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16. Abstract

An evaluation of the suitability of various high-strength materials for anchor bolt applications was made. A selected group of materials meeting ASTM Standard Specifications were tabulated. Based on the material properties, availability, and cost, several of the materials were determined to be most suitable for anchor bolt materials. To further assist the designer in selecting materials not covered by ASTM Standard Specifications, a brief review of AISI Grade Designations is presented and cross-referenced with the ASTM Standard Specifications.

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A GUIDE TO THE SELECTION OF HIGH-STRENGTH ANCHOR BOLT MATERIALS

by

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Research Report No. 29-1

Research Project Number 3-5-74-29
Strength and Behavior of Anchor Bolts

Conducted for

The Texas Highway Department

In Cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

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P R E F A C E

This report is the first in a series aimed toward improving procedures for anchor bolt design. The report deals specifically with high-strength anchor bolt materials. It includes a summary of ASTM Specifications applicable to anchor bolt usage. The most desirable materials for anchor bolt applications are selected on the basis of availability and cost. The ASTM Specifications are cross-referenced with AISI Grade Designations and a brief description of the use of AISI Grade Designations is presented. Subsequent reports will present the results of tests of high-strength anchor bolts and the implications of the tests on design procedure.

The work is being conducted under Research Project 3-5-74-29, which is sponsored by the Texas Highway Department and the Federal Highway Administration, and administered through the Center for Highway Research at The University of Texas at Austin. Close liaison with the Texas Highway Department has been maintained through Mr. Warran A. Grasso, the contact representative, and the Federal Highway Administration through Mr. Jerry Bowman.

A B S T R A C T

An evaluation of the suitability of various high-strength materials for anchor bolt applications was made. A selected group of materials meeting ASTM Standard Specifications were tabulated. Based on the material properties, availability, and cost, several of the materials were determined to be most suitable for anchor bolt materials. To further assist the designer in selecting materials not covered by ASTM Standard Specifications, a brief review of AISI Grade Designations is presented and cross-referenced with the ASTM Standard Specifications.

KEY WORDS: anchor bolts, materials, selection, specifications.

S U M M A R Y

This report presents a guide to selecting high-strength anchor bolt materials. A review of applicable ASTM Standard Specifications is made with a selected group of Specifications tabulated to indicate those materials deemed most suitable on the basis of properties, availability, and cost. AISI Grade Designations are also reviewed and cross-referenced with ASTM Standard Specifications.

I M P L E M E N T A T I O N

With the wide variety of materials available for use as anchor bolt stock, it is often difficult for the designer to make a decision regarding the specific material or specification to use. This report is intended to provide guidance to the designer in carrying out the task of selecting and specifying high-strength anchor bolt material. On the basis of availability and cost, a selected group of materials meeting ASTM Standard Specifications is tabulated. Factors such as labor costs associated with placement or quantity purchased are not considered. Lengths used in the tabulations are not based on rigorous design methods but provide only for relative comparisons. Work underway, to be reported later, should provide guidance in determining embedment lengths. Coupled with the material in this report, the engineer should be able to rationally design and specify the anchor bolt installation.

C O N T E N T S

LIST OF TABLES AND FIGURES

A GUIDE TO THE SELECTION OF HIGH-STRENGTH ANCHOR BOLT MATERIALS

Introduction

The purpose of this report is to provide a means of selecting and specifying material for high-strength ($f_y > 50$ ksi) anchor bolts. The information and suggestions contained herein are based on the results of a survey of materials meeting selected ASTM standards which were considered suitable for anchor bolt applications.

Generally, there are two ways to specify material for an anchor bolt. The more convenient approach is to cite the ASTM Standard Specification which defines the appropriate minimum mechanical properties, level of quality control, etc. A material may also be specified by citing the desired AISI Steel Grade Designation, chemical composition, necessary metallurgical treatment, finishing and machining, and other desired properties. Except in special circumstances such an approach is unnecessary; the end product, a material meeting certain minimum requirements, is far more easily obtained by citing the appropriate ASTM Specification. Consequently, this report is concerned primarily with examining ASTM Specifications suitable for high-strength anchor bolt applications. Appendix B contains supplemental information concerning the AISI Grade Designation approach.

Suitable ASTM Specifications

The selection of high-strength anchor bolt material by ASTM Specifications may not be a straightforward process, because there are a large number of ASTM Specifications for high-strength bars. The specifications range in organization from catalogs of chemical compositions of carbon and alloy steel bars to detailed mechanical and quality control requirements for special application bars. In addition, many specifications contain or imply certain restrictions which limit their usefulness in high-strength anchor bolt applications. Table 1 lists the ASTM Specifications which were examined to determine their suitability for specifying anchor bolt materials. Several of the specifications have been or are being used by the Texas Highway Department to specify anchor bolt material. Each of these specifications is discussed briefly in Appendix A.

Of the twenty ASTM Specifications listed in Table 1, eight appear suitable for high-strength anchor bolt applications. Table 2 lists these specifications and the pertinent mechanical properties.

Relative Cost and Availability

It would be desirable to compare the specifications shown in Table 2 on a basis of relative cost and availability. The present steel market makes it difficult to obtain information of this nature. However, contacts with steel industry sources have provided some data on relative cost. Availability, on the other hand, is difficult to evaluate, except for indications that some materials are not generally available.

Table 3 shows some relative cost information for several of the ASTM Specifications listed in Table 2. Such information for all the material shown in Table 2 was unavailable. The data in Table 3 were compiled assuming a heavy hex head bolt with a length of 20 bar diameters. Length as a function of bar diameter was specified to reflect embedment length requirements. Work currently underway is aimed toward evaluation of the factors influencing the strength of anchor bolts. With completion of the study, design recommendations for the embedment length of high-strength anchor bolts will be developed. Twenty bar diameters were chosen for comparison purposes only, and are not intended as a design recommendation. The cost of an ASTM A307, 1 in. diameter by 20 in. long bolt, was used as a base (100%) because it is a low strength (36 ksi) material readily available and for which costs can be easily obtained. The relative cost data shown in Table 3 do not consider quantity ordered, which will influence actual cost considerably.

TABLE 1. ASTM SPECIFICATIONS APPLICABLE TO ANCHOR BOLT USAGE

1. ASTM A29 - General Requirements for Hot-Rolled and Cold-Finished Carbon and Alloy Steel Bars
2. ASTM A108 - Cold-Finished Carbon Steel Bars and Shafting
3. ASTM A193 - Alloy Steel and Stainless Steel Bolting Material for High Temperature Services
4. ASTM A306 - Carbon Steel Bars Subject to Mechanical Property Requirements
5. ASTM A307 - Carbon Steel Externally and Internally Threaded Standard Fasteners
6. ASTM A311 - Stress Relief Annealed Cold-Drawn Carbon Steel Bars
7. ASTM A320 - Alloy Steel Bolting Materials for Low-Temperature Service
8. ASTM A321 - Quenched and Tempered Carbon Steel Bars
9. ASTM A322 - Hot Rolled Alloy Steel Bars
10. ASTM A325 - High-Strength Bolts for Structural Steel Joints, Including Suitable Nuts and Plain Hardened Washers
11. ASTM A331 - Cold-Finished Alloy Steel Bars
12. ASTM A354 - Quenched and Tempered Alloy Steel Bolts and Studs with Suitable Nuts
13. ASTM A400 - Recommended Practice for the Selection of Steel Bar Composition According to Section
14. ASTM A434 - Quenched and Tempered Alloy Steel Bars, Hot Rolled, or Cold-Finished
15. ASTM A449 - Quenched and Tempered Steel Bolts and Studs
16. ASTM A458 - Hot-Worked, Hot-Cold-Worked, and Cold-Worked Alloy Steel Bars for High-Strength at Elevated Temperatures
17. ASTM A490 - Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints
18. ASTM A540 - Alloy Steel Bolting Materials for Special Applications
19. ASTM A575 - Merchant Quality Hot-Rolled Carbon Steel Bars
20. ASTM A576 - Special Quality Hot-Rolled Carbon Steel Bars

TABLE 2. PROPERTIES OF ASTM SPECIFICATIONS SUITABLE FOR HIGH-STRENGTH ANCHOR BOLT APPLICATIONS

Material	Bar Diameter	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2", %	Reduction in Area, %	Brinell Hardness
ASTM A193 GRADE B7	2-1/2" and under	125	105	16	50	
	Over 2-1/2"-4" incl.	115	95	16	50	
	Over 4"-7" incl.	100	75	18	50	
ASTM A311	9/16" and under	105	85	10-12	35-40	
	Over 9/16"-1-1/4" incl.	100	80	10-12	35-40	
	Over 1-1/4"-2-1/2"incl.	95	75	10-12	35-40	
ASTM A320 GRADE L7	2-1/2" and under	125	105	16	50	
ASTM A321	1" and under	110	75	18	45	
	Over 1"-2-1/2" incl.	105	70	18	45	
	Over 2-1/2"-4" incl.	95	65	18	45	
	Over 4"-6" incl.	90	60	18	40	
	Over 6"-9-1/2" incl.	85	50	18	30	
ASTM A325	1/2"-1" incl.	120	92	14	35	241-331
	1-1/8"-1-1/2" incl.	105	81	14	35	223-293
ASTM A354 GRADE BD	1/4"-1-1/2" incl.	150	125	14	35	302-352
ASTM A449	1/4"-1" incl.	120	92	14	35	241-302
	1-1/8"-1-1/2" incl.	105	81	14	35	223-285
	1-3/4"-3" incl.	90	58	14	35	183-235
ASTM A490	1/2"-1-1/2" incl.	150-170	130	14	40	302-341

TABLE 3. REPRESENTATIVE RELATIVE COSTS FOR TYPICAL HIGH-STRENGTH HEADED ANCHOR BOLTS(1)

Material	1" dia. x 20"			1-1/2" dia. x 30"			1-3/4" dia. x 35"		
	Yield Strength ksi	Relative Cost %	Cost-Strength Ratio(2)	Yield Strength ksi	Relative Cost %	Cost-Strength Ratio(2)	Yield Strength ksi	Relative Cost %	Cost-Strength Ratio(2)
(4)ASTM A307	36	100	3.54	36	308	4.84	36	474	5.48
ASTM A193 GRADE B7	105	194	2.35	105	490	2.64	105	882	3.49
ASTM A325	92	172	2.38	81	444	3.10	Not available in this diameter		
ASTM A354 GRADE BD	125	194	1.98	125	579	2.62	125(3)	1077(3)	3.58(3)
ASTM A449	92	172	2.38	81	444	3.10	58	708	5.08
ASTM A490	130	194	1.90	130	579	2.52	Not available in this diameter		

(1) For heavy hex head bolts, 20 bar diameters long. A length of 20 diameters is for comparison purposes only and is not intended as a design recommendation.

(2) $\text{Cost-Strength Ratio} = \dfrac{\text{Relative Cost, \%}}{(\text{Gross Bar Area, in.}^2)(\text{Yield Strength, ksi})}$

(3) Although available, material in this diameter is not covered by ASTM A354, Grade BD.

(4) ASTM A307 is intended as a basis for comparison only and is not recommended for high-strength anchor bolt applications.

The cost-strength ratio shown in Table 3 provides an index of cost per kip of load-carrying capacity for a given bolt material and size. It is calculated as:

$$\text{Cost-Strength Ratio} = \frac{\text{Relative Cost, \%}}{(\text{Gross Bolt Area, in.}^2)(\text{Yield Strength, ksi})}$$

The "units" of the cost-strength ratio are relative cost/kip. In developing the concept of the cost-strength ratio, it was assumed that the allowable tension in a bolt was some appropriate fraction of the yield strength, and that this fraction was constant for all bolt diameters, lengths, and materials. It was, therefore, possible to compare the various materials in Table 3 on a basis of their yield strengths.

EXAMPLE 1. A force of 150 kips must be carried by an anchor bolt installation. An estimate of the relative economy of using either ASTM A449, 1 in. diameter x 20 in. bolts, or ASTM A193, Grade B7, 1-3/4 in. diameter x 35 in. bolts is desired.

From Table 3, cost-strength ratio for ASTM A449, 1 in. diameter x 20 in. bolts = 2.38

cost-strength ratio for ASTM A193, Grade B7, 1-3/4 in. diameter x 35 in. bolts = 3.49

It can be seen from a comparison of the cost-strength ratios that the ASTM A449 bolts are more economical than the ASTM A193 bolts. Although ASTM A193, Grade B7 bolts provide a 14 percent increase in yield strength over A449 bolts, the cost increases by 47 percent.

EXAMPLE 2. To carry a force of 150 kips, 1 in. diameter bolts are to be used. An estimate of the relative economy of using ASTM A449 or ASTM A193, Grade B7, is desired.

From Table 3, the cost-strength ratio for ASTM A449, 1 in. diameter x 20 in. bolts = 2.38

the cost strength ratio for ASTM A193, Grade B7, 1 in. diameter x 20 in. bolts = 2.35

It can be seen that ASTM A193, Grade B7, bolts are slightly more economical than ASTM A449 bolts.

Figure 1 illustrates the variation in relative cost per cross-sectional bolt area with bolt diameter for bolts up to 4 in. Data are for ASTM A193, Grade B7, material. As before, bolt length was assumed to be 20 diameters, with bolts threaded at both ends and nuts and washers provided. Ten-piece lots were used for obtaining costs. As can be seen, the relative cost per unit area increases rapidly with diameter of bolt. Although not quite a linear relationship exists, it can almost be stated that relative cost per unit area increases in proportion to the diameter of bolt used. It should be noted that if allowable stresses as a function of the tensile strength of the bolt are taken into account, the cost-strength ratio for large bolts will be even higher because the strength is reduced with increase in diameter.

Examination of Table 3 (and Examples 1 and 2) and Fig. 1 illustrates two trends regarding the relative economy of bolt materials and size. First, for a given diameter, an increase in yield strength results in a decrease in the cost-strength ratio. As shown by Example 2, however, the resulting increase in economy is not necessarily proportional to the increase in yield strength.

Second, for a given material, the cost-strength ratio increases as the bolt size increases. Examination of the data for ASTM A193, Grade B7, bolts shows that while the load-carrying capacity of the 1-3/4 in. diameter bolt is about 300 percent that of the 1 in. diameter bolt, the relative cost of the 1-3/4 in. diameter bolt is 455 percent that of the 1 in. diameter bolt. The cost-strength ratio for the two bolts reflects these values. For materials exhibiting a decrease in yield strength with increasing diameter, such as ASTM A449, the increase in cost-strength ratio for larger diameters is even more significant than for a material with a constant yield strength, such as ASTM A193. From comparison of the cost-strength ratios for the five ASTM Specifications suitable for high-strength anchor bolt applications shown in Table 3, it can be seen that the 1 in. diameter bolt with the highest cost-strength

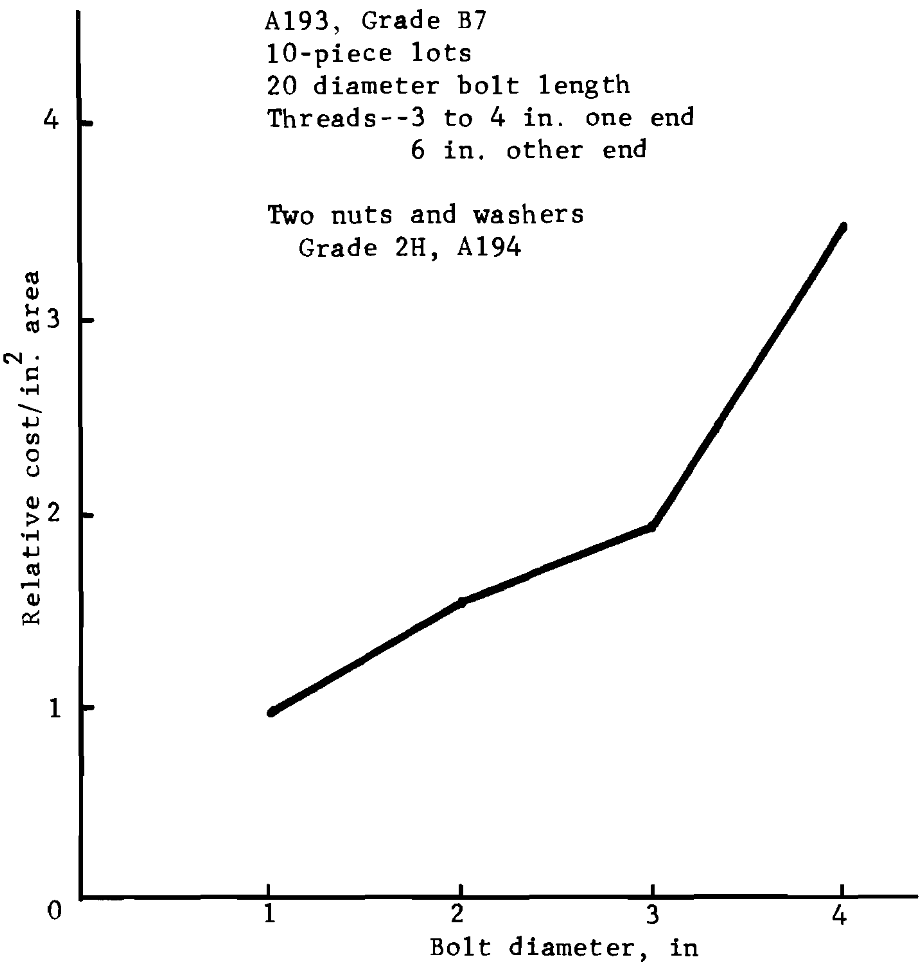

Fig. 1 Variation in cost with bolt diameter.

ratio, ASTM A449 (cost strength ratio = 2.38) is more economical than any 1-1/2 in. or 1-3/4 in. bolt. It should be emphasized that these comparisons consider material cost only and do not include labor costs associated with installation or unit costs based on quantity orders.

Based only on material cost information available, it is apparent that the most economical combination is a small diameter bolt with a high yield strength. Of the materials listed in Table 3, ASTM A490, 1 in. diameter x 20 in. bolts and ASTM A354, Grade BD, 1 in. diameter x 20 in. bolts best satisfy this criterion. However, both materials, and particularly ASTM A490, are presently difficult to obtain. ASTM A193, Grade B7, A325, and A449 can be considered relatively more available.

It was previously noted that Table 3 was developed assuming heavy hex head bolts. ASTM A193, Grade B7; A354, Grade BD; and A449 are more commonly used in anchor bolt applications in a threaded-both-ends configuration. Using the limited information available on the relative costs of headed bolts and bolts threaded both ends, it can be concluded that a headed bolt is generally more costly than a bolt with both ends threaded.

For example, comparing 1 in. diameter by 20 in. headed bolts with bolts threaded both ends (nut on one end), cost information available indicates that the headed A193, Grade B7, bolts are about 10 percent higher and headed A449 bolts are about 20 percent higher than similar bolts threaded both ends. Both materials are listed under ASTM Standard Specifications which include bolts and studs.

In addition to the increased cost of the headed bolt compared to that of the bolt with both ends threaded, headed bolts become difficult to fabricate as length increases. For all practical purposes, headed bolts should be considered unavailable in lengths exceeding 4 ft. It is possible that a bolt with a strength comparable to that of ASTM A490 and a length exceeding 4 ft. may be necessary for a particular application. Appendix B, concerning AISI Grade Designations, provides information for such cases. Appendix B also provides information for cases requiring strengths greater than provided by ASTM A490.

Hydrogen Embrittlement

When working with the high stress levels and the high-hardness steels associated with high-strength anchor bolts, the possibility of hydrogen embrittlement should not be ignored. Although the exact mechanisms are not fully understood, it is known that if embrittlement occurs a delayed fracture is very likely, possibly even at stress levels considerably below normal working stress levels.

Susceptibility to hydrogen embrittlement decreases with decreasing strength or hardness of the steel and with decreasing applied stress; alloy composition is relatively unimportant. Hydrogen may be absorbed by the steel during cleaning (pickling) and plating operations, from electrochemical cell action, and from corrosion processes. Defects in the coating of high-strength steel parts coated with zinc, aluminum, etc., can cause an electrochemical cell when an electrolyte, such as water, is present. Consequently, if the anchor bolt is to be galvanized or otherwise coated and/or is intended for a corrosive environment, use of a material with a yield strength greater than 105 ksi is not recommended; stronger, harder material, which would also be under a greater level of stress, would be too susceptible to hydrogen embrittlement under such circumstances. It should be noted that even this limit may be too high. Further research into the area of hydrogen embrittlement is definitely indicated.

Summary

Based on material costs only, the relative economy of various high-strength anchor bolt materials and bolt sizes was determined. The information gathered indicates that small diameter bolts threaded both ends are generally the most economical choice. The effect of bolt diameter on the cost-strength ratio is so significant that use of any 1 in. diameter by 20 in. high strength bolt represents significant economy over the use of larger diameter bolts if material costs only are considered. Labor costs associated with installation may alter these ratios. Appendix B contains information for dealing with situations that require strengths and/or dimensions that are not available under the ASTM Specifications listed in Tables 2 and 3.

A P P E N D I X   A

DETAILS OF SELECTED ASTM SPECIFICATIONS

Each of the ASTM Specifications listed in Table 1 is discussed briefly. Where applicable, the suitability of particular specifications for high-strength anchor bolt applications is discussed.

ASTM A29: General Requirements for Hot-Rolled and Cold-Finished Carbon and Alloy Steel Bars

ASTM A29 establishes common requirements concerning chemical analysis and physical testing procedures, permissible chemical composition variations, and dimensional tolerances for a "family" of 11 ASTM Specifications, 9 of which are applicable to anchor bolt materials: A108, A306, A311, A321, A322, A331, A434, A575, and A576 (each will be discussed separately). The common requirements apply except when otherwise specified by the purchaser or by a given specification. The main purpose of A29 is that it provides a minimum level of quality control for the specifications under its jurisdiction; in many cases individual specification provisions will prevail over the A29 provisions.

ASTM A108: Finished Carbon Steel Bars and Shafting

Properties Available:	Tensile Strength	= 49-108 ksi
	Yield Strength	= 41.5-90 ksi
	Elongation in 2 in.	= 10-20%
	Reduction in Area	= 30-45%
	Brinell Hardness	= 95-217
	Bar Diameters	= 9 in. and under

ASTM A108, a member of the A29 "family", covers cold-finished carbon steel bars of a type suitable for heat treatment, machining, as-finished shafting, constructional uses, or similar applications. It lists 29 AISI Grade Designations and chemical compositions; no physical properties are specifically defined. The ranges of properties listed above were taken from the SAE Handbook of Metals (see Appendix B for list of properties by AISI Grade Designation). Other sources may give slightly different values. To use ASTM A108 to specify high-strength anchor bolt material, the designer must use sources other than the ASTM Specifications to determine which AISI Grade will provide the properties desired. The physical properties of the bar will vary to some degree with bar diameter. No specific information is available for this variation. Consultation with the fabricator is necessary to determine availability and suitability of selected grades. The entire process is both inconvenient and inefficient. Consequently, the use of ASTM A108 is not recommended for high-strength anchor bolt applications.

ASTM A193: Alloy Steel and Stainless Steel Bolting Material for High Temperature Service

Properties Provided:			
	Tensile Strength	=	75 - 125 ksi
	Yield Strength	=	30 - 105 ksi
	Elongation in 2"	=	12 - 30%
	Reduction in Area	=	45 - 50%
	Bar Diameters	=	7" and under

ASTM A193 covers bolting materials (bars, bolts, screws, studs, and stud bolts) for pressure vessels, flanges, and fittings for high temperature services. It is one of the specifications used by the Texas Highway Department for anchor bolts. Grade B7 provides the highest levels of strength of the grades defined under A193, and is the most commonly available (see Table 2 for a detailed breakdown of Grade B7 properties). Suitable nuts are defined under ASTM A194. Due to the high levels of strength and quality control provided, ASTM A193, Grade B7, is considered suitable for high-strength anchor bolt applications.

ASTM A306: Carbon Steel Bars Subject to Mechanical Property Requirements

Properties Provided:			
	Tensile Strength	=	45 - 90 ksi
	Yield Point	=	22 - 40 ksi
	Elongation in 2"	=	17 - 33%
	Bar Diameters	=	9" and under

ASTM A306, a member of the A29 "family", covers carbon steel bars furnished as-rolled, subject to mechanical property requirements and suitable for general constructional use. Of the 8 grades covered, 7 have yield points less than or equal to A36 steel, and the yield point of the highest grade is only 40 ksi. Obviously A306 would not be suitable for high-strength anchor bolt applications. Even in situations where strengths on the levels shown above are desired, the use of ASTM A36 would be more convenient.

ASTM A307: Carbon Steel Externally and Internally Threaded Standard Fasteners

Properties Provided:		
	Tensile Strength	= 60-100 ksi
	Elongation in 2"	= 18%
	Brinell Hardness	= 121-207
	Bar Diameters	= 1/4"-4" inclusive

ASTM A307 covers the mechanical and chemical requirements for two grades of headed bolts with nuts. Grade A, intended for general applications, should be used for anchor bolts but Grade B, intended for use in cast iron flanges of piping systems, has a higher tensile strength. ASTM A36 refers to A307 for "headed bolts used for anchorage purposes"; however, A36 also notes that the yield strength of A307 steel is lower than that of A36 steel although no specific value is given in either specification. Obviously not suitable for high-strength anchor bolts, ASTM A307 is not recommended even for lower strength anchor bolts since slightly better strength is available from ASTM A36.

ASTM A311: Stress-Relief Annealed Cold-Drawn Carbon Steel Bars

Properties Provided:		
	Tensile Strength	= 90 - 105 ksi
	Yield Strength	= 70 - 85 ksi
	Elongation in 2"	= 10 - 15%
	Reduction in Area	= 35 - 40%
	Bar Diameters	= 9/16" - 2-1/2" inclusive

ASTM A311, a member of the A29 "family", covers stress-relief annealed, cold-drawn carbon steel bars of 4 AISI Grades covered by ASTM A108. These bars are suitable for applications where high strength, good machinability, and decreased distortion are desired. Table 2 gives a breakdown of properties by AISI Grade. A311 alleviates most of the objections to the use of ASTM A108; minimum mechanical properties are defined, the process of specifying material under this Specification is straightforward, and the strengths provided are sufficiently high. Consequently, ASTM A311 can be considered suitable for high-strength anchor bolt applications.

ASTM A320: Alloy Steel Bolting Materials for Low Temperature Service

Properties Provided:	Tensile Strength	= 75 - 125 ksi
	Yield Strength	= 30 - 105 ksi
	Elongation in 2"	= 12 - 35%
	Reduction in Area	= 35 - 50%
	Bar Diameters	= 4" and under

ASTM A320 covers alloy steel bolting material (bars, bolts, screws, studs, and stud bolts) for pressure vessels, valves, flanges, and fittings for low temperature service. Grade L7 provides the highest levels of strength. See Table 2 for a detailed breakdown of Grade L7 properties. A320 is nearly identical to ASTM A193, except that certain impact energy absorption criteria are included to meet low temperature service requirements. Consequently, unless impact is being considered, it is not necessary to use ASTM A320 for high-strength anchor bolt applications.

ASTM A321: Quenched and Tempered Carbon Steel Bars

Properties Provided:	Tensile Strength	= 85 - 110 ksi
	Yield Point	= 50 - 75 ksi
	Elongation in 2"	= 18%
	Reduction in Area	= 35 - 45%
	Bar Diameters	= 9-1/2" and under

ASTM A321, a member of the A29 "family", covers hot-rolled quenched and tempered, carbon steel bars. Mechanical properties are defined by bar diameter (see Table 2). The strengths provided are low compared to that available under other ASTM Specifications, but are nonetheless high enough to consider ASTM A321 suitable for high-strength anchor bolt applications.

ASTM A322: Hot-Rolled Alloy Steel Bars

Properties Available:	Tensile Strength	= 95 - 205 ksi
	Yield Strength	= 75 - 185 ksi
	Brinell Hardness	= 388 - 496

ASTM A322, a member of the A29 "family", covers the chemical requirements for 73 AISI Grade Designations for alloy steel suitable for bars 9" and under in diameter intended for regular constructional applications. No specific properties are defined; the properties listed above were obtained from ASTM A400, Selection of Steel Bar Compositions According to Section (properties could be found for only 42 of the 73 grades, and only for bar diameters 3-1/2" and under). Because of the large number of AISI Grades covered, ASTM A322 is difficult for the designer to use, particularly since there is not a significant difference in the mechanical properties of many of these steels. The major criteria for choosing one or another AISI Grade for a given strength range would be the relative availability of a particular grade and such information is not conveniently available to the designer. Part of the difficulty can be alleviated by noting that A322 includes AISI Grade 4140, which is one of the most common grades of alloy steel available and has strengths in the upper ranges of those listed above. The same difficulties are involved in the use of ASTM A322 as were involved in the use of A108. Consequently, ASTM A322 is not recommended for anchor bolt applications. In special cases, where very high strength is required (f_y > 130 ksi), it would be possible to specify AISI 4140 with appropriate heat treatment. See Appendix B and the discussion of ASTM A540 for further information on very high strength bars; see also the discussion of hydrogen embrittlement.

ASTM A325: High Strength Bolts for Structural Steel Joints, Including Suitable Nuts and Plain Hardened Washers

Properties Provided:		
	Tensile Strength	= 105 - 120 ksi
	Yield Strength	= 81 - 92 ksi
	Elongation in 2"	= 14%
	Reduction in Area	= 35%
	Brinell Hardness	= 223 - 331
	Bar Diameters	= 1/2" - 1-1/2" inclusive

ASTM A325 covers the chemical and mechanical requirements of several types of quenched and tempered, high-strength, headed bolts for use in structural joints. See Table 2 for a list of properties by bolt diameter. ASTM A325 specifically states that bolts for general applications, including anchor bolts, are covered by ASTM A449, Quenched and Tempered Steel Bolts and Studs. Nonetheless, A325 bolts may be used for high-strength anchor bolts if the designer so chooses. It should be noted, however, that high-strength headed bolts are extremely difficult to fabricate in lengths greater than 4 - 5 feet. If greater lengths are required, a headed bolt such as specified in ASTM A325 should not be used.

ASTM A331: Cold-Finished Alloy Steel Bars

Properties Available:		
	Tensile Strength	= 95 - 205 ksi
	Yield Strength	= 75 - 185 ksi
	Brinell Hardness	= 388 - 496

ASTM A331, a member of the A29 "family", covers the chemical requirements for 73 AISI Grade Designations for cold-finished alloy steel bars suitable for heat-treatment, machining into components or in the as-finished condition for constructional pruposes. Except for provisions allowing heat treatment, A331 is nearly identical to ASTM A321, and the same objections to its use for anchor bolt applications apply. The properties listed above were taken from A400. It should be noted, however, that although A400 does refer specifically to ASTM A321, it does not refer at all to ASTM A331.

ASTM A354: Quenched and Tempered Alloy Steel Bolts and Studs with Suitable Nuts

Properties Provided:		
	Tensile Strength	= 105 - 150 ksi
	Yield Strength	= 83 - 125 ksi
	Brinell Hardness	= 217 - 352
	Bolt Diameters	= 1/4" - 4" inclusive

ASTM A354 covers the chemical and mechanical requirements for quenched and tempered alloy steel studs and headed bolts for three levels or grades of strength (see Table 2). Grade BD provides the highest strengths and is the most commonly available. ASTM A354 defines suitable nuts as Grades 2 and 2H of ASTM 194, Carbon and Alloy Steel Nuts for Bolts for High Pressure and High Temperature Service. ASTM A193 cites this Specification as suitable for alloy bolting materials for use at the lower range of high temperature service. Because of the high strengths provided, ASTM A354 is suitable for high strength anchor bolt applications.

ASTM A400: Recommended Practice for the Selection of Steel Bar Compositions According to Section

ASTM A400 provides a means of selecting AISI Grade Designations according to desired tensile and yield strength, bar diameter, and severity of service condition. It provides three levels of service conditions, yield strength ranges from 30 ksi to 185 ksi, and diameters 3-1/2" and under; over 150 carbon and alloy steel AISI Grade Designations are listed. A400 is not a procurement specification. Once a particular AISI Grade has been chosen, the designer or the purchaser must cite ASTM A108, A306, A311, or A322 (Appendix B provides the information necessary to find which specification or specifications cover a particular AISI Grade). In general, since AISI 4140 (see discussion under ASTM A322) is the most common alloy steel available and can, with the proper heat treatment, reach the highest levels of strength listed in the A400 Selection Tables, it is not necessary to use ASTM A400 to select high-strength anchor bolt materials.

ASTM A434: Quenched and Tempered Alloy Steel Bars, Hot-Rolled or Cold-Finished

Properties Available:		
	Tensile Strength	= 90-155 ksi
	Yield Strength	= 65-130 ksi
	Elongation in 2"	= 14-30%
	Reduction in Area	= 35-50%
	Bar Diameters	= 9-1/2" and under

ASTM A434, a member of the A29 "family", covers three classes of hot-rolled and two classes of cold-finished, quenched and tempered alloy steel bars. Grade BD provides the highest levels of strength (see Table 2) and is available hot-rolled or cold-finished. The specification provides good quality control and high strengths. However, contacts with the steel industry indicate that this material is virtually unavailable. Therefore, ASTM A434 is not recommended for high-strength anchor bolt applications.

ASTM A449: Quenched and Tempered Steel Bolts and Studs

Properties Provided:		
	Tensile Strength	= 90 - 120 ksi
	Yield Strength	= 58 - 92 ksi
	Elongation in 2"	= 14%
	Reduction in Area	= 35%
	Brinell Hardness	= 183 - 302
	Bolt Diameters	= 1/4" - 3" inclusive

ASTM A449 covers the mechanical and chemical requirements for quenched and tempered steel bolts and studs for general applications where high strength is required (see Table 2 for a list of mechanical properties by diameters). It can be considered a generalized version of ASTM A325, which cites A449 for use in specifying anchor bolt materials. ASTM A449 can be considered suitable for high-strength anchor bolt applications; it is particularly useful where strengths equal to those provided by A325 bolts are desired, but the lengths required are too great to permit easy fabrication of a headed bolt.

ASTM A458: Hot-Worked, Hot-Cold-Worked, Cold-Worked Alloy Steel Bars for High Strengths at Elevated Temperatures

Properties Provided:		
	Tensile Strength	= 95 - 120 ksi
	Yield Strength	= 45 - 90 ksi
	Elongation in 4Xdiam.	= 18 - 20%
	Reduction in Area	= 30 - 35%
	Brinell Hardness	= 255 - 321
	Bar Diameters	= 8" and under

ASTM A458 covers the chemical and mechanical requirements of Grade 651 hot/cold rolled high strength alloy steel bars for use at elevated temperatures. The material is available under two classes or conditions - Condition B represents a lower degree of cold work, and, consequently, a lower strength level than Condition A, and is intended for very long-term applications. Considering that this specification covers one specific steel grade for which little information is presently available and that similar strength levels are available under other specifications (such as ASTM A193, Grade BD), ASTM A458 is not recommended for high-strength anchor bolt applications.

ASTM A490: Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints

Properties Provided:		
	Tensile Strength	= 150 - 170 ksi
	Yield Strength	= 130 ksi
	Elongation in 2"	= 14%
	Reduction in Area	= 40%
	Bolt Diameters	= 1/2" - 1-1/2" inclusive

ASTM A490 covers the chemical and mechanical requirements for quenched and tempered high-strength alloy steel headed bolts intended for use in structural joints; it defines suitable nuts as ASTM A194 Grade 2H nuts. The high strengths (see Table 2) available under ASTM A490 make it well suited for high strength anchor bolts. Like ASTM A325, however, A490 is subject to length limitations, and should be considered unavailable in lengths greater than four feet.

ASTM A540: Alloy Steel Bolting Materials for Special Applications

Properties Provided:	Tensile Strength	= 115 - 165 ksi
	Yield Strength	= 100 - 150 ksi
	Elongation in 2"	= 10 - 15%
	Reduction in Area	= 35 - 50%
	Brinell Hardness	= 248 - 444
	Bar Diameters	= 9-1/2" and under

ASTM A540 covers the chemical and physical requirements for regular and special quality alloy steel rolled or forged bars to be machined into bolts, studs, washers, and nuts which may be used for nuclear and other special applications. ASTM A540 provides a high degree of metallurgical quality control, and also includes provisions concerning impact properties. Seven optional supplementary requirements are provided if special quality is desired. Unfortunately, no information on the cost or the availability of material under A540 is available; fabricators contacted were totally unfamiliar with this specification. ASTM A540 is not recommended for general use in high-strength anchor bolt applications. It is recommended, however, that A540 be considered for possible use in special situations where very high-strength and rigid quality control are required.

ASTM A575: Merchant Quality Hot-Rolled Carbon Steel Bars

Properties Available:	Tensile Strength	= 44 - 80 ksi
	Yield Strength	= 24.5 - 44 ksi
	Elongation in 2"	= 16 - 30%
	Reduction in Area	= 40 - 55%
	Brinell Hardness	= 86 - 163
	Bar Diameters	= 3" and under

ASTM A575, a member of the A29 "family", covers 9 AISI Grade Designations for hot-rolled merchant quality carbon steel bars intended for structural and miscellaneous bar applications involving moderate cold bending, hot forming, and welding as used in the production of noncritical parts. No specific properties were defined by the Specification itself; the properties listed above were obtained from the SAE Handbook of Metals. Due to the low strengths available, ASTM A575 is not recommended for high-strength anchor bolt applications

ASTM A576: Special Quality Hot-Rolled Carbon Steel Bars

Properties Available:	Tensile Strength	= 44 - 122 ksi
	Yield Strength	= 24.5 - 67 ksi
	Elongation in 2"	= 10 - 30%
	Reduction in Area	= 25 - 55%
	Brinell Hardness	= 86 - 248

ASTM A576, a member of the A29 "family", covers 67 AISI Grade Designations for hot-rolled special quality carbon steel bars suitable for forging, heat treating, cold drawing, machining, and many structural applications. No specific properties or bar diameter ranges are provided (for hot-rolled bars, ASTM A29 specifies 7/16" and larger bar diameters); the properties listed above were obtained from the SAE Handbook of Metals. Due to the low strengths available, ASTM A576 is not recommended for high-strength anchor bolt applications.

A P P E N D I X B

AISI GRADE DESIGNATIONS

An AISI Grade Designation is a numerical code used to define within certain limits the chemical composition of a steel. Table B1 summarizes the basic code. The first number shows the type of steel - "1" signifies a carbon steel, "2" a nickel steel, etc. The second number usually defines an alloying element or alloy combination, and sometimes shows the approximate percentage of the major alloying element. The last two or three numbers usually designate the approximate carbon content in hundredths of 1 percent. Thus, AISI 4140 indicates a chromium-molybdenum steel with about 0.75 percent chromium, 0.20 percent molybdenum, and 0.40 percent carbon. It should be noted that AISI Grade Designations conform with SAE grade designations.

Although the AISI Grade Designation approach to specifying high-strength anchor bolt materials is not considered particularly advantageous, it may, at times, be necessary for the designer to be familiar with the properties of various AISI steel grades. Table B2 lists the properties of 70 carbon steel AISI Grade Designations, and the corresponding ASTM Specifications in which these grade designations are cited. The information in Table B2 was taken from the 1973 SAE Handbook of Metals. Appropriate heat-treating will develop higher strengths.

It is not expected that the designer will have to concern himself with carbon steels in the event that the AISI Grade Designation approach must be used. Should a situation arise that requires strengths and/or dimensions unavailable under the more commonly used ASTM Specification, the practical solution would be to specify a heat-treated alloy steel. The main advantage of heat-treated alloy steels over heat-treated carbon steels, as illustrated in Fig. B1, is that an alloy steel is considerably more ductile than a carbon steel heat-treated to the same level of strength, particularly at high tensile strengths.

Possibly the single most significant steel property to be considered in the selection of an alloy steel for heat-treatment is hardenability, which is a measure of the response of the material to heat-treatment. Hardenability controls the depth and distribution of hardness induced by

TABLE B1. BASIC NUMBER SYSTEM FOR AISI GRADE DESIGNATIONS

Series Number	Type Steel	Series Number	Type Steel
10xx 11xx 12xx 15xx	Carbon Steels	46xx 48xx	Nickel-Molybdenum Steels
13xx	Manganese Steels	50xx 51xx 501xx 511xx 521xx	Chromium Steels
23xx 25xx	Nickel Steels	61xx	Chromium-Vanadium Steels
31xx 32xx 33xx 34xx	Nickel-Chromium Steels	71xx 72xx	Tungsten-Chromium Steels
40xx 44xx	Molybdenum Steels	92xx	Silicon-Manganese Steels
41xx	Chromium-Molybdenum Steels	9xx	Low-Alloy High-Tensile Steels
43xx 43BVxx 47xx 81xx 86xx 87xx 88xx 93xx 94xx 97xx 98xx	Nickel-Chromium-Molybdenum Steels	302xx 303xx 514xx 515xx	Stainless Steels
		xxBxx	Boron Intensified Steels (B denotes Boron Steel)
		xxLxx	Leaded Steels (L denotes Leaded Steel)

TABLE B2. ESTIMATED MINIMUM MECHANICAL PROPERTIES OF CARBON STEEL BARS BY AISI GRADE DESIGNATIONS

AISI Grade	Process[1]	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2", %	Reduction in Area, %	Brinell Hardness	Average[2] Machin-ability	ASTM Specifi-cation
1008	CD	49	41.5	20	45	95	55	A108
	HR	44	24.5	30	55	86		A575, A576
1010	CD	53	44	20	40	105	55	A108
	HR	47	26	28	50	95		A575, A576
1012	HR	48	26.5	28	50	95		A575, A576
1015	CD	56	47	18	40	111	60	A108
	HR	50	27.5	28	50	101		A575, A576
1016	CD	61	51	18	40	121	70	A108
	HR	55	30	25	50	111		A576
1017	HR	53	29	26	50	105		A575, A576
1018	CD	64	54	15	40	126	70	A108
	HR	58	32	25	50	116		A576
1019	HR	59	32.5	25	50	116		A576
1020	CD	61	51	15	40	121	65	A108
	HR	55	30	25	50	111		A575, A576
1021	HR	61	33	24	48	116		A576
1022	CD	69	58	15	40	137	70	A108
	HR	62	34	23	47	121		A576
1023	HR	56	31	25	50	111		A575, A576
1024	HR	74	41	20	42	149		A576
1025	CD	64	54	15	40	126	65	A108
	HR	58	32	25	50	116		A575, A576
1026	HR	64	35	24	49	126		A576
1027	HR	75	41	18	40	149		A576
1028	HR							A576
1029	HR							A576
1030	CD	76	64	12	35	149	70	A108
	HR	68	37.5	20	42	137		A576
1035	CD	80	67	12	35	163	65	A108
	HR	72	39.5	18	40	143		A576

(continued)

TABLE B2 (Continued)

AISI Grade	Process[1]	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2", %	Reduction in Area, %	Brinell Hardness	Average[2] Machin-ability	ASTM Specifi-cation
1036	HR	83	45.5	16	40	163		A576
1037	HR	74	40.5	18	40	143		A576
1038	HR	75	41	18	40	149		A576
1039	HR	79	43.5	16	40	156		A576
1040	CD	85	71	12	35	170		A108
	HR	76	42	18	40	149		A576
1041	HR	92	51	15	40	187		A576
1042	HR	80	44	16	40	163		A576
1043	HR	82	45	16	40	163		A576
1044	HR	80	44	16	40	163		A575, A576
1045	CD	91	77	12	35	179	55	A108
	HR	82	45	16	40	163		A576
1046	HR	85	47	15	40	170		A576
1048	HR	96	53	14	33	197		A576
1049	HR	87	48	15	35	179		A576
1050	CD	100	84	10	30	197	45	A108
	HR	90	49.5	15	35	179		A576
1051	HR							A576
1052	HR	108	59.5	12	30	217		A576
1053	HR							A576
1055	HR	94	51.5	12	30	192		A576
1066	HR	98	54	12	30	201		A576
1070	HR	102	56	12	30	212		A576
1078	HR	100	55	12	30	207		A576
1080	HR	112	61.5	10	25	229		A576
1084	HR	119	65.5	10	25	241		A576
1090	HR	122	67	10	25	248		A576
1095	SACD	99	76	10	40	197	45	A108
	HR	120	66	10	25	248		A576
1109	HR	50	27.5	30	50	101		A576

(continued)

TABLE B2 (Continued)

AISI Grade	Process[1]	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2", %	Reduction in Area, %	Brinell Hardness	Average[2] Machin-ability	ASTM Specifi-cation
1110	HR							A576
1115	CD	61	51	20	40	121	80	A108
1116	HR							A576
1117	CD	69	58	15	40	137	90	A108
	HR	62	34	23	47	121		A576
1118	CD	72	61	15	40	143	85	A108
	HR	65	36	23	47	131		A576
1119	HR	62	34	23	47	121		A576
1132	HR	83	45.5	16	40	167		A576
1137	CD	98	82	10	30	197	70	A108
	SRACD	95	75	15	40			A311
	HR	88	48	15	35	179		A576
1139	HR							A576
1140	HR	79	43.5	16	40	156		A576
1141	CD	105	88	10	30	212	70	A108
	SRACD	100	80	12	40			A311
	HR	94	51.5	15	35	187		A576
1144	CD	108	90	10	30	217	80	A108
	SRACD	100	80	12	40			A311
	HR	97	53	15	35	197		A576
1145	HR	85	47	15	40	170		A576
1146	HR	85	47	15	40	170		A576
1151	CD	102	86	10	30	207	65	A108
	SRACD	100	80	10	35			A311
	HR	92	50.5	15	35	187		A576
1211	CD&HR							A108, A576
1212	CD&HR							A108, A576
1213	CD&HR							A108, A576

(continued)

TABLE B2 (Continued)

AISI Grade	Process[1]	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2", %	Reduction in Area, %	Brinell Hardness	Average[2] Machin-ability	ASTM Specifi-cation
12L14	CD							A108
	HR	57	34	22	45	121		A576
1215	HR							A576
B1010	CD							A108
B1111	CD&HR							A108, A576
B1112	CD&HR							A108, A576
B1113	CD&HR							A108, A576

(1) Process: HR = Hot-Rolled; CD = Cold-Drawn; SACD = Spheroidize Annealed Cold-Drawn; SRACD = Stress Relief Annealed Cold-Drawn

(2) Average Machinability: Cold-Drawn 1112 Steel = 100%

Mechanical properties shown above are for general information only; they are typical of bars with diameters between 3/4" and 1/4". The properties of cold-drawn steels will vary with different cold-drawing procedures, or with a combination of cold-drawing and heat treatment for grades 1050 and lower. Grades with higher carbon content than 1050 are often annealed before cold-drawing.

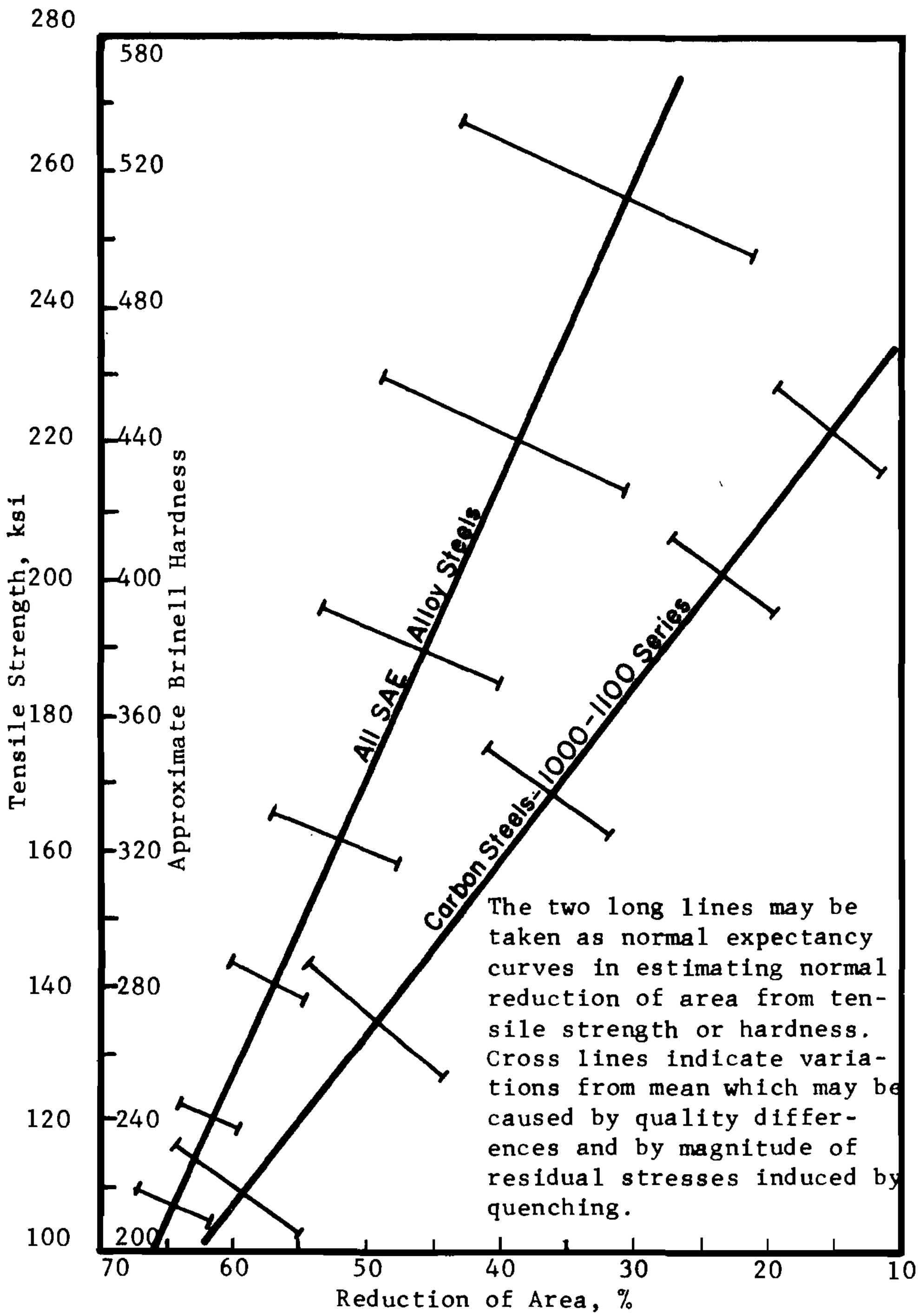

Fig. B1. Relationship between Brinell Hardness and reduction of area. (From SAE Handbook of Metals.)

quenching. The higher the hardenability, the deeper and more evenly distributed is the hardness. The process of hardening involves a transformation of the grain structure of the steel to a harder form. This transformation is caused by heating the steel to a suitable temperature and then cooling, or quenching, at a certain minimum rate. The proper minimum rate of quenching is a function of the alloy content of the steel. The more thorough the quenching, the more complete the transformation.

The maximum obtainable hardness of a steel quenched at the appropriate minimum cooling rate is a function of carbon content only. The thoroughness of quenching determines how closely the hardness of the steel approaches maximum obtainable value. Mechanical properties such as yield strength and toughness are also a function of the completeness of quenching. If a steel is quenched such that the transformation is at least 90 percent complete, and is then properly tempered, it can be assumed that the hardness of the steel is a reasonable measure of its mechanical properties.

The concept that steels of the same hardness, after quenching and tempering, have approximately the same mechanical properties regardless of chemical composition is shown in Figs. B1, B2, and B3, which are taken from the 1973 SAE Handbook of Metals. The figures represent a summary of information from mechanical property charts published by steel manufacturers and suppliers. Given a required strength and level of ductility, the designer can use Figs. B1, B2, and B3 to determine an approximate Brinell hardness. The fabricator can then determine the necessary tempering temperature. The main task of the designer is to choose a steel with the proper hardenability characteristics to ensure that the section can be completely quenched.

ASTM A322 and ASTM A331 list 73 alloy steel AISI Grade Designations. These are only a fraction of the total number of AISI Grade Designations and do not even involve all the types covered in Table B1. In selecting a steel for heat-treatment it would not be feasible to examine hardenability data for all the grade designations listed under ASTM A322 and A331. It is sufficient to know that two AISI Grade Designations, AISI 4140 - a medium-hardenability steel, and AISI 4340 - a high-hardenability steel, are among

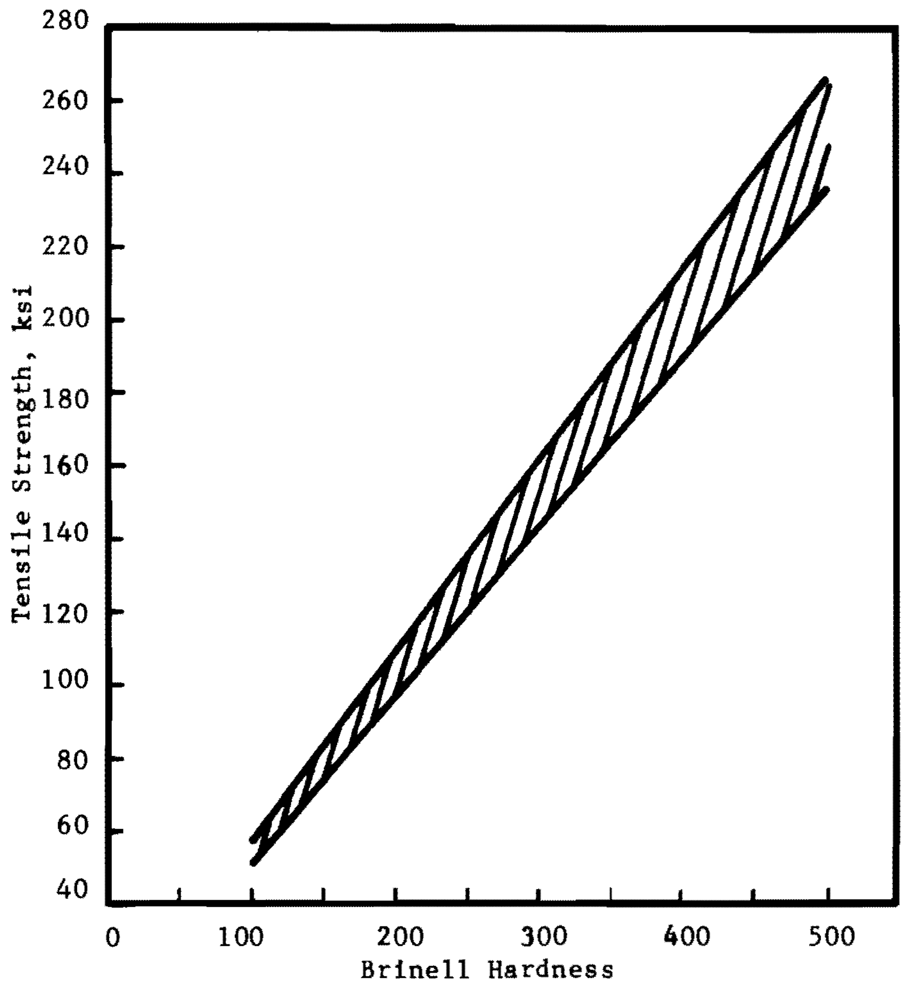

Fig. B2. Relationship between Brinell Hardness and tensile strength. (From SAE Handbook of Metals.)

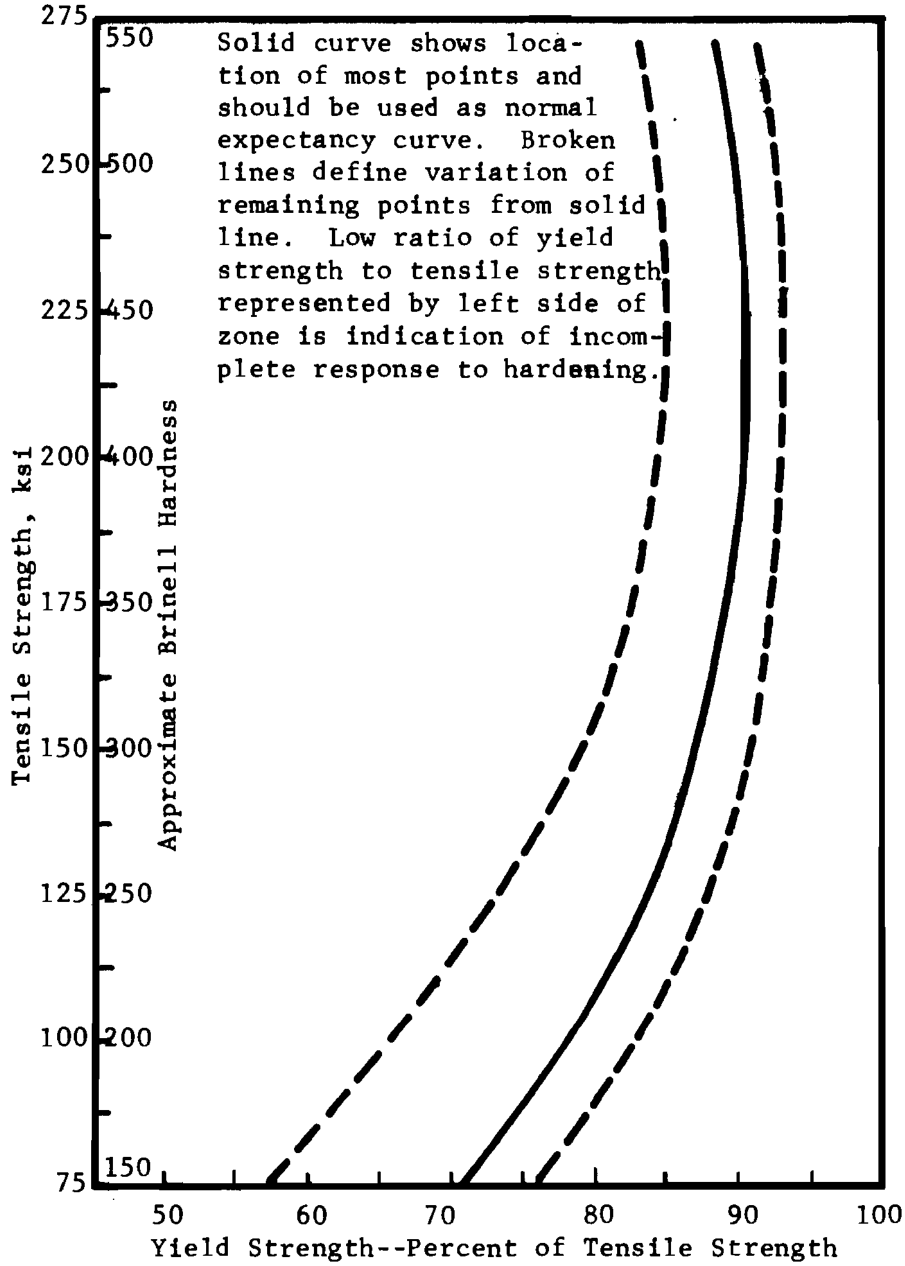

Fig. B3. Relationship between Brinell Hardness and Yield Strength. (From <u>SAE Handbook of Metals</u>.)

the most common alloy steels made and can be heat-treated to very high strength levels.

As an example in specifying heat-treated alloy steel for high strength anchor bolts, suppose a yield strength of 180 ksi is required. From Fig. B3, a tensile strength of approximately 200 ksi corresponds to a yield strength (0.9 x 200) of 180 ksi. An approximate Brinell hardness of 400 is indicated. From Fig. B1, an approximate Brinell hardness of 400 indicates a reduction of area of about 44 percent. Reduction in area can be considered a measure of ductility. Note that for most of the material listed in Table 2 the reduction in area ranges from 35 to 50 percent and the corresponding elongation in 2 in. ranges from 10 to 18 percent. An approximate Brinell hardness of 480 indicates a reduction of area of about 35 percent, which for purposes of illustration will be designated as a minimum value. For this illustration a typical specification would be as follows:

> AISI Grade 4140, quenched and tempered, minimum tensile strength = 200 ksi, minimum yield strength = 180 ksi, minimum Brinell Hardness = 400, maximum Brinell Hardness = 480.

The minimum hardness serves to specify minimum strength, and the maximum hardness serves to specify minimum ductility. The designer may wish to specify other measures of quality control in addition to standard tensile strength tests.

It should be noted that when AISI 4140 and AISI 4340 are heat-treated to high strength levels, special precautions are necessary to avoid hydrogen embrittlement and to reduce stress concentrations. AISI 4340, which may be heat-treated to extremely high strength levels, is particularly susceptible to embrittlement at such levels. In addition, special measures are usually required during fabrication. Consequently, tensile strengths exceeding 150 ksi are not recommended.