



Metallic Materials Properties Development and Standardization (MMPDS)

MMPDS-16

CHAPTERS 1-9

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MMPDS-16

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FOREWORD

The Metallic Materials Properties Development and Standardization (MMPDS) Handbook, is an accepted source for metallic material and fastener system allowables recognized by the Federal Aviation Administration (FAA), all Departments and Agencies of the Department of Defense (DoD), and the National Aeronautics and Space Administration (NASA) within the limitations of the certification requirements of the specific government agency. Some of these limitations are noted below.

Federal Aviation Administration (FAA):

Per guidance provided by FAA Advisory Circular (AC) 25.613-1 and FAA policy memorandum PS-AIR100-2006-MMPDS, the ‘A’ and ‘B’ basis values published for materials in the MMPDS have been determined by the FAA to satisfy the material strength probability levels required by Title 14 of the Code of Federal Regulations (14 CFR) §§ 27.613(d), § 29.613(d), §25.613(b) and § 23.613(b). These values can be used to demonstrate compliance with the static strength requirements of 14 CFR without further showing. Other data provided (e.g. S-basis properties, fatigue, crack growth, stress-strain curves) in the Handbook might be used for design following FAA ACs and policy. The final determination on their applicability rests with the civil aviation authority responsible for finding compliance for the particular aircraft system on a case-by-case basis.

Department of Defense (DoD):

Per guidance provided in the Joint Service Specification Guide (JSSG) 2006 and MIL-STD-1530, the “A” and “B” basis design allowables published for materials in the MMPDS have been determined by Department of Defense (DoD) services to satisfy the strength and statistical variability requirements for airframe metallic materials. Other data (e.g. S-basis properties, fatigue, crack growth, stress-strain curves) in the Handbook may be used for design. However, the final determination of the acceptability of data rests with the cognizant design authority responsible for finding compliance for the particular aircraft system.

National Aeronautics and Space Administration (NASA):

The “A” and “B” basis design allowables published in the MMPDS handbook have been accepted by the National Aeronautics and Space Administration (NASA) as satisfying the strength requirements for metallic materials used in spacecraft and launch vehicles, as tailored in NASA-STD-6016. Other data (e.g. S-basis properties, fatigue, stress-strain curves) in the Handbook may be used for design. However, the final determination of the acceptability of data rests with the NASA design authority responsible for the particular system.

MMPDS-16 supersedes MMPDS-15 and prior editions of the MMPDS Handbook as well as all editions of MIL-HDBK-5, Metallic Materials and Elements for Aerospace Vehicle Structures Handbook that was maintained by the U.S. Air Force. The last edition, MIL-HDBK-5J was cancelled by the U.S. Air Force in March 2006.

This document contains design information on the mechanical and physical properties of metallic materials and joints commonly used in aircraft and aerospace vehicle structures. All information contained in this Handbook has been reviewed and approved using a standardized process. The development and

ongoing maintenance process involves certifying agencies, including the FAA, DoD, and NASA, and major material suppliers and material users worldwide. The information and procedures in this Handbook are continuously reviewed, and modified or removed as determined to be appropriate. With advances in materials and fastener systems, and with the review process of existing information, periodic updates of the MMPDS should be expected. As such, it is recommended that the latest version of the MMPDS be used.

The allowables contained in the published document, or from approved minutes of the Metallic Materials Properties Development and Standardization (MMPDS) handbook coordination meetings, are acceptable to the Federal Aviation Administration (FAA), the Department of Defense (DoD), and the National Aeronautics and Space Administration (NASA), per the conditions as outlined above. The minutes are copyright protected and are considered approved 30 days after release of meeting minutes, if no objections or corrections have been received by Battelle, or 30 days after a technical change. Approval by the procuring or certifying agency must be obtained for the use of design values for products not contained herein.

Beneficial comments (recommendations, additions, deletions) and any pertinent data that may be of use in improving this document should be addressed to Secretariat, MMPDS Coordination Activity (614-424-6557 voice or bcommpds@battelle.org email), Battelle, MMPDS, 505 King Avenue, Columbus, OH 43201. You may also contact the Secretariat through the handbook website, www.mmpds.org.

This Handbook has been approved for public release with unlimited distribution.

Preparing activity:
FAA - William J. Hughes Technical Center

EXPLANATION OF NUMERICAL CODE

For chapters containing materials properties, a deci-numeric system is used to identify sections of text, tables, and illustrations. This system is explained in the examples shown below. Variations of this deci-numerical system are also used in Chapters 1, 8, and 9.

Example A

	2.4.2.1.1
General material category (in this case, steel)	
A logical breakdown of the base material by family characteristics (in this case, intermediate alloy steels); or for element properties.	
Particular alloy to which all data are pertinent. If zero, section contains comments on the family characteristics.	
If zero, section contains comments specific to the alloy; if it is an integer, the number identifies a specific temper or condition (heat treatment)	
Type of graphical data presented on a given figure (see following description).	

Example B

	3.2.3.1.X
Aluminum	
2000 Series Wrought Alloy	
2024 Alloy	
T3, T351, T3510, T3511, T4, and T42 Tempers	
Specific Property as Follows	
Tensile properties (ultimate and yield strength)	1
Compressive yield and shear ultimate strengths	2
Bearing properties (ultimate and yield strength)	3
Modulus of elasticity, shear modulus	4
Elongation, total strain at failure, and reduction of area	5
Stress-strain curves, tangent-modulus curves	6
Creep	7
Fatigue	8
Fatigue-Crack Propagation	9
Fracture Toughness	10

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REGISTERED TRADEMARKS

<u>Trademark</u>	<u>Registered by</u>	<u>Chemistry</u>	<u>UNS Number</u>
15-5PH®	AK STEEL CORP.	15Cr - 4.6Ni - 0.22Cb - 2.8Cu	J92110
		15Cr - 4.5Ni - 0.30Cb - 3.5Cu	S15500
17-4-PH® ¹	ARMCO INC. CORP.	16Cr - 4.1Ni - 0.28Cb - 3.2Cu	J92200
		16.5Cr - 4.0Ni - 4.0Cu - 0.30Cb	S17400
17-7PH®	ARMCO INC. CORP.	17Cr-7.1Ni-1.1Al	J17700
ACRES® sleeves	CLICK BOND, INC.	NA	NA
AerMet® 100	CRS HOLDINGS INC.	3.1Cr-11.5Ni-13.5Co-1.2Mo (0.21 - 0.25C)	K92580
AlBeMet®	MATERION CORP.	Al-62Be	NA
AM-350™	ALLEGHENY LUDLUM CORP.	16.5Cr - 4.5Ni - 2.9Mo - 0.10N	S35000
AM-355™	ALLEGHENY LUDLUM CORP.	15.5Cr - 4.5Ni - 2.0Mo - 0.10N	S35500
Cherry®	TEXTRON FASTENING SYSTEMS, INC.	NA	NA
Cherrybucks®	TEXTRON FASTENING SYSTEMS, INC.	NA	NA
Custom450®	CRS HOLDINGS INC.	15Cr - 6.5Ni - 0.75Mo - 0.30 (Cb + Ta) - 1.5Cu	S45000
Custom455®	CRS HOLDINGS INC.	12Cr-8.5Ni-2.0Cu-1.1Ti	S45500
Custom465®	CRS HOLDINGS INC.	6Al- 6V - 2SN	none
Ferrium® S53®	Ques Tek Innovations LLC	10Cr-5.5Ni-14Co-2Mo-1W (0.19-0.23C)	S10500
Hastelloy® X	HAYNES INTERNATIONAL, INC.	47.5Ni-22Cr-1.5Co-9.0Mo	N06002
Elektron® 21	MAGNESIUM ELEKTRON	EV31A	Similar to M12310
HAYNES®	HAYNES INTERNATIONAL, INC.	NA	NA
230®	HAYNES INTERNATIONAL, INC.	59Ni-22Cr-2Mo-14W-0.35Al	N06230
Hi-Lok®	HI-SHEAR CORP.	NA	NA
Hi-Shear®	HI-SHEAR CORP.	NA	NA
HR-120®	HAYNES INTERNATIONAL, INC.	35Fe - 24Cr - 37Ni - 0.65Cb - 0.2N	N08120
HSL180™	HITACHI METALS AND SUMITOMO PRECISION PRODUCTS	12.5Cr-1.0Ni-15.5Co-2.0Mo	NA

¹ Shown in the customary form of 17-4PH in the Handbook.

REGISTERED TRADEMARKS (Continued)

<u>Trademark</u>	<u>Registered by</u>	<u>Chemistry</u>	<u>UNS Number</u>
INCONEL®	HUNTINGTON ALLOYS CORP.	NA	NA
MP159®	SPS TECHNOLOGY	19Cr - 36Co - 25Ni - 7.0Mo - 0.50Cb - 2.9Ti - 0.20Al - 9.0Fe	R30159
MP35N®	SPS TECHNOLOGY	20Cr - 35Ni - 35Co - 10Mo	R30035
PH13-8® Mo	ARMCO INC. CORP.	13Cr-8.0Ni-2.2Ni-1.1Al	S13800
PH15-7® Mo	ARMCO INC. CORP.	15Cr - 7.1Ni - 2.5Mo - 1.1Al	S15700
RENE'® 41	TELEDYNE INDUSTRIES INC.	54Ni - 19Cr - 11Co - 9.8Mo - 3.2Ti - 1.5Al - 0.006B	N0704
ToughMet® 3	MATERION CORP.	77Cu-15Ni-8Sn	C72900

CHAPTER 1

GENERAL

1.1 PURPOSE AND USE OF DOCUMENT

1.1.1 INTRODUCTION — Since many aerospace companies manufacture both commercial and military products, the standardization of metallic materials design data which are acceptable to Government procuring and/or certification agencies is very beneficial to those manufacturers as well as governmental agencies. Although the design requirements for military and commercial products may differ greatly, the required design values for the strength of materials and elements and other needed material characteristics are often identical. Therefore, this publication provides standardized design values and related design information for metallic materials and structural elements used in aerospace structures.

MMPDS-16 was prepared by Battelle under contract with the FAA William J. Hughes Technical Center. It is covered under U.S. Copyright and is the only current form of the MMPDS Handbook. If computerized third-party MMPDS databases are used, caution should be exercised to ensure that the information in these databases is identical to that contained in the Handbook.

Approved printed and electronic copies of MMPDS-16 are available for purchase through Battelle and its approved licensees. Official copies of MMPDS-16 may also be obtained through participation in the MMPDS Industrial Steering Group (ISG) or Government Steering Group (GSG), whichever is appropriate. The ISG is open to membership by all commercial and education organizations, while the GSG is open to membership by all U.S. and foreign government entities. See www.mmpds.org for further information.

1.1.2 SCOPE OF HANDBOOK — The primary purpose of this Handbook is to provide a source of statistically based design values for commonly used metallic materials and joints. Additionally, other mechanical and physical properties needed for the design of aerospace structures are included. The material properties and joint data used to derive values published in this Handbook were obtained from tests conducted by material and fastener producers, government agencies, and members of the airframe industry. The data submitted to MMPDS are reviewed and analyzed per the methods detailed in this Handbook. Results of these analyses are submitted to the membership during coordination meetings and if determined to meet the set document standards they are published in this Handbook.

This Handbook also contains some useful basic formulas for structural element analysis. These formulas are provided in Chapter 1 to illustrate how the material data contained in the Handbook may be used. However, structural design and analysis are beyond the scope of this Handbook. While an attempt is made to assure the accuracy of the formulas and analytical methods contained in Chapter 1, there is no attempt in this Handbook to provide currently accepted design or analytical methods.

References for data and various test methods are listed at the end of each chapter. The reference number corresponds to the applicable paragraph of the chapter cited. Such references are intended to provide sources of additional information, but should not necessarily be considered as containing data suitable for design purposes.

Applicable testing standards are identified by number only in the text. Full titles for these standards are listed in Appendix D.

The content of this Handbook is arranged as follows:

Chapter(s)	Subjects
1	Nomenclature, Systems of Units, Formulas, Material Property Definitions, Failure Analysis, Column Analysis, Thin-Walled Sections
2-7	Material Properties
8	Joint Allowables
9	Data Requirements, Statistical Analysis Procedures

1.2 NOMENCLATURE

1.2.1 SYMBOLS AND DEFINITIONS — The various symbols used throughout the Handbook to describe properties of materials, grain directions, test conditions, dimensions, and statistical analysis terminology are included in Appendix A.

1.2.2 INTERNATIONAL SYSTEM OF UNITS — Design properties and joint allowables contained in this Handbook are given in customary units of U.S. measure to ensure compatibility with government and industry material specifications and current aerospace design practice. Appendix A.4 may be used to assist in the conversion of these units to Standard International (SI) units when desired.

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1.3 COMMONLY USED FORMULAS

1.3.1 GENERAL — Formulas provided in the following sections are listed for reference purposes. Sign conventions generally accepted in their use as quantities associated with tension action (loads, stresses, strains, etc.) are usually considered as positive, and quantities associated with compressive action are considered as negative. When compressive action is of primary interest, it is sometimes convenient to identify associated properties with a positive sign. Formulas for all statistical computations relating to allowables development are presented in Chapter 9.

1.3.2 SIMPLE UNIT STRESSES —

$$\begin{aligned} f_t &= P / A \text{ (tension)} & [1.3.2(a)] \\ f_c &= P / A \text{ (compression)} & [1.3.2(b)] \\ f_b &= My / I = M / Z \text{ (bending) (where } z = I/y = \text{section modulus)} & [1.3.2(c)] \\ f_s &= S / A \text{ (average direct shear stress)} & [1.3.2(d)] \\ f_s &= SQ / Ib \text{ (longitudinal or transverse shear stress)} & [1.3.2(e)] \\ f_s &= Ty / I_p \text{ (shear stress in round tubes due to torsion)} & [1.3.2(f)] \\ f_s &= (T/2At) \text{ (shear stress due to torsion in thin-walled structures of closed} & [1.3.2(g)] \\ &\quad \text{section. Note that } A \text{ is the area enclosed by the median line of the section.)} \\ f_A &= Bf_H ; f_T = Bf_L \text{ (axial and tangential stresses, where } B = \text{biaxial ratio)} & [1.3.2(h)] \end{aligned}$$

1.3.3 COMBINED STRESSES (SEE SECTION 1.5.3.5) —

$$\begin{aligned} f_A &= f_c + f_b \text{ [Axial (tension or compression) and bending]} & [1.3.3(a)] \\ f_{1,2} &= \{(f_x + f_y)/2\} \pm [f_s^2 + \{(f_x - f_y)/2\}^2]^{1/2} \text{ [Bi-axial (tension or compression) + shear]} & [1.3.3(b)] \\ &\text{where } f_1 \text{ is the maximum principal stress, } f_2 \text{ is the minimum principal stress, positive } f_x \text{ or } f_y \text{ is tension.} \end{aligned}$$

1.3.4 DEFLECTIONS (AXIAL) —

$$\begin{aligned} e &= \delta / L \text{ (unit deformation or strain) (in./in.)} & [1.3.4(a)] \\ E &= f/e \text{ (This equation applied when } E \text{ is obtained from the same tests in which} & [1.3.4(b)] \\ &\quad \text{f and e are measured.)} \\ \delta &= eL = (f / E)L & [1.3.4(c)] \\ &= PL / (AE) \text{ (This equation applies when the deflection is to be} & [1.3.4(d)] \\ &\quad \text{calculated using a known value of } E \text{.) (units in inches)} \end{aligned}$$

1.3.5 DEFLECTIONS (BENDING) —

$$\begin{aligned} di/dx &= M / (EI) \text{ (Change of slope per unit length of a beam; radians per unit length)} & [1.3.5(a)] \\ i &= \text{slope of a beam} \end{aligned}$$

$$i_2 = i_1 + \int_{x_1}^{x_2} [M/(EI)] dx \text{ — Slope at Point 2. (This integral denotes the area under the curve of } M/EI \text{ plotted against } x, \text{ between the limits of } x_1 \text{ and } x_2.) \quad [1.3.5(b)]$$

$$y_2 = y_1 + i(x_2 - x_1) + \int_{x_1}^{x_2} (M/EI)(x_2 - x) dx \text{ — Deflection at Point 2.} \quad [1.3.5(c)]$$

y = deflection of the beam

(This integral denotes the area under the curve having an ordinate equal to M/EI multiplied by the corresponding distances to Point 2, plotted against x , between the limits of x_1 and x_2 .)

$$y_2 = y_1 + \int_{x_1}^{x_2} i dx \text{ — Deflection at Point 2. (This integral denotes the area under the curve of } x_1(i) \text{ plotted against } x, \text{ between the limits of } x_1 \text{ and } x_2.) \quad [1.3.5(d)]$$

1.3.6 DEFLECTIONS (TORSION) —

$$d\phi / dx = T / (GJ) \text{ (Change of angular deflection or twist per unit length of a member, radians per unit length.)} \quad [1.3.6(a)]$$

$$\Phi = \int_{x_1}^{x_2} [T/(GJ)] dx \text{ Total twist over a length from } x_1 \text{ to } x_2. \text{ (This integral denotes the area under the curve of } T/GJ \text{ plotted against } x, \text{ between the limits of } x_1 \text{ and } x_2.) \quad [1.3.6(b)]$$

$$\Phi = TL/(GJ) \text{ (Used when torque } T/GJ \text{ is constant over length } L.) \quad [1.3.6(c)]$$

1.3.7 BIAXIAL ELASTIC DEFORMATION —

$$\mu = e_T/e_L \text{ (Unit lateral deformation/unit axial deformation.) This identifies Poisson's ratio in uniaxial loading.} \quad [1.3.7(a)]$$

$$Ee_x = f_x - \mu f_y \quad [1.3.7(b)]$$

$$Ee_y = f_y - \mu f_x \quad [1.3.7(c)]$$

$$E_{\text{biaxial}} = E / (1 - \mu B) = \text{where } B = \text{biaxial elastic modulus.} \quad [1.3.7(d)]$$

1.3.8 BASIC COLUMN FORMULAS —

$$F_c = \pi^2 E / (L' / \rho)^2 \text{ — standard Euler formula} \quad [1.3.8]$$

where $L' = L / \sqrt{c}$ where c may vary from 1 to 4 depending on degree of end fixity for simply supported columns having varying degrees of rotational fixity (flag pole columns, for example, may have a fixity coefficient of $c=0.25$ or less).

If the cross section has no thin outstanding members subject to crippling, then a conservative form of Euler's formula uses the tangent modulus E_t :

$$F_c = \pi^2 E_t / (L' / \rho)^2 \text{ - conservative using tangent modulus where } \rho = \sqrt{I/A} \quad [1.3.8(a)]$$



If the cross section is subject to local instability before the full buckling load can be realized, then the Euler buckling allowable load can be unconservative. In this case, further analysis may be required such as crippling and local buckling. A column instability curve should then be constructed to take these effects into consideration.

1.3.9 INELASTIC STRESS-STRAIN RESPONSE —

$$e_{total} = f/E + e_p \text{ (elastic strain response plus inelastic or plastic strain response)} \quad [1.3.9(a)]$$

where

$$e_p = 0.002 (f/F_{ty})^n, \quad [1.3.9(b)]$$

n = Ramberg-Osgood parameter

Equation [1.3.9(b)] implies a log-linear relationship between inelastic strain and stress, which is observed with many metallic materials, at least for inelastic strains ranging from the material's proportional limit to its yield stress.

Traditionally, the Ramberg-Osgood fit to the stress-strain data has used a single exponential term (i.e., n- value). For some materials, however, the stress-strain data can be better fit to a modified form of the Ramberg-Osgood. This modified form entitled the Bron Model, uses two exponential terms characterized by an n1 and an n2 factor and an alpha parameter. Stress-Strain analyses since MMPDS-05 show values of the Ramberg-Osgood parameter, n, and, when considered relevant, the Bron Model parameters, n₁, n₂, and alpha for each material. When the Bron Model analyses are considered relevant, the user should decide whether the Ramberg-Osgood or Bron Model is more applicable to their analyses.

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1.4 BASIC PRINCIPLES

1.4.1 GENERAL — It is assumed that users of this Handbook are familiar with the principles of strength of materials. A brief summary of that subject is presented in the following paragraphs to emphasize principles of importance regarding the use of allowables for various metallic materials.

Requirements for adequate test data have been established to ensure a high degree of reliability for allowables published in this Handbook. Statistical analysis methods, provided in Chapter 9, are standardized and approved by all government regulatory agencies as well as MMPDS members from industry.

1.4.1.1 Basis — Primary static design properties shown in Chapters 2-7 are provided for the following conditions:

Tension	F_{tu} and F_{ty}
Compression	F_{cy}
Shear	F_{su}
Bearing	F_{bru} and F_{bry}

These design properties are presented as A- and B- or S-Basis room temperature values for each alloy. Design properties for other temperatures, when determined in accordance with Section 1.4.1.3, are regarded as having the same basis as the corresponding room temperature values.

Mechanically fastened joint allowables shown in Chapter 8, which were developed since 2012 (MMPDS-07), are presented as A- or B-Basis depending on the type of joint and property as described in Section 9.7. Values in earlier tables (from MIL-HDBK-5) were determined using different methods and did not show a basis on the tables. See Section 9.1.7.2 for more information on data basis for mechanically fastened joint allowables.

It is important to note that the minimum sample size requirements for mechanical properties in Chapters 2-7 and mechanically fastened joint allowables in Chapter 8 differ. The minimum requirements are identified in Chapter 9 and summarized in Table 9.2.4. Definitions of A-, B- and S-Basis are:

A-Basis - The lower of either a statistically calculated T_{99} value (see Appendix A for definition), or the specification minimum (S-Basis). The T_{99} value indicates that at least 99 percent of the population is expected to equal or exceed it, with a confidence of 95 percent.

B-Basis - Based on the calculated T_{90} (see Appendix A for definition), at least 90 percent of the population of values are expected to equal or exceed the B-Basis mechanical property allowable with a confidence of 95 percent.

S-Basis - The S-value represents or is based on the minimum property value specified by the governing industry specification (as issued by standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. For certain products heat treated by the user (for example, steels hardened and tempered to a designated F_{tu}), the S-value may reflect a specified quality-control requirement. Statistical assurance associated with this value is not known. The S-Basis value may also represent downgraded derived properties where reduced ratios were questionable, even though the primary tensile values have A- and B-Basis allowables. For more information see Section 9.1.7 Data Basis.

For aerospace application of mechanical properties shown in Chapters 2-7, A-Basis values are generally used for single loadpath applications (like lugs) and B-Basis values for redundant loadpath applications (like skins, stringers and frames).

Elongation and reduction of area design properties listed in room temperature property tables represent procurement specification minimum requirements and are designated as S-values. Elongation and reduction of area at other temperatures, as well as moduli, physical properties, creep properties, fatigue properties, and fracture toughness properties, are all typical values unless another basis is specifically indicated.

Use of B-Values — The use of B-Basis design properties is permitted in design by the Air Force, the Army, the Navy, and the FAA, subject to certain limitations specified by each agency. Reference should be made to specific requirements of the applicable agency before using B-values in design.

1.4.1.2 Statistically Calculated Values — Statistically calculated values are S (since 1975), T_{99} and T_{90} . S, the minimum properties guaranteed in the material specification, are calculated using the same requirements and procedure as AMS as explained in Chapter 9. T_{99} and T_{90} are the tolerance bounds, and are defined and may be computed using the data requirements and statistical procedures explained in Chapter 9. Note that the sample size must be considered in determining which statistical procedure is appropriate.

1.4.1.3 Ratioed Values — A ratioed design property is one that is determined through its relationship with an established design value. This may be a tensile stress in a different grain direction from the established design property grain direction or it may be another stress property, e.g., compression, shear or bearing. It may also be the same stress property at a different temperature. Refer to Chapter 9 for specific data requirements and data analysis procedures.

Derived properties are presented in two manners. Room temperature-derived properties are presented in tabular form with their baseline design properties. Other than room temperature-derived properties are presented in graphical form as percentages of the room temperature value. Percentage values apply to all forms and thicknesses shown in the room temperature design property table for the heat treatment condition indicated therein unless restrictions are otherwise indicated. Percentage curves usually represent short time exposures to temperature (30 minutes) followed by testing at the same strain rate as used for the room temperature tests. When data are adequate, percentage curves are shown for other exposure times and are appropriately labeled.

1.4.1.4 Values for Non-Standard Test Locations - The material property tables are generated with data provided per the referenced material specifications, which have very specific testing requirements in terms of test planes, sample locations, etc. Properties from test planes or sample locations different from those specified by material or test specifications may not be represented by the Design Mechanical and Physical Properties Tables. If there is a difference in material property allowables when based on cross-sectional area versus minimum thickness (such as with some aluminum extrusions), use the lower allowable. Additional testing may be required to determine characteristic properties at these other locations.

There are two possible scenarios for establishing properties at a non-standard location for a given, fixed shape by testing, using a published mechanical property table containing A/B or S values which are based on specimens from standard locations.

The first scenario is when the property at the new location will be compared to a different property at the standard location, e.g., BYS at the new location vs TYS at the standard location. This situation is analogous to the current indirect method where the appropriate data requirements from Section 9.2.4 should be followed. If a full complement of properties at the new location are desired, then this method should be used and compared to the tensile properties from the standard location.

The second scenario is when the property at the new location will be compared to the same property at the standard location, e.g., TYS(L) at each location or if only a few properties are of interest. In this case the current indirect method is modified, relaxing the data requirements from a minimum of 3 heats and 10 lots to a minimum of 2 heats and 5 lots, with at least 2 pairs of data per lot. Use the more conservative of values as calculated by the following;

- 1) Compute the 95% lower confidence interval on the ratios and apply to the published value,
- 2) Compute the 95% lower confidence interval on the differences and apply to the published values.

1.4.1.5 STRESS — Revision of B-basis Allowables Based on Reduction of A-basis Allowables – For many years the A-basis value has been defined within the MMPDS Handbook as the lower of either the statistically calculated T_{99} value (See Appendix A for definition), or the specification minimum (S-Basis). This is done in order to recognize the degree of protection provided by the specification to the A-basis design value. However, if the S-basis is considerably lower than the T_{99} value, the T_{90} value of the material may "drift down" over time, while all individual test results still meet the specification requirements of the material. MMPDS guidelines have required that B-basis values be defined based solely on the statistically calculated T_{90} value. But if individual test results do drift downward, the B-basis values may not be protected by the material specifications as they are for the A-basis values. If an analyst or organization chooses to reduce a calculated B-basis (T_{90}) value for a material based on a reduction in A-basis allowables, it is recommended that the following procedure be used:

$$\text{Reduced B} = \text{Rounded } T_{90} * (S/\text{Rounded } T_{99}).$$

1.4.1.6 EXTRAPOLATION OF MECHANICAL PROPERTIES – Not all tables contain design allowable properties across all thickness ranges and for all orientations. The user is cautioned against extrapolating properties or assuming a constant relationship between tensile properties and secondary properties (such as compression, shear, and bearing).

1.4.2 STRESS — The term stress, written as f (for an applied stress) or as F (for an allowable stress), implies a force per unit area and is a measure of the intensity of the force acting on a definite plane passing through a given point (see Equations 1.3.2(a) and 1.3.2(b)). The stress distribution may or may not be uniform, depending on the nature of the loading condition. For example, tensile stresses identified by Equation 1.3.2(a) are considered to be uniform. The bending stress determined from Equation 1.3.2(c) refers to the stress at a specified distance perpendicular to the normal axis. The shear stress acting over the cross section of a member subjected to bending is not uniform. (Equation 1.3.2(d) gives the average shear stress.)

1.4.3 STRAIN — Strain is the change in length per unit length in a member or portion of a member. It can be expressed in terms of the original length L_o of the specimen, as in $\epsilon = L/L_o$, in which case it is called "engineering strain", or in terms of the final length L of the specimen using the natural log $\epsilon = \ln(L/L_o)$, in which case it is called "true strain". In this handbook the "engineering strain" is given and tabulated.

As in the case of stress, the strain distribution may or may not be uniform in a complex structural element, depending on the nature of the loading condition. Strains are usually present in directions other than the directions of applied loads.

1.4.3.1 Poisson's Ratio Effect — (Written as μ in this Handbook) A normal strain is that which is associated with a normal stress; a normal strain occurs in the direction in which its associated normal stress acts. Normal strains that result from an increase in length are designated as positive (+), and those that result in a decrease in length are designated as negative (-).

Under the condition of uniaxial loading, strain varies directly with stress. The ratio of stress to strain has a constant value (E) within the elastic range of the material, but decreases when the proportional limit is

exceeded (plastic range). Axial strain is always accompanied by lateral strains of opposite sign in the two directions mutually perpendicular to the axial strain. Under these conditions, the absolute value of a ratio of lateral strain to axial strain is defined as Poisson's ratio. For stresses within the elastic range, this ratio is approximately constant. For stresses exceeding the proportional limit, this ratio is a function of the axial strain and is then referred to as the lateral contraction ratio. The maximum value of Poisson's Ratio is 0.5 for the fully plastic case. Information on the variation of Poisson's ratio with strain and with testing direction is available in Reference 1.4.3.1.

Under multiaxial loading conditions, strains resulting from the application of each directional load are additive. Strains must be calculated for each of the principal directions taking into account each of the principal stresses and Poisson's ratio (see Equation 1.3.7 for biaxial loading).

1.4.3.2 Shear Strain — When an element of uniform thickness is subjected to pure shear, each side of the element will be displaced in opposite directions. Shear strain is computed by dividing this total displacement by the right angle distance separating the two sides.

1.4.3.3 Strain Rate — Strain rate is a function of loading rate. Test results are dependent upon strain rate, and the American Society for Testing and Materials (ASTM) testing procedures specify appropriate strain rates. Design properties in this Handbook were developed from test data obtained from coupons tested at the stated strain rate or up to a value of 0.01 in./in./min, the standard maximum static rate for tensile testing materials per specification ASTM E8.

1.4.3.4 Elongation and Reduction of Area — Elongation and reduction of area are measured in accordance with specification ASTM E8.

1.4.4 INTRODUCTION TO STRESS STRAIN CURVES IN MMPDS - A stress strain curve is the fundamental constitutive relationship describing a material's response to loading. A basic design goal of aerospace structures is the minimization of weight to increase the overall performance of the vehicle. This aspect of aerospace design has been and continues to be a primary driver in the development of literally hundreds of high performance alloys. Additionally, advances in matrix methods of structural analysis have allowed analysts to evaluate structural arrangements to a scale and level of detail undreamt of by the original pioneers of the industry. The common link between application of a new, improved, or the evaluation of vintage, legacy alloys and its selection for an application is the stress strain curve of its anticipated performance.

There are three types of stress-strain curves contained in MMPDS handbooks: tensile, compressive and full-range tensile. All stress-strain curves in MMPDS are Engineering, not True, stress-strain curves.

The adjective "typical" in MMPDS indicates that the curve is representative of the material, but has been derived from a small number of experiments. This is the case for all curves contained in MMPDS, whether tensile or compressive, and is indicated by the text box "typical" contained in the figures. Section 1.4.4.7 outlines a procedure that can be used to define statistically based stress strain curves.

MMPDS is upgrading the tensile or compressive curve captions to indicate whether the curve is representative of the behavior up to the yield point or all the way to failure; however this is being done for new materials and as materials undergo legacy material review. In the absence of this information, "typical" curves not specifically denoted "full range" or curves labeled "typical stress-strain response through yield" whether tensile or compressive, only capture the material response up to and slightly beyond the yield strength of the material. The amount of post-yield information in a given curve is dependent upon the original data set provided to MMPDS. 'Large' strain level, post-yield response of the material is not captured in these curves.

Additionally, compressive curves contain plots of the compressive tangent Modulus, E_t , as a function of strain level. E_t is an important material parameter used to assess buckling beyond the Proportional Limit stress of the material.

The adjective “full-range” in the caption or the new terminology “typical stress-strain response to failure” indicates that the curve represents experiments that have been carried out to rupture of the component, and thus contains ‘Ultimate’ or the highest stress level sustained by the material. Full-Range curves are based upon tensile tests. Full-Range curves are also ‘typical’, in that they are generally representative, but are not statistically based.

Generally speaking, the basic information contained in a typical stress strain curve through yield published in MMPDS is sufficient to fully characterize static tensile loading conditions. Figure 1.4.4.3(a) illustrates stress-strain curves typical of aerospace usage, and are of the Full Range type. These curves graphically illustrate strength of materials information which can be used to assess deformation and strength of a component.

Stress strain curves contain some, or all, of the following information when published in MMPDS: The slope(s) of interest between stress and strain; Primary or Secondary Young's Modulus, Tangent, or Secant Modulus. Material strengths noted on the curves include the Proportional Limit, Yield Strength, and Ultimate Strength. Total Elongation and an important parameter(s) noted as the Ramberg-Osgood number, n_i , where i is any number of subscripts depending upon the context of its usage. For example, i is 2 for the Bron formulation. Additionally, ‘clad’ materials may define a ‘Secondary’ Young’s Modulus, which is associated with the post yield strength behavior of cladding. Further discussion and definitions of these quantities are contained in the paragraphs identified in Table 1.4.4.

Table 1.4.4. Stress-Strain Curve Subject Matter MMPDS References

Stress-Strain Curve Quantity or Subject	Section
Single Ramberg-Osgood Parameter n -or- Dual Bron Parameters n_1, n_2	1.3.9 9.8.4.2, 9.8.4.3 Figures 9.8.4.1.3(a) and (b)
Cladding Primary and Secondary Modulus	1.4.4, Fig. 1.4.4.3(a) Fig. 1.4.4.3(b), Fig. 1.4.4.3(c)
Tangent Modulus, E_t Secant Modulus, E_s	1.4.4.4, Fig. 1.4.4.4
Compressive Properties	1.4.5
Buckling and Stability Related Failures of Columns	1.6
Relationship of E_t , Ramberg-Osgood and Bron Stress-Strain Parameter(s) to Compact Buckling	1.6.5

A given structure's response to tension, compression and shear types of loads vary to a great extent. Furthermore, it is well established by experiment and experience that a given alloy's response to tensile load is different enough from compression loading to warrant independently characterizing each condition. The aerospace industry's emphasis to minimize weight drove designers to create thin structures that introduce the very real possibility of instability or 'buckling' types of failure, for compressive loads. The critical load associated with instability is frequently well below the yield, let alone the ultimate strength of the material.

It is common aerospace design practice to cap estimates of the allowable buckling stress by the F_{cy} of the material.

Structures loaded primarily in compression, and in some instances shear, require additional information contained within the stress-strain curve than the properties noted above to assess their stability with respect to their load condition. A measurement regarding the stiffness of the material in both the elastic and inelastic range is needed to assess structural stability, in addition to the analogous information contained in a tensile curve. The measure of stiffness in the inelastic range, (i.e. when the stress is above the proportional limit), is the tangent modulus, E_t , which is a measure of the local rate of change of stress versus strain at a given stress level. MMPDS publishes curves summarizing E_t values for a given stress level in compressive stress strain curve figures.

For purpose of illustrating the use of E_t values, the standard, 'Euler' buckling stress relationship in terms of radius of gyration ρ for a 'long', compact, pinned ended column of length L is given in Section 1.6.2.1 as:

$$F_{CR} = \frac{\pi^2 E_t}{(L/\rho)^2} \quad [1.4.4]$$

Provided the column length and geometry are such that F_{CR} is less than F_p , then E_t equals the initial Young's Modulus E of the material, and the column may be examined for stability without much further thought for this check. However, a review of Figures 9.8.4.2(a) through 9.8.4.2(d) illustrate that E_t varies as a function of stress, and takes on lower values for F_{CR} stresses above F_p . These figures also show that E_t falls off drastically once $f > f_{PL}$. For example, in Figure 9.8.4.2(b), at RT, the $E_t = 16.2$ msi up to f_{PL} and then drops off to less than 4 msi at F_{cy} . Therefore, it is important that the proper value of E_t be used in this formula, or in any other column formulas or design charts.

It is necessary to perform a trial and error process to ensure convergence between an estimated F_{CR} , the E_t assumed to derive the F_{CR} , and the actual E_t associated with the estimated F_{CR} . The trial and error process is repeated until the value presumed for E_t corresponds to the value of F_{CR} of the column's cross section it produces on the material's stress strain curve. Hence, the E_t associated with a given compression stress level of a material is a fundamental quantity required to assess the stability of the component.

It is apparent that a seemingly straight forward analysis task can rapidly devolve into a great deal of work if resort must be made to an individual stress strain curve for each application. However, stress, strain and E_t values, (curves), can be made dimensionless for various materials and products, thereby allowing for rapid determination or incorporation into specialty codes to perform stability checks. This simplifying task has been addressed by the Ramberg-Osgood method of analytically characterizing stress strain curves, and provides a justification for including these parameters in MMPDS.

1.4.4.1 The One Parameter Ramberg-Osgood Stress Strain Curve - Aerospace analysts are constantly required to assess the stability of structures in the inelastic range of the material's compressive stress strain curve. The original paper published by Ramberg and Osgood in 1943 is given in NACA TN902 [Reference 1.4.4.1(a)], wherein they proposed an equation to expeditiously define the stress strain curve in the region of the yield stress of the material. The time savings associated with defining the simplest, yet accurate stress-strain expression is readily apparent given the very large number of combinations of alloys, product forms and service temperatures.

The original Ramberg-Osgood formulation employed two secant modulus stress levels to define a relationship between local stress level, E_t and local strain in the region of the stress strain curve between F_p and F_{ty} or F_{cy} . $F_{0.7}$ and $F_{0.85}$ are stress levels defined at secant modulus values of 70% and 85% of the Young's Modulus. The parameter n defines the shape of the stress strain curve in the region of the yield stress of the material. Generally speaking, examination of stress levels out to the $F_{0.7}$ region encompasses the needed

inelastic material response for fundamental stability checks. Figure 1.4.4.1 is an original illustration of Ramberg-Osgood's construction.

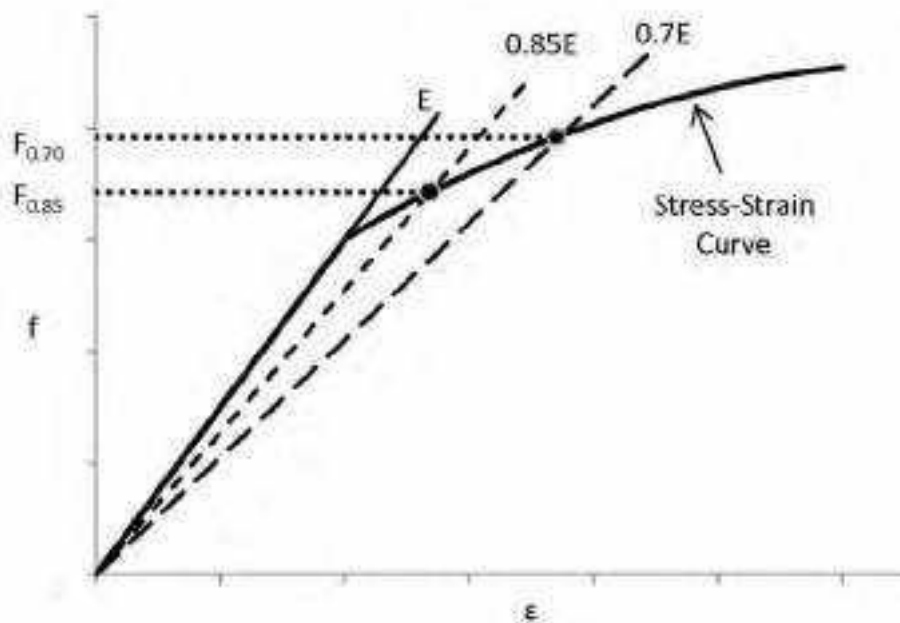


Figure 1.4.4.1. Original Ramberg-Osgood Formulation Secant Moduli.

The inelastic stress-strain relationship proposed by Ramberg and Osgood is given by the following expression:

$$\frac{E\varepsilon}{F_{0.7}} = \frac{f}{F_{0.7}} + \frac{3}{7} \left(\frac{f}{F_{0.7}} \right)^n \quad [1.4.4.1(a)]$$

Where the Ramberg-Osgood parameter, n , is given by the following:

$$n = 1 + \ln(17/7) / \ln(F_{0.7}/F_{0.85}) \quad [1.4.4.1(b)]$$

The methodology contained in MMPDS uses an equivalent formulation per NACA Tech Note 927 [Reference 1.4.4.1(b)], authored by Hill. An advantage of this simplification is that derivation of n , and its relationship to E_t is based upon F_{ty}/F_{cy} of the material, a strength level well characterized in MMPDS datasets. Note that for compression, E , F_{ty} , and n are replaced by E_c , F_{cy} , and n_c .

$$\varepsilon = \frac{f}{E} + 0.002 \left(\frac{f}{F_{ty}} \right)^n \quad [1.4.4.1(c)]$$

$$E_t = \frac{f}{\frac{f}{E} + \left[0.002n \left(\frac{f}{F_{ty}} \right)^n \right]} \quad [1.4.4.1(d)]$$

NACA Tech Notes 902 and 927 were originally published in the 1940s, and therefore have been widely implemented in aerospace design and analysis organizations. Individual companies have invested resources, and developed established methods that take advantage of the efficiencies provided by Ramberg and Osgood's formulation. The reader is encouraged to refer to Section 9.8.4.1 of Chapter 9 to review the details associated with deriving the single parameter version stress strain curves.

1.4.4.2 The Two Parameter Bron Stress Strain Curve - Section 9.8.4.1.3 illustrates an example material response where the single Ramberg-Osgood parameter does not seem to characterize the material response very well. This behavior is attributed to violation of a linear relationship assumption between the log of stress vs. log of plastic strain component between F_p and F_{ty} . Another way to say this is that the legacy single Ramberg-Osgood parameter is sufficient to characterize the slope of linear relationships between log stress and log plastic strain. Reference Figures 9.8.4.1.3(a) and (b) for illustrations of these effects. Further refinement is needed for materials that 'heel over' rapidly to gross level plastic strain components.

Current MMPDS text notes that in cases where the single parameter formulation is not adequate, dividing the region between F_p and F_{ty} into two segments, each characterized individually by Ramberg-Osgood types of factors, provides satisfactory characterizations of the data. Another way of stating this condition is that there exists a bi-linear functional relationship between log stress and log plastic strain. The implementation of a two parameter method can handle this more complicated material response. The MMPDS coordination committee reviewed an original dual parameter proposal developed by Rice, but instead utilizes a refined version developed by Bron.

Here, the plastic strain component is further extended to be composed of two elements:

$$\varepsilon_{Total} = \varepsilon_e + \alpha \varepsilon_{p1} + (1 - \alpha) \varepsilon_{p2} \quad [1.4.4.2(a)]$$

where

$$\varepsilon_{p1} = 0.002 \left(\frac{f}{F_{ty}} \right)^{n1} \quad \text{and} \quad \varepsilon_{p2} = 0.002 \left(\frac{f}{F_{ty}} \right)^{n2} \quad [1.4.4.2(b)]$$

The relative contributions of ε_{p1} and ε_{p2} are determined by a third variable α , as shown in the following equation for total strain:

$$\varepsilon = \frac{f}{E} + 0.002 \left[\alpha \left(\frac{f}{F_{ty}} \right)^{n1} + (1 - \alpha) \left(\frac{f}{F_{ty}} \right)^{n2} \right] \quad [1.4.4.2(c)]$$

The variable α is determined by a fitting process, as described in Section 9.8.4.1.3.

MMPDS current practice is to provide definition of the dual Bron parameters if examination of the available stress strain curves warrants this more complicated model. Additionally, current practice is to report a 'best fit', single parameter version, in addition to the two parameter formulation. Users of the data can then leverage legacy tools and programs written for the original one parameter formulation for stability analyses. Additional comments regarding buckling, the single parameter Ramberg-Osgood and the dual parameter Bron formulation are contained in Section 1.6.5.

1.4.4.3 Tensile Properties — Tensile strengths are given for the longitudinal, long-transverse, and short-transverse directions wherever data are available. Short-transverse strengths may be relatively low, and transverse properties should not be assumed to apply to the short-transverse direction unless so stated. In those instances where the direction in which the material will be used is not known, the lesser of the applicable longitudinal or transverse properties should be used.

When a metallic specimen is tested in tension using ASTM E8 standard procedures, it is customary to plot results as a stress-strain diagram. Typical tensile stress-strain diagrams are characterized in Figure 1.4.4.3(a). Such diagrams, drawn to scale, are provided in appropriate chapters of this Handbook. The general format of such diagrams is to provide a strain scale nondimensionally (in./in.) and a stress scale in 1000 lb/sq.in. (ksi). The stress-strain relationships presented, which include elastic and compressive tangent moduli, are typical curves based on three or more lots of test data. Being typical, these curves will not correspond to yield strength data presented as design allowables (minimum values). However, the stress-strain relationships are no less useful, since there are well-known methods for using these curves in design by reducing them to a minimum curve scaled down from the typical curve or by using Ramberg-Osgood parameters obtained from the typical curves. Properties required for design and structural analysis are discussed in Sections 1.4.4.4 to 1.4.4.10.

Note that in the bottom stress-strain curve shown in Figure 1.4.4.3(a), which represents a clad alloy, the initial slope of the modulus line typically has two different linear segments, representing the primary and secondary modulus lines for the stress-strain curve, as shown in Figure 1.4.4.3(b). This is caused by yielding of the very low strength cladding material in the range of 8 to 12 ksi; leaving only the higher strength base material to continue to respond elastically with increasing stress (up to the proportional limit for the base material).

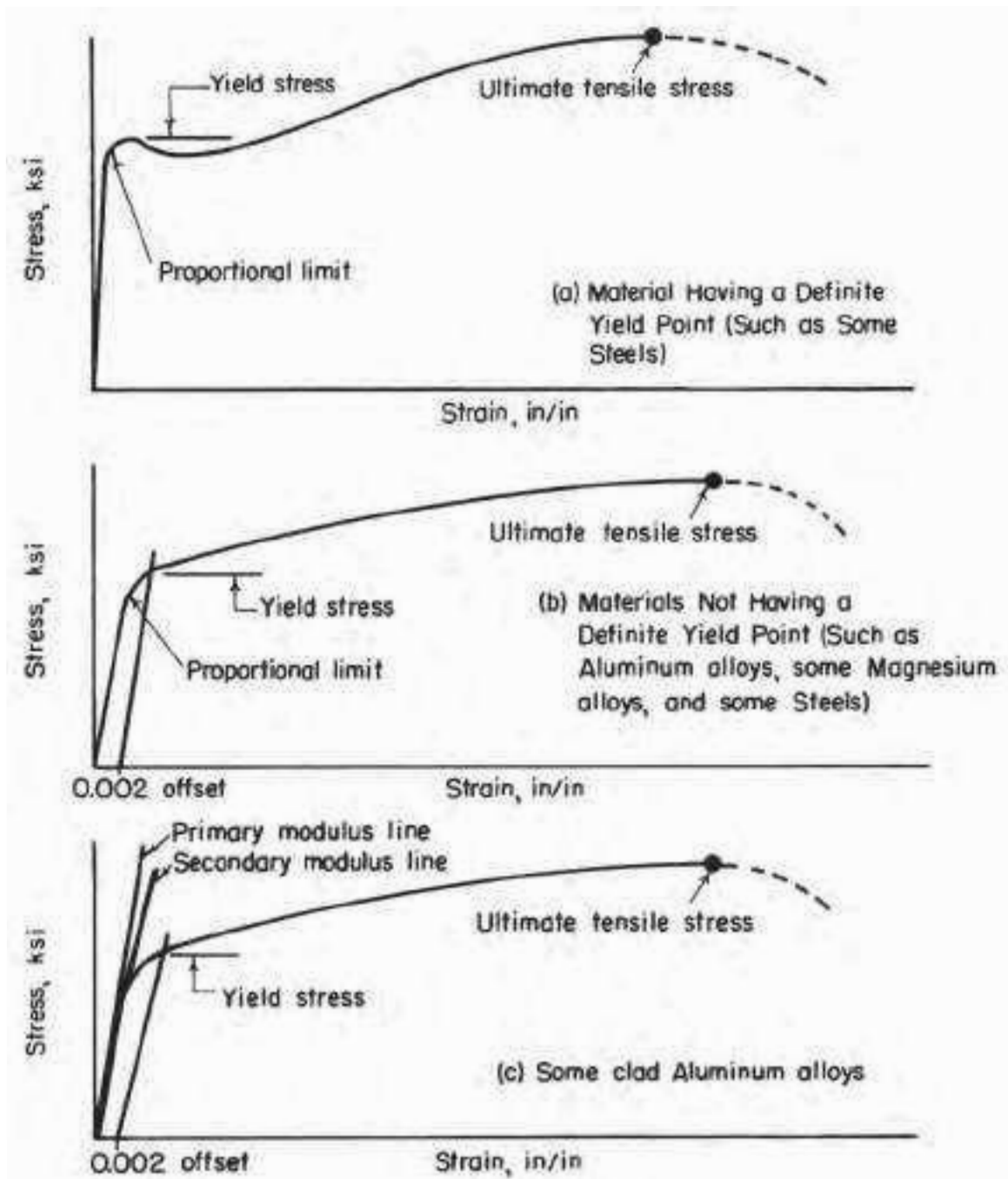


Figure 1.4.4.3(a). Typical tensile stress-strain diagrams.

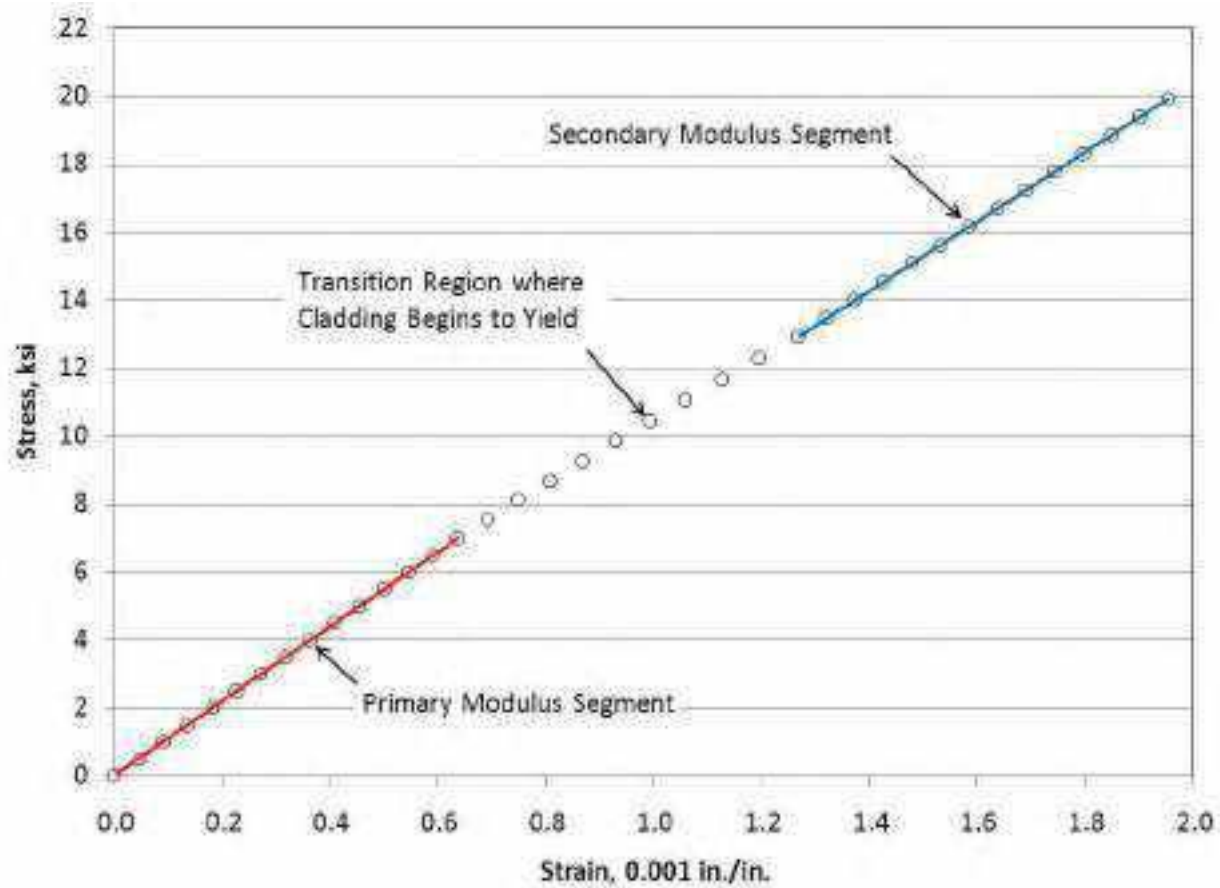


Figure 1.4.4.3(b). Illustration of primary and secondary modulus segments of a stress-strain curve for a clad material.

The secondary modulus can be approximated from the primary modulus as follows:

$$E_{sec} \sim E_p * (t_1 - t_0) / t_1$$

where

E_{sec} = secondary modulus
 E_p = primary modulus
 t_0 = total cladding thickness
 t_1 = sheet or plate thickness

The exact yield strength of the cladding typically is unimportant with respect to the bulk yield behavior of high strength clad aluminum products. However, the thickness of the cladding relative to the thickness of the core typically does have a substantial effect on the bulk modulus of the clad product because it yields long before the core material reaches its proportional limit. The change in "linear elastic" slope is subtle in the stress-strain curve, but it is quite obvious in the initial portion of a compression tangent-modulus curve, as shown in Figure 1.4.4.3(c). (Definitions for tangent and secant moduli are given in the next section.) The change from primary to secondary modulus can be approximated on the tangent modulus curve by beginning the "yielding" of the cladding at 8 ksi and to considering it "fully yielded" at 12 ksi. This can be approximated on the tangent modulus curve by simply connecting with a straight line the primary modulus at 8 ksi with the secondary modulus at 12 ksi (as shown in Figure 1.4.4.3(c)).

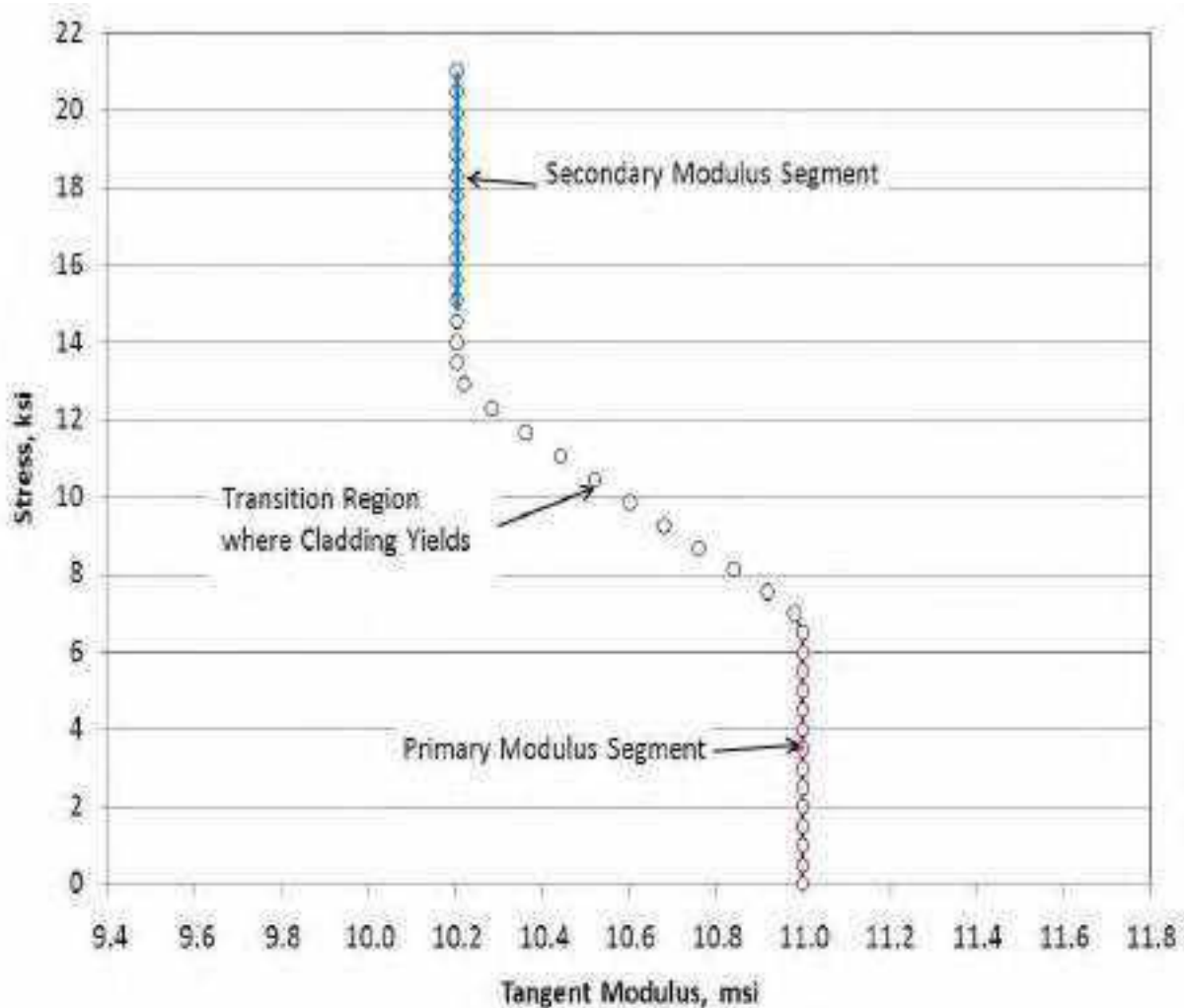


Figure 1.4.4.3(c). Illustration of Initial Portion of Tangent Modulus Curve for a Clad Material

1.4.4.4 Modulus of Elasticity (E) — Referring to Figure 1.4.4.3(a), it is noted that the initial part of stress-strain curves are straight lines. This indicates a constant ratio between stress and strain. Numerical values of such ratios are defined as the modulus of elasticity, denoted by the letter E . This value applies up to the proportional limit stress (see Section 1.4.4.5) at which point the initial slope of the stress-strain curve then decreases. Modulus of elasticity has the same units as stress. See Equation 1.3.4(b).

Other moduli of design importance are tangent modulus, E_t , and secant modulus, E_s . Both of these moduli are functions of strain. Tangent modulus is the instantaneous slope of the stress-strain curve at any selected value of strain. Secant modulus is defined as the ratio of total stress to total strain at any selected value of strain. See Figure 1.4.4.4.

Both of these moduli are used in structural element designs. Except for materials described with discontinuous behaviors, such as the upper stress-strain curve in Figure 1.4.4.3(a), tangent modulus is the lowest value of modulus at any state of strain beyond the proportional limit. Similarly, secant modulus is the highest value of modulus beyond the proportional limit.

Clad aluminum alloys may have two separate modulus of elasticity values, as indicated in the typical stress-strain curve shown in Figure 1.4.4.3(b) and Figure 1.4.4.3(c). The initial slope or primary modulus denotes a response of both the low-strength cladding and higher-strength core elastic behaviors. This value applies only up to the proportional limit of the cladding. For example, the primary modulus of 2024-T3 clad sheet applies only up to about 6 ksi. Similarly, the primary modulus of 7075-T6 clad sheet applies only up to approximately 12 ksi. A typical use of primary moduli is for low-amplitude, high-frequency fatigue. Primary moduli are not applicable at higher stress levels. Above the proportional limits of cladding materials, a short transition range occurs while the cladding is developing plastic behavior. The material then exhibits a secondary elastic modulus up to the proportional limit of the core material. This secondary modulus is the slope of the second straight line portion of the stress-strain curve. In some cases, the cladding is so little different from the core material that a single elastic modulus value is used.

Certain metallurgical conditions can affect the variability of the modulus. For example, highly textured materials such as Ti-6Al-4V sheet and plate can have modulus values which have large Coefficients of Variation, COV(%), defined as the standard deviation divided by the mean value as a percent. For materials which have COV values greater than or equal to 3%, the modulus values provided within the Handbook are ranges rather than a single value. The range provided in the Handbook is the lower of the minimum test or minus 2 standard deviations from the mean and the higher of the maximum test or plus 2 standard deviations from the mean. The sample size, average, and standard deviation are footnoted.

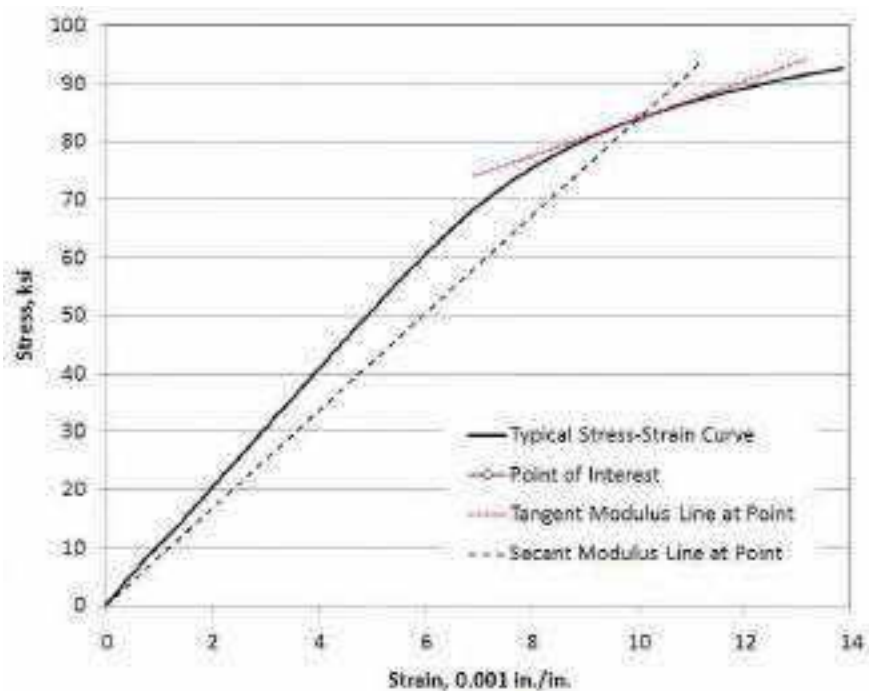


Figure 1.4.4.4. Modulus of elasticity

1.4.4.5 Tensile Proportional Limit Stress (F_{tp}) — The tensile proportional limit is the maximum stress for which strain remains proportional to stress. Since it is practically impossible to determine precisely this point on a stress-strain curve, it is customary to assign a small value of plastic strain to identify the corresponding stress as the proportional limit. In this Handbook, the tension and compression proportional limit stress corresponds to a plastic strain of 0.0001 in./in.

1.4.4.6 Tensile Yield Stress (TYS or F_{ty}) — Stress-strain diagrams for some ferrous alloys exhibit a sharp break at a stress below the tensile ultimate strength. At this critical stress, the material elongates considerably with no apparent change in stress. See the upper stress-strain curve in Figure 1.4.4.3(a). The stress at which this occurs is referred to as the yield point. Most nonferrous metallic alloys and most high strength steels do not exhibit this sharp break, but yield in a monotonic manner. This condition is also illustrated in Figure 1.4.4.3(a). Permanent deformation may be detrimental, and the industry adopted 0.002 in./in. plastic strain as an arbitrary limit that is considered acceptable by all regulatory agencies. For tension and compression, the corresponding stress at this offset strain is defined as the yield stress (see Figure 1.4.4.3(a)). This value of plastic axial strain is 0.002 in./in. and the corresponding stress is defined as the yield stress. For practical purposes, yield stress can be determined from a stress-strain diagram by extending a line parallel to the elastic modulus line and offset from the origin by an amount of 0.002-in./in. strain. The yield stress is determined as the intersection of the offset line with the stress-strain curve.

1.4.4.7 Tensile Ultimate Stress (TUS or F_{tu}) — Figure 1.4.4.3(a). shows how the tensile ultimate stress is determined from a stress-strain diagram. It is simply the maximum stress attained. It should be noted that all stresses are based on the original cross-sectional dimensions of a test specimen, without regard to the lateral contraction due to Poisson's ratio effects. That is, all strains used herein are termed engineering strains as opposed to true strains, which take into account actual cross-sectional dimensions. Ultimate tensile stress is commonly used as a criterion of the strength of the material for structural design, but it should be recognized that other strength properties may often be more important.

1.4.4.8 Elongation (e) — An additional property that is determined from tensile tests is elongation. This is a measure of ductility. Elongation, also stated as total elongation, is defined as the permanent (plastic strain) increase in gage length, measured after fracture of a tensile specimen. It is commonly expressed as a percentage of the original gage length. Elongation is usually measured over a gage length of 2 inches for rectangular tensile test specimens and in 4D (inches) for round test specimens. Welded test specimens are the exception. Refer to the applicable material specification for appropriate specified gage lengths. Although elongation is widely used as an indicator of ductility, this property can be significantly affected by testing variables such as thickness, strain rate, and gage length of test specimens. Elongation values are included in the tables of room temperature mechanical properties. In some cases where the elongation is a function of material thickness, a supplemental table is provided. Short-transverse elongations may be relatively low, and long-transverse values should not be assumed to apply to the short-transverse direction. See Section 1.4.1.1 for data basis.

1.4.4.9 Reduction of Area (RA) - Another property determined from tensile tests is reduction of area, which is also a measure of ductility. Reduction of area is the difference, expressed as a percentage of the original cross-sectional area, between the original cross section and the minimum cross-sectional area adjacent to the fracture zone of a tested specimen. This property is less affected by testing variables than elongation, but is more difficult to compute on thin section test specimens. See Section 1.4.1.1 for data basis.

1.4.4.10 Design Stress-Strain Curves - When designing aircraft structure it is normal practice to use a statistically based stress-strain curve when a stress-strain curve is needed. The curves appearing in MMPDS are typical curves, so the analyst must generate statistically based curves from the available handbook data.

The most straightforward approach to generate a curve, accurate up to yield, is to use the Hill formulation to determine the strain from material properties found in this handbook. Extrapolation of this curve above yield, using this method, is not recommended.

Statistically based material properties are used for F_{cy} or F_{ty} , while typical values are used for the Ramberg-Osgood number and the modulus of elasticity in compression or tension, as appropriate.

The Hill formulation gives

[1.4.4.10]

$$e = \frac{f}{E_c} + 0.002 \left(\frac{f}{F_{cy}} \right)^{n_c} \quad \text{Compression}$$

$$e = \frac{f}{E_t} + 0.002 \left(\frac{f}{F_{ty}} \right)^{n_t} \quad \text{Tension}$$

where

f is the stress at which the strain is to be calculated (psi)

E_c, E_t are the compression or tension elastic modulus (typical) (psi)

F_{cy}, F_{ty} are the compression or tension yield strength (A or B Basis, as required) (psi)

n_c, n_t are the compression or tension Ramberg-Osgood numbers (typical)

To generate a stress-strain curve, uniform incremental values of stress between 0 and F_{cy} or F_{ty} are selected depending on whether compression or tension is desired. The strain is calculated per the above equation. A stress-strain plot can then be generated using the assumed values of stress and the calculated values of strain. Stress is generally plotted on the y-axis and strain on the x-axis.

If a statistically based, temperature adjusted stress-strain curve is required, first adjust the statistically based material properties from the handbook by the appropriate temperature reduction factors, then follow the steps outlined above.

It should be noted that this approach is based on a typical Ramberg-Osgood factor. Actual Ramberg-Osgood values for a particular lot of material may be higher or lower. Lower Ramberg-Osgood values will tend to increase total strain estimates below the yield strength and decrease total strain estimates above the yield strength. Conversely, higher Ramberg-Osgood values will tend to decrease total strain estimates below the yield strength and increase total strain estimates above the yield strength. However, because the Ramberg-Osgood parameter is used only as an exponent in the calculation, the formulation is somewhat insensitive to variations in the Ramberg-Osgood parameter and is considered acceptable for use in the generation of basis stress-strain curves.

1.4.4.11 Dynamic Modulus (E_D) — Dynamic Young's Modulus (E_D) is determined using either the ASTM test standard E1875, "Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Sonic Resonance" or the ASTM test standard E1876, "Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration." ASTM E1875 and ASTM E1876 are the preferred test methods for the determination of modulus values at test temperatures where time dependent plasticity (e.g. creep) may affect the results.

From ASTM E1875 and ASTM E1876, specimens possess specific mechanical resonant frequencies that are determined by the elastic modulus, mass, and geometry of the test specimen. Therefore, the dynamic

elastic properties of a material can be computed if the geometry, mass, and mechanical resonant frequencies of a suitable test specimen of that material can be measured. Dynamic Young's modulus is determined using the resonant frequency in the flexural mode of vibration. The test method is specifically appropriate for materials that are elastic, homogeneous, and isotropic. This test method is not satisfactory for specimens that have cracks or voids that are major discontinuities in the specimen. In addition, the test method is not satisfactory when these materials cannot be fabricated in a uniform rectangular or circular cross section.

Certain metallurgical conditions can affect the variability of the modulus. For example, highly textured materials such as Ti-6Al-4V sheet and plate can have modulus values which have large Coefficients of Variation, COV(%), defined as the standard deviation divided by the mean value as a percent. For materials which have COV values greater than or equal to 3%, the modulus values provided within the Handbook are ranges rather than a single value. The range provided in the Handbook is the lower of the minimum test or minus 2 standard deviations from the mean and the higher of the maximum test or plus 2 standard deviations from the mean. The sample size, average, and standard deviation are footnoted.

1.4.5 COMPRESSIVE PROPERTIES — Compressive strengths are given for the longitudinal, long-transverse, and short-transverse directions wherever data are available. Short-transverse strengths may be relatively low, and transverse properties should not be assumed to apply to the short-transverse direction unless so stated. In those instances where the direction in which the material will be used is not known, the lesser of the applicable longitudinal or transverse properties should be used. Results of compression tests completed in accordance with ASTM E9 are plotted as stress-strain curves similar to those shown for tension in Figure 1.4.4.3(a). Preceding remarks concerning tensile properties of materials, except for ultimate stress and elongation, also apply to compressive properties. Moduli are slightly greater in compression for most of the commonly used structural metallic alloys. Special considerations concerning the ultimate compressive stress are described in the following section. An evaluation of techniques for obtaining compressive strength properties of thin sheet materials is outlined in Reference 1.4.5 and ASTM E9.

1.4.5.1 Compressive Ultimate Stress (F_{cu}) — Since the actual failure mode for the highest tension and compression stress is shear, the maximum compression stress is limited to F_{tu} . The driver for all analysis of structure loaded in compression is the slope of the compression stress-strain curve, the tangent modulus.

1.4.5.2 Compressive Yield Stress (CYS or F_{cy}) — Compressive yield stress is measured in a manner identical to that done for tensile yield strength. It is defined as the stress corresponding to 0.002-in./in. plastic strain.

1.4.6 SHEAR PROPERTIES — Shear strengths vary to some extent with plane of shear and direction of loading, but the differences are not as consistent as with bearing strengths. Shear strength values were historically presented either with the grain direction, L, LT, and ST, or with no grain direction. Values presented with no grain direction may be the result of "punch" or "blanking" shear tests, where specimens were "punched" from the L-LT plane of material. It was determined that values from this test may be conservative with respect to ASTM B831 [See Reference 1.4.6(a)].

Since MMPDS-04, the grain orientation is referenced using the ASTM test orientations, when known. The naming convention for grain orientation is based on the expected shearing plane and the direction of loading. This differs for thin material or thicker rectangular or round material, due to test specimen geometry. For thin products, ASTM B831 slotted shear) is used. In this specification the first letter designates the normal to the expected shear plane. The second letter designates the direction of force application or expected fracture direction. For thicker sections and round bar, ASTM B769 (Amsler or pin shear) is used. See Figures 1.4.6(a), 1.4.6(b), and 1.4.6(c), respectively. For hand forgings, the shear strength in the short-transverse direction may be significantly lower than for the other two grain directions.

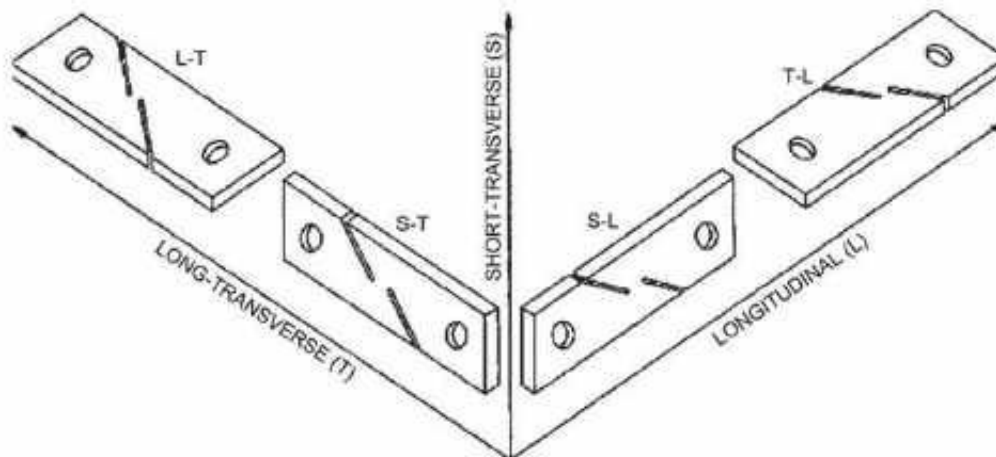


Figure 1.4.6(a). Orientation and Naming Convention for Shear of Thin Products. (Figure reprinted with permission¹ from ASTM B831.).

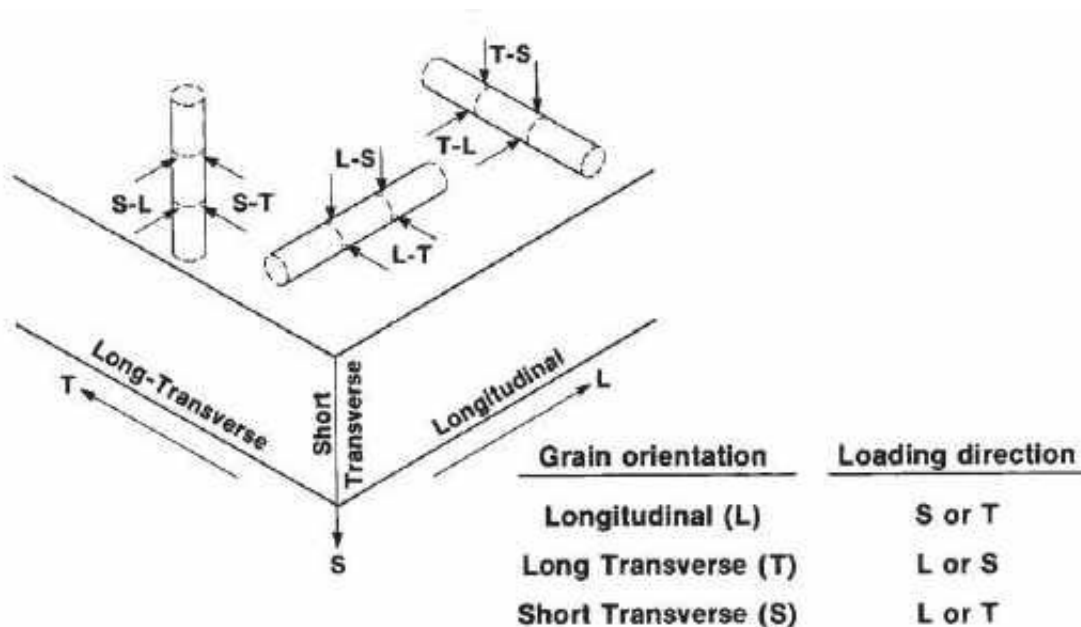


Figure 1.4.6(b). Orientation and Naming Convention for Shear Testing of Thick Rectangular Products.

(Figure reprinted with permission¹ from ASTM B769.)

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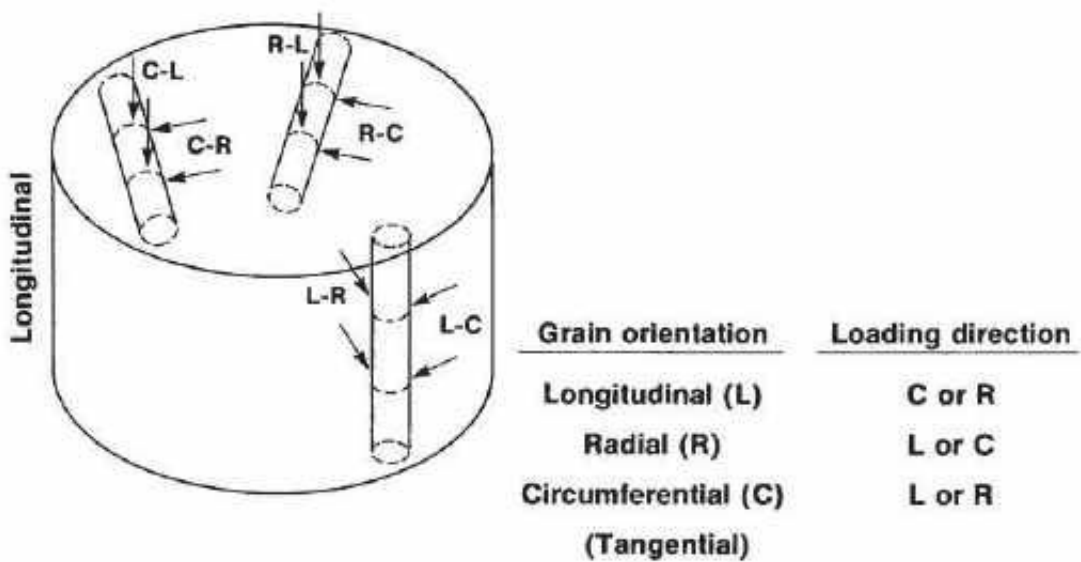


Figure 1.4.6(c). Orientation and Naming Convention for Shear Testing of Thick Cylindrical Products.
(Figure reprinted with permission¹ from ASTM B769.)

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Results of torsion tests on round tubes or round solid sections are plotted as torsion stress-strain diagrams. The shear modulus of elasticity is considered a basic shear property. Other properties, such as the proportional limit stress and shear ultimate stress, cannot be treated as basic shear properties because of form factor effects. The theoretical ratio between shear and tensile stress for homogeneous, isotropic materials is 0.577. The actual ratio between shear and tensile stress may vary considerably, depending on the degree of anisotropy of individual materials. Reference 1.4.6(b) contains additional information on this subject.

The relationship between the shear orientation as defined above (and in the property tables) and shearing stress in application to actual structure may be confusing. Consider the example of a wing rib machined from a thick plate shown in Figure 1.4.6(d). A free body diagram of typical loading applied to the rib is shown in Figure 1.4.6(e). Figure 1.4.6(f) shows the free body diagram of a section cut of the rib, with shear flow load in the web. The in-plane shear stress in the web corresponds to the shear strength determined from testing the thin material as shown in Figure 1.4.6(g). Conversely, for thick structural elements subject to beam bending, the shear stress corresponds to the shear strength determined from testing thick material as shown in Figure 1.4.6(h).

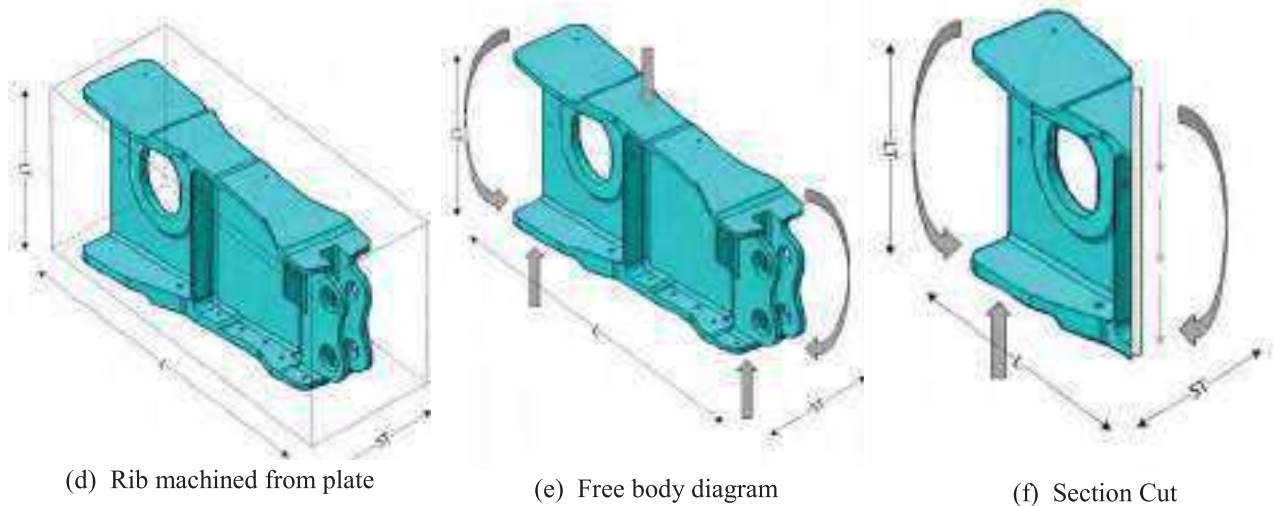


Figure 1.4.6(d-f). Example of a Structural Element under Shear Loading.

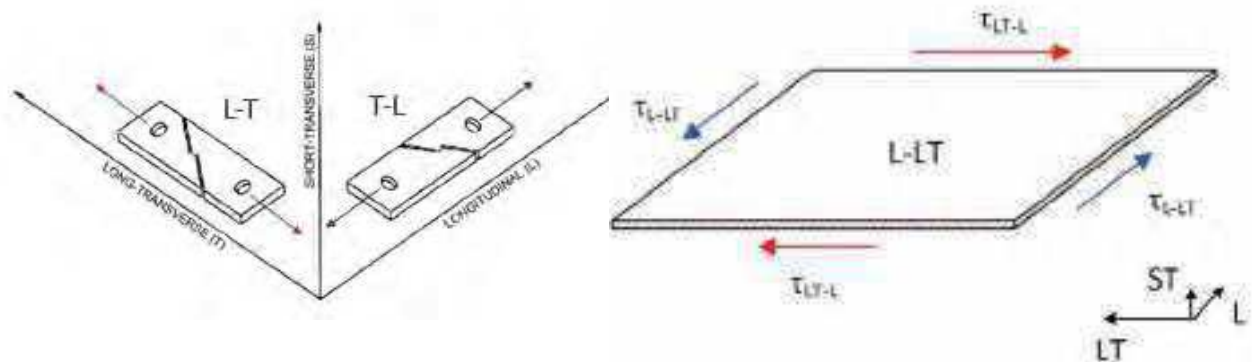


Figure 1.4.6(g). Relation between Shear Testing and a Thin Structural Element under Shear Loading.

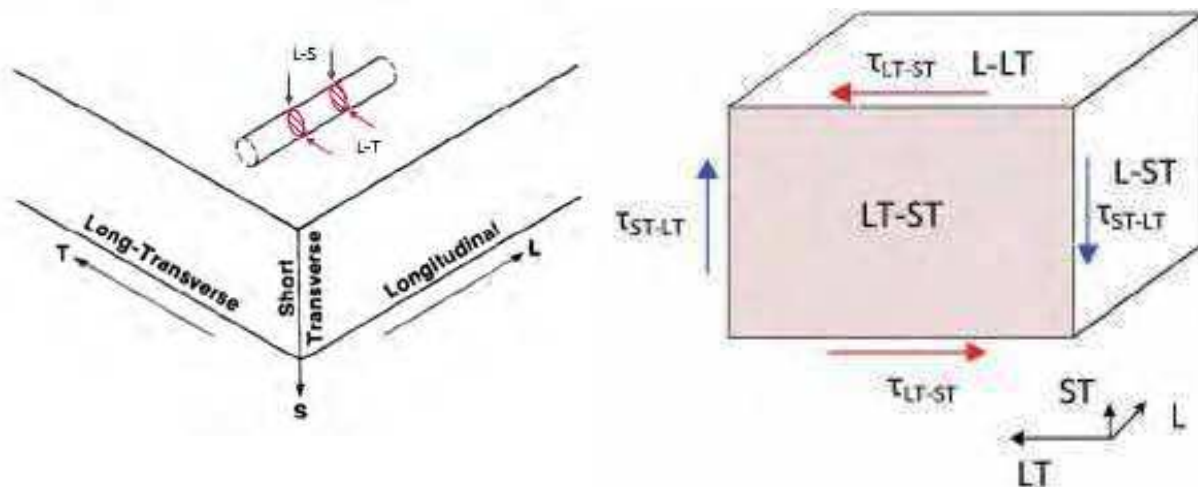


Figure 1.4.6(h). Relation between Shear Testing and a Thick Structural Element under Shear Loading.

1.4.6.1 Modulus of Rigidity (G) — This property is the initial slope of the shear stress-strain curve. It is also referred to as the modulus of elasticity in shear. The relation between this property and the modulus of elasticity in tension is expressed for homogeneous isotropic materials by the following equation:

$$G = \frac{E}{2(1 + \mu)} \quad [1.4.6.1]$$

When the Elastic Modulus, E , is provided as a range, the Modulus of Rigidity should be calculated as a range using Equation 1.4.6.1 and the elastic modulus bounds. This calculated range should be placed in the Handbook rather than a single value.

1.4.6.2 Ultimate and Yield Stresses in Shear (S_{su} or F_{su}) and (S_{sy} or F_{sy}) — These properties, usually obtained from tests using ASTM test procedures, are not strictly basic properties, as they will depend on the shape of the test specimen. Test results from one type of shear test shall not be combined with the same properties obtained from other specimen configuration tests.

Design values reported for shear ultimate strength (F_{su}) in room temperature property tables are based on slotted shear type test per ASTM B831, for thin sheet products, typically less than 0.25 inches, except when noted. Thicker products use a cylindrical shear specimen per ASTM B769, otherwise known as the Amsler shear test. These two tests provide ultimate strength and are designed for aluminum alloys, but are often used for steels, titanium, magnesium, and heat resistant alloys. These tests cannot predict shear yield strength and, therefore, only F_{su} values are given in the MMPDS Handbook. Because the results from these tests are not interchangeable, it is essential to reference the specific ASTM standard used.