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

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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 a high-strength ($f_y > 50$ ksi) 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.

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.

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. A number of the ASTM Specifications 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.

Of the twenty ASTM Specifications, five appear suitable for high strength anchor bolt applications and are listed in Table 1.

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

Material	1" dia. × 20"			1-1/2" dia. × 30"			1-3/4" dia. × 35"		
	Yield Strength ksi	Relative Cost %	Cost-(2) Strength Ratio	Yield Strength ksi	Relative Cost %	Cost-(2) Strength Ratio	Yield Strength ksi	Relative Cost %	Cost-(2) Strength Ratio
(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) Cost-Strength Ratio $= \dfrac{\text{Relative Cost, \%}}{(\text{Gross Bar Area, in.}^2)(\text{Yield Strength, ksi})} = \text{Cost}/\text{k}$.

(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.

Relative Cost and Availability

It is desirable to compare the specifications shown in Table 1 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.

The data in Table 1 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. 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 1 do not consider quantity ordered, which will influence actual cost considerably.

The cost-strength ratio shown in Table 1 provides an index of cost per kip of load-carrying capacity for a given bolt material and size. In developing the concept of the cost-strength ratio, it was assumed that the allowable tension in a bolt was a fraction of the yield strength, which remained constant for all bolt diameters, lengths, and materials. On this basis, the various materials in Table 1 could be compared using yield strengths.

Examination of Table 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. 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. From comparison of the cost-strength ratios for the five ASTM Specifications suitable for high-strength anchor bolt applications shown in Table 1, it can be seen that the 1-in. diameter bolt with the highest cost-strength 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 1, ASTM A354 and 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 1 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. 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.

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 mechanics 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.

AISI Grade Designations

An AISI Grade Designation is a numerical code used to define within certain limits the chemical composition of a steel. 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. 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 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. 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 and represent only a fraction of the total number of AISI Grade Designations. 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 the most common alloy steels made and can be heat-treated to very high strength levels. 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.

Summary

Based on material costs only, the relative economy of various high-strength anchor bolt materials and bolt sizes was studied. 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.

KEY WORDS: anchor bolts, materials, selection, specifications

The full text of Research Report 29-1 can be obtained from Mr. Phillip L. Wilson, Engineer-Director, Planning & Research Division, File D-10, Texas Highway Department, P.O. Box 5051, Austin, Texas, 78763.