2.3 Does your state publish its own bridge evaluation manual?

Yes ☐ No ☐

2.4 If you responded 'Yes' to 2.3, is the rating process for concrete bridges with no plans addressed in this manual? Please attach (or provide links to) any applicable material with your survey responses.

Yes ☐ No ☐

2.5 Does your approach to rating concrete bridges with no plans follow the procedures recommended in the Manual for Bridge Evaluation (MBE)?

Yes ☐ No ☐

2.6 Do you use any specific technologies to aid in the process of rating concrete bridges with no plans?

Yes ☐ No ☐

2.7 If you responded 'Yes' to 2.6, what specific technologies have you used, and what information has this provided? How is this information used in the load rating process?

2.8 Please provide any additional information related to your methods for rating concrete bridges you feel would be beneficial for us as we look into this issue.

2.9 Please list any relevant documentation you have attached to this survey to supplement your responses.

3: Quantifying Scope of this Issue:

3.1 How many bridges exist in your state for which you have no plans?:

3.2 Provide the quantity of no-plan bridges in each of the following categories:

Rolled steel girders:

Built-up (welded/riveted/ bolted) steel plate girders:

Railroad flatcar structures:

Other steel structures:

Timber structures:

Reinforced concrete girders:

Prestressed concrete girders:

Reinforced concrete culverts:

Reinforced concrete slabs:

Other concrete structures (please specify):

Other concrete structures (please specify):

Other (please specify):

3.3. Are all of these bridges currently load rated? If no, are they in the process of being load rated?

3.4. Are Special Haul Vehicle postings currently required for any rated bridges in your state? If so, explain the sign(s) you are using for posting and if they are used in conjunction with any MUTCD signs such as R12-1 or R12-5.

3.5 In your state, who is responsible for rating bridges owned by counties/localities?:

3.6 Has your state ever been required to develop a Plan of Corrective Action for bridge load rating?

Yes ☐ No ☐

3.7 If you responded 'Yes' to 3.6, did this include bridges for which you had no plans?

Yes ☐ No ☐

3.8 Has your FHWA Division Bridge Engineer approved or disallowed specific methods for load rating bridges with no plans?

Yes ☐ No ☐

3.9 If you responded 'Yes' to question 3.8, what methods were approved? What methods were disallowed?

3.10 Has your FHWA Division Bridge Engineer ever requested additional information regarding the rating of bridges with no plans?

Yes ☐ No ☐

3.11 If you responded 'Yes' to question 3.10, what additional information was required? How did you approach this situation?

3.12 Please provide any additional information you feel would be beneficial for us as we look into this issue.

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# Estimation of Steel Rebar Strength in Existing Concrete Bridges

Alessandro P. Fantilli and Bernardino Chiaia

**Synopsis**: To design a retrofit and/or maintenance protocol for existing reinforced concrete bridges, the assessment of rebar steel strength is generally required. The current methodology consists of uniaxial tensile tests performed on bar segments extracted from a structural element. Nevertheless, in several situations (e.g., the assessment of bridges in service), this traditional method cannot be used. Hence, a new simplified approach is introduced herein. It consists of the so-called "strength-for-age curves," which relate the average strength of steel to the year of construction. Such curves are statistically computed from a database stored in the Department of Structural and Geotechnical Engineering of Politecnico di Torino (Italy). As a result, the yield and tensile strength values experimentally measured from rebar in two existing bridges in Northern Italy, built in 1930 and 1975, respectively, were correctly predicted using the proposed model.

**Keywords:** reinforced concrete, existing bridges, tensile strength, yield strength, steel reinforcing bar, strength-for-age curves, uniaxial tensile test

## INTRODUCTION

Although the recent failure of the Morandi Bridge has scared Genoa and set off a huge debate on the reasons of such a disaster [1], bridges frequently collapse in Italy, as in the rest of the world [2]. For instance, Wardhana and Hadipriono [3] has investigated more than 500 failures of bridge structures that occurred in the United States between 1989 and 2000, whereas the database of 1254 bridges, failed from 1980 to 2012 in different Countries, has been studied by Lee et al. [4].

As collapse during a bridge's service life might be ascribed to several potential causes; safety assessment of existing bridges and prediction of their load bearing capacity are essential activities [5]. In this context, field-tests are largely used, especially in reinforced concrete (RC) bridges, when material properties are unknown and analytical/numerical methods cannot be applied. As the mechanical responses of both concrete and steel rebar are frequently uncertain, the AASHTO Manual for Bridge Evaluation [6] provides the minimum compressive strength of concrete and the yield strength of rebar as well, depending on the year of construction. Obviously, the theoretical evaluation of load capacity of RC bridges tends to be conservative, if it is computed according to this estimation. Thus, a more accurate assessment of the material properties is desirable.

In the case of structural concrete, the compressive strength can be better evaluated by means of the strength-for-age curves proposed by Fantilli et al. [7]. The strength-for-age curves were based on the data stored in the historical database situated in the Department of Structural, Building and Geotechnical Engineering (DISEG) of Politecnico di Torino, and they were effectively used to assess the seismic vulnerability of small dams [8]. Similar curves do not exist for the steel rebar, even if some researchers report the main properties, and their evolution with time, of the reinforcing bars used in Italy from 1950 to 1980 [9, 10].

The introduction of the strength-for-age curves is more urgent for rebar than for concrete. Indeed, the mechanical properties of steel, included in the existing RC structures and infrastructures, cannot be measured through nondestructive tests. On the other hand, the traditional destructive tests cannot be performed, because the bridge is usually in service. Moreover, such tests can permanently damage the RC structure because it is practically impossible to re-establish the continuity of the reinforcement after the extraction of a piece of rebar.

## RESEARCH SIGNIFICANCE

Different approaches can be used to rate the performance of existing reinforced concrete bridges. The theoretical calculations, for instance, evaluate the load bearing capacity of a specific bridge based on the mechanical response of steel and concrete. Nevertheless, the properties of old materials are frequently unknown and, especially for the steel reinforcement, cannot be easily measured on site. On the other hand, models capable of estimating the mechanical properties of existing rebar are very scarce in the technical literature. Thus, the authors believe that the current study, dealing with the definition of the strength-for-age curves of the most common Italian rebar, can be effectively used to assess safety of existing RC bridges.

## THE HISTORICAL DATABASE AT POLITECNICO DI TORINO

Since its foundation in 1906, the laboratory of Politecnico di Torino has certified the mechanical performances of structural materials. Among them, several steel reinforcing bars of RC structures have been tested and certified with the purpose of quality control and material acceptance. Figure 1 shows a typical certificate issued in 1965, including a series of seven uniaxial tensile tests on steel rebar of different diameters. Such certificates generally show the:

- certificate number
- name of the client/contractor
- name of construction site
- steel producer
- sequential number of the letter
- diameters of rebar
- effective area of the cross-sections
- yield strength in terms of load and stress
- load and stress at failure

- elongation at failure
- date on which the certificate was released
- signatures of the technician and of the laboratory director.

In some certificates, the type of steel is also indicated. The main mechanical properties of the steel have changed during the last century, as revealed by the Italian construction codes [11, 12, 13, 14, 15]. In particular, the tensile and the yield strength, as defined by the Italian code rules, are summarized in Table 1. The strengths have been measured by means of uniaxial tests performed in accordance with standards similar to those given by the current EN ISO 15630-1 [16]. It is worth nothing that, similar to the compressive strength of concrete [7], the yield strength of the required steel has also increased over the years.

## ANALYSIS OF THE DATA

The results of 17080 uniaxial tensile tests, performed in about one century (i.e., from 1908 to 2005), have been extracted from the database. The aim is to use these data to define the tensile and yield strength of rebar by year of construction, similar to the strength-for-age curves already introduced for concrete [7]. However, the mechanical response of the steel used to reinforce the concrete structures can show a large variation. This is due to both the type of steel and the diameter of the rebar.

Table 1 shows the properties of the most common steels, whereas Figure 2a illustrates their percentage of use in six different years (comprised between 1908 and 2005). It is possible to observe a large difference in tensile and yield strength of the rebar used in the same year. For instance, in 1975, 50% of rebar were made with the steel FeB32 and 50% with the steel FeB44, the latter having a yield strength 37% larger (Table 1). Similarly, the average tensile strength of the steel rebar Aq.42 and that of Aq.60, as measured at the Politecnico di Torino in the years 1943-1960, are compared in Figure 2b; a large difference of strength (about 40%) is also evident for these two types of steel.

Regarding the geometry of rebar, the histogram depicted in Figure 3a shows the probability density of the bar diameter of the tests taken into consideration. In the years comprised between the 1939 and 1960, the average strength of the most used diameter (i.e., 10 mm = 0.39 in.) is larger than that of the rebar having a diameter equal to 20 mm (0.79 in.). As illustrated in Figure 3b, the difference between the two diameters was 250 MPa (36.2 ksi) in the year 1949, even if it tends to reduce at the end of the 1950's.

## PREDICTION MODELS

According to the previous observations, a model capable of predicting the strength of rebar should depend not only on the year of construction, but also on the size of the bar diameter and on the type of steel. As the last two independent variables are not always known, two different approaches can be followed to define prediction models.

Approach #1: the year of construction is the only independent variable
In this case, the strength-for-age curves, similar to those of concrete [7], can be introduced. However, the strength of rebar can be evaluated through a weighted average of the steel types used in a specific year of construction. In other words, the value of the strength is calculated with the following formula:

$$f_j = \frac{\sum_{i=1}^{n} r_{j,i} \cdot p_{j,i}}{100\%} \tag{1}$$

where, $f_j$ = value of strength (tensile, $f_u$, or at yielding, $f_y$) in the year $j$; $r_{j,i}$ = value of the strength (as computed with data extracted from the database) in the year $j$; $p_{j,i}$ = percentage of the $i^{th}$ type of steel used in the year $j$ (Figure 2a); $n$ = number of the types of steel used in the year $j$.

The values of $f_u$, obtained by applying Eqn. (1) to the results of the 17080 uniaxial tensile tests on rebar in three different situations, are reported in Figure 4a. More precisely, $r_{j,i}$ is not only the average value of the ultimate strength (i.e., the 50$^{th}$ percentile), but also the 5$^{th}$ percentile and 95$^{th}$ percentile of the values are considered herein. Figure 4a also depicts the trend lines of each percentile as the tensile stress at failure increases with the years. In general, the tensile strength-for-age curves are defined by the following equation:

$$f_u = a \cdot year - b \tag{2}$$

where the values of the coefficient $a$ and $b$, depending on the percentile, are reported in Table 2. With respect to Eqn. (2), the tensile strength of the steel rebar of the existing structure shows a large dispersion in the first years of the last century (Figure 4a).

With regard to the yield strength, before 1950, this mechanical property was seldom measured and reported in the certificates stored at Politecnico di Torino. From this year on, 14069 values of $f_y$ have been extracted from the database and treated with Eqn. (1). The results are reported in Figure 4b. As observed for $f_u$, the yield strength of rebar, computed by considering the 5th, 50th, and 95th percentile of the values included in the database, increases with the years. The least square approximation of the test results provides the linear relationship (i.e., the trend line):

$$f_y = c \cdot year - d \tag{3}$$

where the values of the coefficient $c$ and $d$, depending on the percentile, are reported in Table 2.

The values of $f_y$ given by Eqn. (3) are compared, in Figure 5, with those suggested by the AASHTO Manual for Bridge Evaluation [6] in the case of unknown reinforcing steel. Before 1954, the AASHTO Manual provides only one value of yield strength (i.e., $f_y$ = 228 MPa = 33 ksi), regardless of the type of steel and of the year of construction. After 1954, the same manual indicates four values of $f_y$ depending on the type of steel (i.e., Structural Grade, Grade 40, Grade 50 and Grade 60), even if such values remain constant in the following years. Obviously, the approach proposed by the AASHTO Manual for Bridge Evaluation [6] appears more conservative than that proposed herein.

Approach #2: both the year of construction and the bar diameter are independent variables

The diameter of rebar may be known in addition to the year of construction. As a matter of fact, it is easily measured in several cases through nondestructive tests. However, it is impossible to obtain a simple formulation to be used in practical applications, like Eqn. (2) and Eqn. (3), in which the strength of steel rebar is also a function of the bar diameter. On the contrary, by using the strength data of a specific year stored in the database, the probability density of the strength, referred to a single bar diameter, can be computed.

As an example, Figure 6 shows the Gaussian distribution of $f_y$ in the bar with a diameter of 10 mm (0.39 in.), calculated in the years 1955 (Figure 6a) and 2005 (Figure 6b). This strength increases with the years, and the standard deviation tends to become larger as well. The statistical distributions are useful to compute the yielding probability of a steel rebar when a prescribed value of strength is assumed. For instance, if $f_y$ = 345 MPa (50 ksi), as suggested by the AASHTO Manual [6] for steel Grade 50, the probability of yielding is 24% in 1955 (see Figure 6a) and only 1.3% in 2005 (see Figure 6b). In other words, if the same yield strength is used regardless of the year of construction, the probability of material failure is larger in the oldest bridges.

## APPLICATION OF THE MODELS

In the following sections, the models previously described are used to predict the steel strength of two bridges in Northern Italy and two bridges in North America. Due to confidentiality reasons, the name of the Italian bridges and the place where they are located is undisclosed.

Bridge #1 (1930)

Bridge #1 has a plate girder superstructure supported by seven piers, which are composed of columns and horizontal beams (Figure 7). The total length of Bridge #1 is about 100 m (328 ft), whereas the span lengths of the longitudinal girders varies from 9 to 15 m (29.5 to 49.2 ft). All of the RC structural elements, including the foundations, were cast *in-situ* in the year 1930.

Some pieces of the steel reinforcing bars were extracted from the structural elements of Bridge #1 and tested in uniaxial tension, in accordance with EN ISO 15630-1 [16]. In total, the strengths of 11 samples, whose diameters varied from 5 to 30 mm (0.197 to 1.18 in.), were measured. Table 3 shows the values of yield and tensile strength obtained from such tests. The average values of $f_u$ and $f_y$ , and of the corresponding range of variation, are reported in Figure 8, where they are compared with the strength-for-age curves of Eqn. (2) (Figure 8a) and Eqn. (3) (Figure 8b), respectively. The average value of the tensile strength predicted by Eqn. (2) for the steel rebar used in 1930 overestimates the average value experimentally measured in Bridge #1, even if a large number of the test results are within the range bordered by the 5th and 95th percentile lines (Figure 8a). Conversely, the average yield strength of the rebar used to reinforce Bridge #1 is correctly predicted by Eqn. (3), as illustrated in Figure 8b. Figure 8b also shows the lower dispersion of the measured values of $f_y$ (compared to those of $f_u$), and all the experimental data fall within the range defined by Eqn. (3). Accordingly, in the case of old bridges (i.e., built before the Second World War), the number of samples necessary to correctly evaluate the tensile strength ($f_u$) has to be larger than that used for the estimation of $f_y$.

Bridge #2 (1975)

Built in 1975, Bridge #2 also has a plate girder superstructure supported by 12 piers (Figure 9). The longitudinal girders, cast and post-tensioned *in-situ*, have a double-T cross section with a height of 1.50 m (49.2 ft) and a length of 29.70 m (97.4 ft). The longitudinal girders are transversely connected by RC beams and support a RC deck with a height of 200 mm (7.87 in.). Both the beams and the deck were cast-in-place.

A series of uniaxial tensile tests were performed on 15 samples extracted from the structural elements of the bridge. Only rebar, whose diameters varied from 10 to 20 mm (0.394 to 0.787 in.), are investigated herein. The properties of post-tensioned and pre-tensioned tendons will be the object of future studies. Both the tensile and the yield strength of the rebar are reported in Table 4, whereas the average values of $f_u$ and $f_y$, and the corresponding range of variation, are illustrated in Figure 10. Figure 10 also shows the prediction lines of tensile strength (Eqn. (2) in Figure 10a) and yield strength (Eqn. (3) in Figure 10b). The average values of the strength-for-age curves are in good agreement with the experimental data for Bridge #2. In addition, similar to the measurements taken for the rebar of Bridge #1, $f_y$ shows a lower dispersion than $f_u$.

Additional study can be performed on the steel in Bridge #2 because the Politecnico's database allows for the statistical analysis of the steel rebar used in the year 1975; the study specifically focused on rebar with a 16 mm (0.63 in.) diameter. Figure 11 shows the value $f_y$ = 345 MPa (50 ksi), as prescribed by the AASHTO Manual for Bridge Evaluation [6] for Grade 50, which is associated with a percentile of 15% with respect to the Gaussian distribution of the yield stress. On the contrary, the yield stress provided by Eqn. (3) shows a larger percentile (> 50%), but it is lower than that experimentally measured. Thus, the strength-for age curve gives less conservative values of $f_y$, with respect to AASHTO Manual for Bridge Evaluation [6] for Grade 50 rebar, even if they are more conservative than those of the reinforcing bar of Bridge #2.

Two bridges in the United States

To assess the reliability of the proposed model with respect to the rebar used in other countries, the results of tests carried out on two bridges in the United States were taken into consideration. The first was the Franklin Avenue Bridge, built from 1919 to 1923 [17]. This is an open-spandrel, concrete arch bridge located near Minneapolis and St. Paul, MN, crossing over the Mississippi River Valley. Before its retrofit, segments of reinforcing bars were extracted from the structural elements and tested in uniaxial tension. Jonsonn et al. [17] reported that the yield strength measured with the destructive tests varied from 310 to 470 MPa (45 to 68.1 ksi), depending on the shape of the rebar cross section. These values are shown in Figure 12, where they are compared with the range defined by the strength-for-age lines and the strength provided by the AASHTO Manual for Bridge Evaluation [6]. The latter method underestimates the real yield strength of the existing rebar, which is, on the contrary, close to the 95th percentile defined by Eqn. (3).

Figure 12 also shows the yield strength measured by Zaborac et al. [18] on 24 pieces of steel rebar obtained from two bent caps of a RC bridge; the bridge was built in 1960 and demolished after 50 years of service [18]. An average yield strength of 340 MPa (49.3 ksi) was reported and is within both the range defined by the proposed strength-for-age lines (Eqn. (3) for 5th and 95th percentile) and that defined by the yield strength of Structural Grade and Grade 60 [6] rebar. Nevertheless, the maximum and minimum values experimentally measured (i.e., 520 MPa (75 ksi) and 210 MPa (30.5 ksi), respectively) are outside the range of the possible yield strength suggested by the AASHTO Manual for Bridge Evaluation [6]. Whereas, only the minimum value of yield strength falls outside the range defined by Eqn. (3).

## CONCLUSIONS

Based on the results of the theoretical and experimental investigations on the steel rebar of existing bridges, the following conclusions were drawn:

1. New strength-for-age curves can be introduced to predict the average tensile and yield strength of steel rebar in existing concrete structures. Such equations are based on results from tests performed from 1908 to 2005 at the Politecnico di Torino (Italy) and used to certify the mechanical performances of structural materials.
2. For all the types of steel used from 1908 to 2005 in RC bridges, the average values of the yield strength predicted by the strength-for-age curve (i.e., Eqn. (3)) are, in general, less conservative than those suggested by the AASHTO Manual for Bridge Evaluation [6].
3. The estimation of the average value of yield strength provided by the strength-for-age curves is reliable and can be effectively used to assess rebar strength in the existing Italian RC bridges considering the results of destructive tests carried out on Bridges #1 (built in 1930) and #2 (built in 1975). The same is also valid for the steel in bridges built in the United States.

## FUTURE RESEARCH

Future research should extend the proposed approach to define new strength-for-age curves for strands and cables used in pre-stressed and post-tensioned concrete elements.

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