Construction and Building Materials 145 (2017) 292–302

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Stress-strain response of A706 grade 80 reinforcing steel

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## HIGHLIGHTS

- A706 grade 80 use in seismic design is currently restricted.
- 788 tensile tests of A706-80 rebar were conducted.
- Values of five major stress-strain parameters were statistically identified.
- No observable susceptibility to strain aging.

ARTICLE INFO

*Article history:*
Received 27 July 2016
Received in revised form 18 March 2017
Accepted 26 March 2017

*Keywords:*
Seismic
Reinforced concrete
Reinforcing steel
Grade 80

ABSTRACT

Before ASTM A706 grade 80 rebar may be specified in the seismic design of structures, its mechanical properties must be well understood and calibrated on a statistical basis. Based on the results of 788 tensile tests of A706 grade 80 rebar encompassing bar sizes No. 4–No. 18 (approx. metric No. 13–No. 57), five major stress-strain parameters are statistically evaluated and used to develop recommendations for an expected monotonic stress-strain curve. An existing material model is shown to accurately capture the shape of the monotonic stress-strain curve. Additional tests are used to evaluate the strain-aging performance of the steel.



## 1. Introduction

The basic principles of seismic design follow the capacity design philosophy as outlined by Paulay and Priestley [26] that consists of three steps: (1) Locations of inelastic action are chosen; (2) The chosen locations are detailed to sustain the deformation demands expected during the design basis earthquake; and (3) All other elements of the system are protected against inelastic action. In the case of seismic design of reinforced concrete bridges, locations of inelastic action occur in the columns, while all other actions in the column (i.e. shear), and all other elements in the bridge (i.e., footing, cap-beams, joints, superstructure) are protected against failure. This role is switched in the case of reinforced concrete frames such that the columns are designed to remain elastic while the beams dissipate energy though plastic hinge formation. In all cases, it is the reinforcing steel that acts as the critical link between a ductile response and a brittle failure. As a result, for seismic applications, it is essential that reinforcing steel exhibit sufficient inelastic strain capacity and strain hardening such that plasticity is spread over a sufficiently long length. Furthermore, strength properties should be tightly controlled to ensure efficiency in design by limiting the overstrength factor for the design of capacity protected members and actions.

In regions where high seismicity requires large quantities of longitudinal and transverse reinforcing steel to ensure adequate ductility, congestion at joints is a major problem. The use of high strength reinforcing steel in these cases offers a potential solution to this problem; however, one of the concerns associated with the use of high strength rebar in seismic design is the general trend that as the strength of the steel increases, its maximum elongation capacity reduces, a trend which could undermine its potential benefits. As such, numerical test data must be available to validate its use.

As of the writing of this paper, ASTM A615 and ASTM A706 represent the most typical reinforcing steel designations in the Unites States. A615 reinforcement exhibits more loosely controlled material properties [7] making it an undesirable choice in the context of seismic design. However, A706 specifications contain minimum and maximum yield strength limits, as well as larger requirements for elongations while also meeting chemical composition requirements which enable the steel to be weldable [8]. Because of these

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http://dx.doi.org/10.1016/j.conbuildmat.2017.03.200
0950-0618/

properties, A706 steel is routinely specified in high seismic regions, especially for members expected to form plastic hinges.

Prior to December 2009, the only grade of reinforcing steel available in the A706 specification was grade 60. Since that time, ASTM has included requirements for 80 ksi (550 MPa) steel (A706 grade 80) in the A706 specification. The grade designation denotes the minimum allowable yield strength of the steel.

It should be noted that grade requirements are specified in terms of a minimum allowable value. As a consequence, actual reinforcing steel strengths are typically higher than their specified values since producing mills must maintain an average strength that is above the minimum. The resulting material overstrength must be accounted for in seismic design practice such that the possible failure of capacity protected members due to higher than anticipated moment demands is avoided. In the absence of actual data, conservative estimates of material overstrength may be used, however, this may lead to inefficient design that not only complicates construction, but increases cost.

### 1.1. Summary of prior research

Likely owing to the relatively recent addition of grade 80 rebar to the ASTM A706 specification, there is an overall lack of experimental data available in the published literature. This is compounded by the limited production of A706 grade 80 reinforcing steel as mills are hesitant to produce steel that is currently in limited use, and users are reluctant to specify the material given the limited test data available. As of the writing of this paper, five reports [29,34,21,33,9] were found to either directly reference or include material test results associated with A706 grade 80 rebar. As several of the reports were written regarding the same data, the available A706 grade 80 stress-strain data is limited to two datasets consisting of twelve tensile tests and the accompanying stress-strain curves. The available experimental data is further limited in that only a few bar sizes have been considered and that strains were generally not provided to accompany the included yield and tensile strength data. A short summary of the past research is included below, however, the interested reader is referred to Overby et al. [24] and Overby [25] for a more thorough discussion of past research. Table 1 presents the results from the twelve tests.

Rautenberg et al. [29] presented the findings of a study on the applicability of high strength reinforcement in reinforced concrete columns resisting lateral earthquake loads. Their research, which was based on testing conducted as part of Rautenberg's PhD dissertation at Purdue in 2011 [28], aimed to evaluate the 60 ksi (414 MPa) limit imposed by the American Concrete Institute (ACI) on the yield strength of rebar used in regions expected to form plastic hinges [3]. They evaluated 8 columns constructed from either ASTM A706 grade 60, A706 grade 80, or A1035 grade 120 longitudinal reinforcement. They conducted tensile tests on three No. 7 A706 grade 80 bars for the purpose of calibrating numerical models, with the data available on the NEES website [20]. Data from the Rautenberg study was also shown in a later report by Wiss et al. [34].

The second dataset first appeared in a report by Trejo et al. [33] as part of a study on the seismic performance of 24-inch (610 mm) diameter circular reinforced concrete bridge columns constructed with A706 grade 80 reinforcement. A total of six of these half-scale columns were constructed and tested using either No. 5 or No. 6 longitudinal reinforcement, No. 3 transverse reinforcement, and either A706 grade 60 or A706 grade 80 steel. Three tensile tests were conducted for each bar size and the results presented in their paper. This study proved to be the most informative for comparison purposes at it included both stress and strain data. The same results appeared in a later paper by the same authors [9].

### 1.2. Code limitations

The overall lack of experimental data on A706 grade 80 rebar in the literature is reflected in the hesitancy of design codes to allow its use in regions expected to form plastic hinges. In some cases, the use of A706 grade 80 reinforcement is directly restricted while in others it is passively restricted by setting upper limits on yield strength that are below 80 ksi (550 MPa). A brief summary of the guidelines (or lack thereof) for use of A706 grade 80 steel in design codes is presented below. More detailed summaries may be found elsewhere as well as in several of the reports already mentioned [14,34,21,33].

ACI 318-14 Section 20.2.2 limits deformed reinforcement used in special seismic systems to be of grade 60 or lower "because of insufficient data to confirm applicability of existing code provisions for structures using the higher grade [A706 grade 80]" [4]. However, the commentary to Section 18.2.6 makes provision for higher grades where sufficient test data is available to support their use: "Section 18.2.1.7 permits alternative material such as ASTM A706 Grade 80 if results of tests and analytical studies are presented in support of its use" [4].

Section 3.2.1 of the Caltrans SDC 1.7 states that the "capacity of concrete components to resist all seismic demands except shear, shall be based on most probable (expected) material properties to provide a more realistic estimate for design strength" [11]. While the code offers recommendations for the expected stress-strain properties of ASTM A706 grade 60 rebar, the use of ASTM A706 grade 80 reinforcing steel is not directly addressed.

Based on research by Shahrooz et al. [32], the AASHTO LRFD Bridge Design Specification [2] permits the use of reinforcing steel with specified minimum yield strength of up to 100 ksi (690 MPa) for all elements and connections in Seismic Zone 1 where permitted by specific articles. Section C5.4.3.3 states that "Reinforcing steels with a minimum specified yield strength between 75.0 and 100 ksi may be used in seismic applications, with the Owner's

**Table 1**
Summary of literature test data (1 ksi = 6.9 MPa).

| Reference | Bar Size | No. of Tests | Yield Point (0.2% offset) | | Yield Point (0.0035 EUL) | | Onset of Strain Harding | | Tensile Strength | | Ultimate Strain | | Elong.% in 8 inch |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Stress, ksi | Strain, in/in | Stress, ksi | Strain, in/in | Stress, ksi | Strain, in/in | Stress, ksi | Strain, in/in | Stress, ksi | Strain, in/in | |
| Rautenberg et al. [29] | 7 | 1 | 83 | – | – | – | – | – | 119 | – | – | – | 11.7 |
| | 7 | 1 | 83 | – | – | – | – | – | 117 | – | – | – | 15.6 |
| | 7 | 1 | 84 | – | – | – | – | – | 118 | – | – | – | 14.8 |
| Trejo et al. [33] | 3 | 3 | 85.6 | 0.0055 | 73.3 | 0.0035 | N.A. | N.A. | 120.5 | 0.0947 | 85.2 | 0.1378 | 13 |
| | 4 | 3 | 86.2 | 0.0051 | 85.4 | 0.0035 | 85.9 | 0.0084 | 114.3 | 0.1066 | 86.8 | 0.1555 | 14 |
| | 5 | 3 | 86.1 | 0.0048 | 84.3 | 0.0035 | 85.5 | 0.0098 | 114.0 | 0.1225 | 93.9 | 0.1893 | 15 |