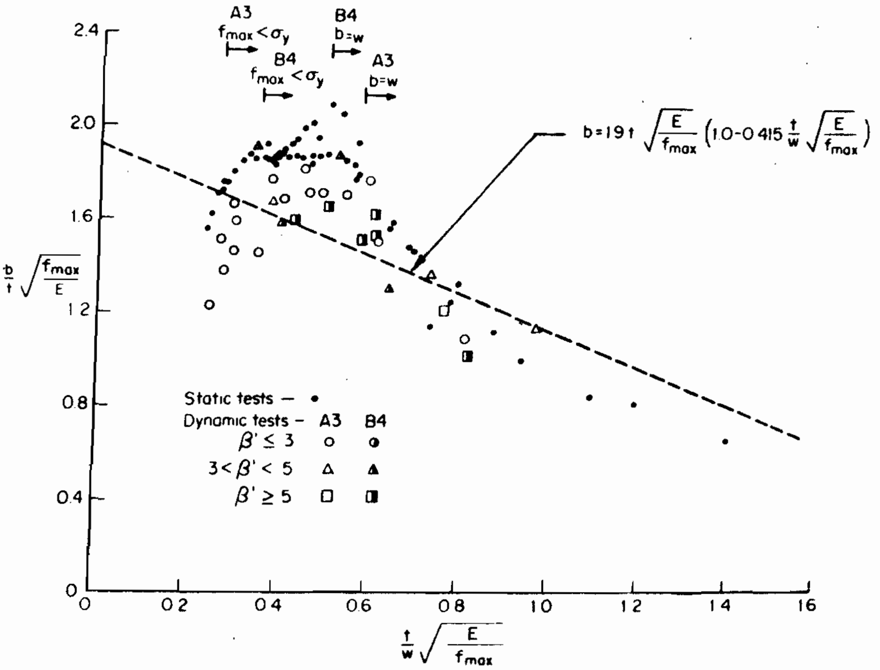


Fig. 5.1 Correlation Between the Effective Design Width Formula and Test Data[5.8]

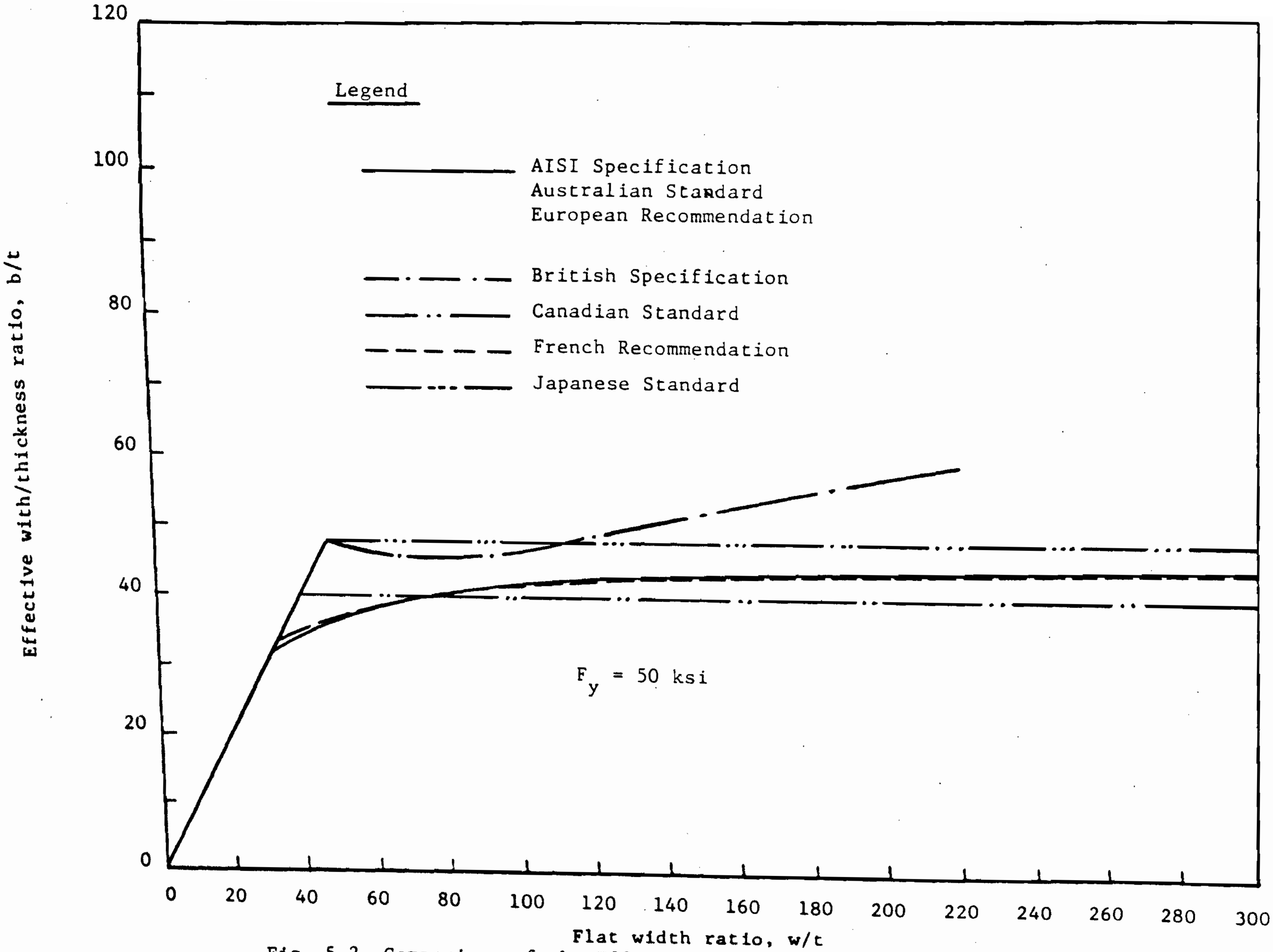
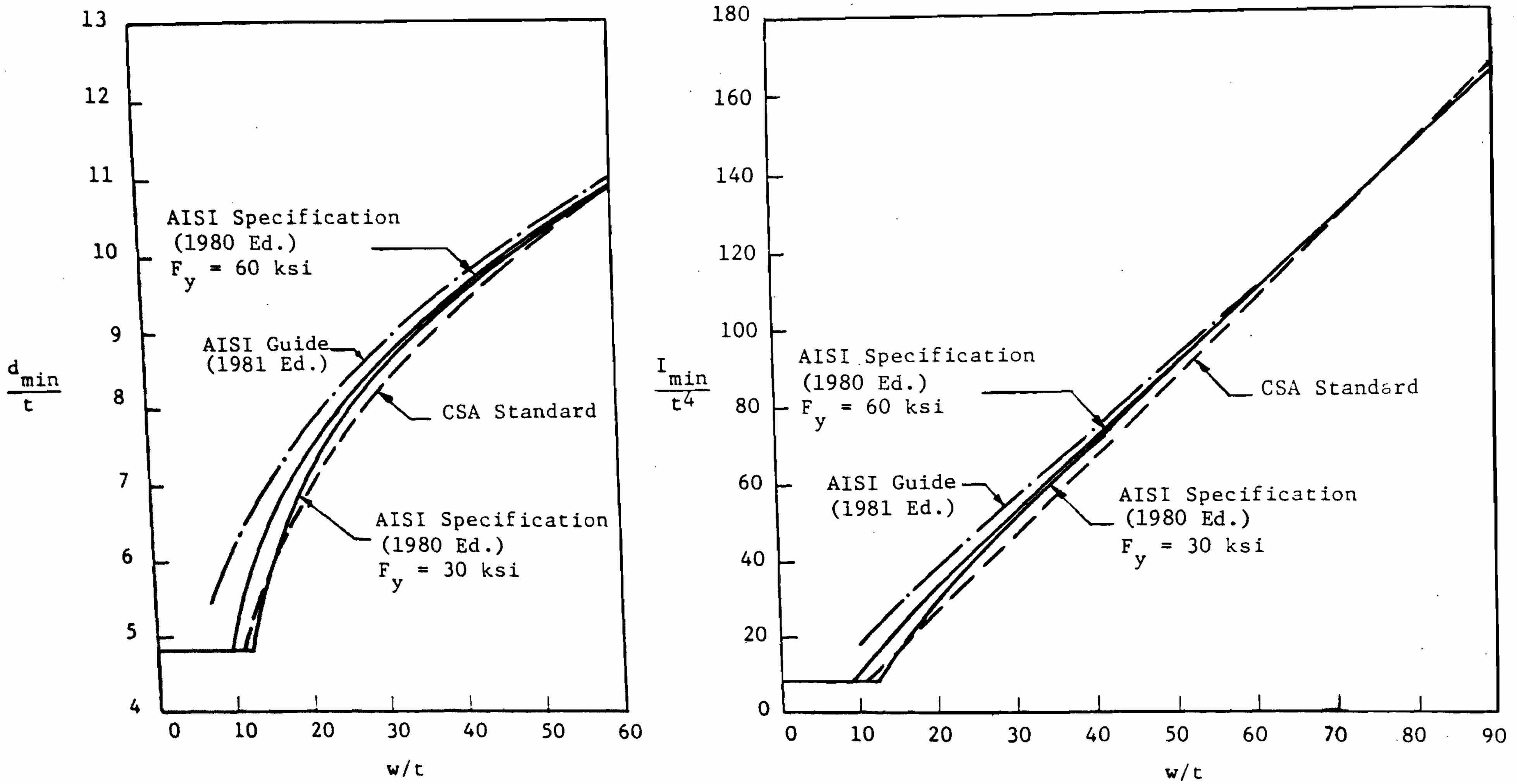


Fig. 5.2 Comparison of the Effective Design Widths for Load Determination by Using Various Design Specifications[5.2]



(a) Simple lip edge stiffener

(b) Any other shape of edge stiffener

Fig. 5.3 Comparison of the AISI and Canadian Requirements for Edge Stiffeners[5.2]

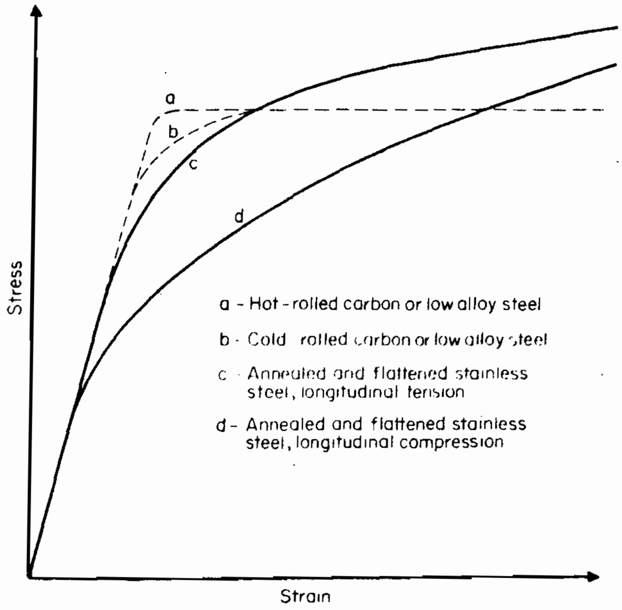


Fig. 5.4 Difference Between Stress-Strain Curves of Carbon and Stainless Steels[5.59]

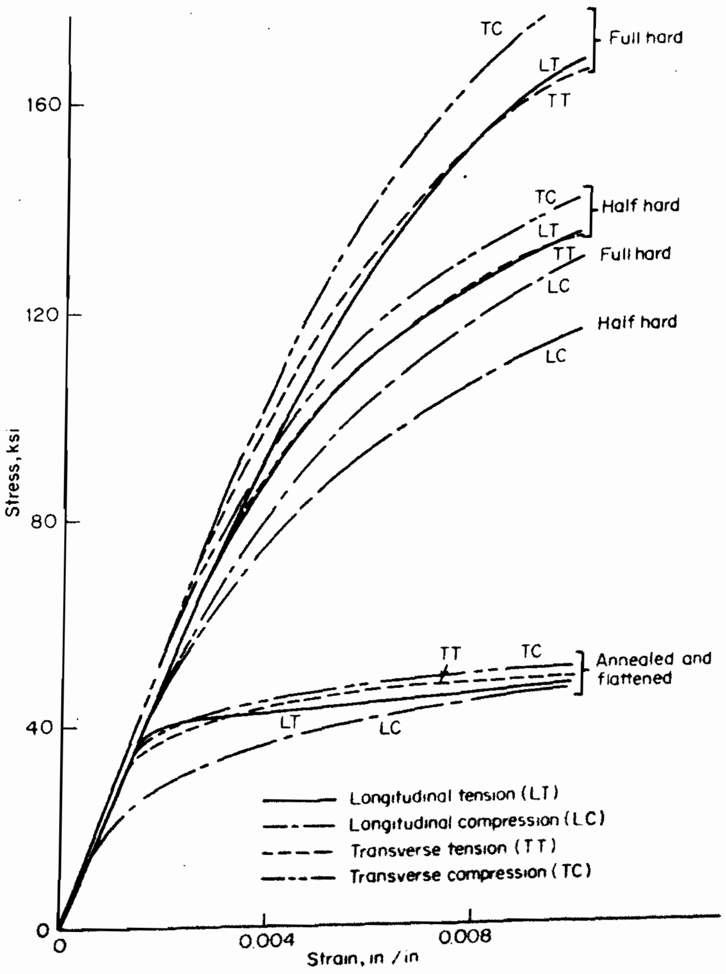


Fig. 5.5 Comparison of Stress-Strain Curves of Annealed, Half-Hard and Full-Hard Stainless Steels[5.59]