

READER COMMENTS

Japanese Develop Low Carbon Heat Treated Prestressing Steel*

by Morris Schupack

Comments by Akira Doi and Author

AKIRA DOI†

The author has reported the position of the use of low carbon heat treated prestressing steel in Japan, and also presented the properties of low carbon silicon-chrome steel recently developed by a Japanese manufacturer. However, the writer believes that the author has overlooked some aspects of the use of the new Japanese prestressing steel and that he has overestimated the improving effects of silicon and chrome on the physical and chemical properties of the steel.

The overwhelming majority of low carbon prestressing steel produced in Japan has been used for concrete piles, poles and railroad ties, as acknowledged by the author. Only a very small quantity of the steel has been used for other prestressed concrete products and structures. Because it is well known that heat treated prestressing steel, especially with a tensile strength of more than 155 ksi, is very sensitive to stress corrosion cracking, such steel should be used only at precast plants under well controlled conditions.

In the Japanese Industrial Standard for steel bars for prestressed concrete, it is noted in its supplemental explanation that the user should carefully select the application of this type of steel. In addition, the Japanese Highway Public Corporation restricts the use of high strength steel bars of more than 155 ksi,

which are generally manufactured by a heat treating process.

Although the author has indicated that heat treated steel has been successfully used for the past decade in Japan, and no stress corrosion has been reported, the writer would like to point out the following facts:

There have been some cases where heat treated prestressing steel used for post-tensioning failed after some period of years from the stressing. Four of these cases were reported at a FIP stress corrosion symposium held in the Netherlands in 1971.¹ In every case the tensile strength of the heat treated steel has more than 155 ksi, and the cause of failure was believed to be stress corrosion or delayed fracture due to poor grouting.

Recently, another case of breakage of heat treated steel was reported in a Japanese technical journal.² In this case, heat treated steel with a tensile strength of 185 ksi was used in prestressed concrete beams of a school building. After 4 years, three of 640 tendons were found broken from the stressing. The cause of the steel failures also was believed to be due to stress corrosion.

In addition, similar cases of failure of prestressing bars have been reported in Europe.

As mentioned before, heat treated steel is not always a reliable material for prestressed concrete. This writer admires the wisdom of the American prestressed concrete industry for the clear attitude it has taken against heat treated steel, which presented many problems in the early days of prestressing and

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Table A. Comparison of stress levels for low carbon silicon chrome steel and stress relieved strand.

Stress	Low carbon silicon chrome Steel bars	Stress relieved strand
Lower stress, ksi	123.6	162
Upper stress, ksi	150.4	197.1
Stress amplitude, ksi	13.4	17.55

was excluded from the specifications for prestressed concrete. As the record shows, very few stress corrosion problems have been experienced when drawn and stress relieved steel has been used.

The writer also believes that this attitude of the industry has greatly contributed to the establishment of the good reputation prestressed concrete enjoys as a whole and the steady growth of the industry. If heat treated steel should be introduced into America and used unconditionally, it will not only cause unnecessary anxiety, but perhaps some day, destroy the public acceptance of prestressed concrete.

The writer admits that thick prestressing bars have their inherent merits, and in fact can be used advantageously in a variety of applications. However, thin and high strength bars can not replace stress relieved wire and strand. Therefore, it is hoped that the use of heat treated steel—particularly of thin diameter—should be carefully examined and restricted to limited applications if it is to be used.

In regard to the characteristics of low carbon silicon-chrome steel, the author has indicated that the properties are similar to those of stress relieved strand. However, in some instances, the writer disagrees.

In Table 5, fatigue test results for low carbon silicon-chrome steel are shown comparing the values with those for stress relieved strand. In this table, lower and upper stresses are shown in percent of ultimate strength of steel and the results for the former seem to be similar to, or better than those of the latter. The writer, however, believes that the fatigue test results should be compared by stress applied to steel. As an example, Table A in my discussion shows the stress of the result of line four in Table 5.

It is clear from Table A that stress relieved strand can be used at a higher stress level and with a wider stress amplitude as compared to low carbon silicon-chrome steel.

According to the author's conclusion, the stress corrosion property of low carbon silicon-chrome steel is superior to that of normal low carbon steel and is similar to stress relieved strand. However, the writer believes that the effect of silicon-chrome alloy is overestimated and the author's tests are not sufficient enough to derive any conclusion regarding a comparison between silicon-chrome steel and stress relieved steel. What the author has failed to do is explain the reason or mechanism for improvement in the stress corrosion resistance of steel when silicon and chrome are added.

In general, silicon or chrome is considered useful in reducing the corrosion sensitivity of steel. However, the improvement can hardly be expected to such an extent as that experienced when using cold drawn and stress relieved steel. The low carbon silicon-chrome steel is manufactured by a quenching and tempering process. Metallurgically speaking, it has a martensitic structure which is sensitive to stress corrosion cracking. Heat treated steel or quench and tempered steel—or whatever it may be called—has the same metallurgical structure as the oil tempered wire which has long been dreaded in the prestressed concrete industry.

For comparison of the stress corrosion property of two types of steel, the stress corrosion test should be continued at least up to the time when any one of the specimens breaks. If the failure of any of the specimens does not occur under some testing conditions, such as another type of solution—applied stress level, or higher testing temperature—should be considered. In this context,

Table B. Summary of stress corrosion test results.

Specimen	Chemical contents		Ultimate tensile strength, ksi	Applied tensile stress, ksi	Time at failure, hours
	C	Si			
Normal low carbon steel	0.32%	0.23%	207	50% of UTS	1.6, 1.7, 1.78
Low carbon steel with added silicon	0.35%	1.03%	228	50% of UTS	2.4, 2.26, 2.37
Drawn and stress relieved wire	0.82%	0.15%	267	70% of UTS	90, 88.2, 80.5

Note: Ammonium nitrate of 20 weight percent was used at 100 C as corrosive solution.

the author's stress corrosion tests, including the results shown in Table 6, are not sufficient.

Table B shows the stress corrosion test results conducted by the writer. According to these results, the effect of silicon added to low carbon steel is recognized. On the other hand, it is clear that in spite of higher applied stress, the time to failure of drawn and stress relieved wire is much longer than that of low carbon steels. Therefore, the writer believes that the author's conclusion is not necessarily a reasonable one.

References

1. Doi, A., Takeo, K., Yamazaki, T., Nakagawa, A., "Japanese Report on Cases of Spontaneous Rupture and Laboratory Research," FIP Stress Corrosion Symposium, the Netherlands, 1971.
2. Aihara, T., "Rupture of a Steel Bar for Prestressed Concrete and Results of Investigations Concerning It," *Kenchiku Gijutsu*, No. 300, August, 1976.

AUTHOR'S CLOSURE

The thoughtful comments of Dr. Doi are appreciated. As a structural engineer, it is out of my province to engage in a metallurgical debate with such a renowned metallurgist as Dr. Doi. From a structural engineer's viewpoint, however, Dr. Doi's comments do not inform us additionally as to the advantages or disadvantages of low carbon silicon-chrome quenched and tempered steel containing at least 1.5 percent silicon.

The author is very much aware of the po-

tential problems encountered with oil tempered and other types of heat treated prestressing steel. As a member of the original joint ACI-ASCE Committee on "Prestressed Concrete," I had the privilege of being a member of the executive group that drafted the first "Tentative Recommendations for Prestressed Concrete," published in January 1958. Also, as a participant on the Prestress Committee, I was very much in favor of excluding oil tempered prestressing steel, and Paragraph 304.2—High Tensile Strength Single Wires, states: "High tensile strength wire produced by the oil tempering process is not recommended for use in prestressed concrete."

This was based on some suspension bridge cable problems and also other corrosion problems in the early days of prestressing including the early work of Everling,³ which indicated that under accelerated testing, oil tempered wire had a relatively short time to failure when compared to as-drawn or stress relieved wire.

In evaluating a new type of prestressing steel, it is necessary to evaluate all the physical characteristics, accelerated corrosion tests and actual performance in practice. To avoid the stigma of past rejection and experience, particular care must be taken in appraising the value of a heat treated steel, or for that matter, any new type of prestressing steel which does not have a significant precedent.

In order to establish a means of accepting a new prestressing steel, it is necessary that besides physical requirements of stress-strain, elongation, reduction of area and repeated load, accelerated corrosion tests and

relaxation tests should be required. Currently, no U.S. standard has these requirements. Based on this lack of data, the joint ACI-ASCE Committee on "Prestressed Concrete," of which the author is a member, is now trying to formulate such requirements. In future standards, the author believes that, in addition to the minimum ultimate tensile strength, a maximum ultimate tensile strength should also be specified for each grade of steel.

Accelerated corrosion testing performed in Japan on the low carbon silicon-chrome quenched and tempered steel has indicated excellent performance. Based on these tests and the excellent performance reported in the use of over 450,000 metric tons of primarily a low carbon steel (mostly in piles and sleepers) in the past 11 years in Japan, the author believes that this steel deserves consideration and technical dialogue in the engineering profession.

Dr. Doi's reference to the four failures of quenched and tempered bars, reported in Reference 1, were all based on conditions which would probably eventually corrode or damage any prestressing steel, since grouting was neglected. It is the author's understanding that in only one of these cases was a bar manufactured by the Neturen process.

The fifth case referred to in Dr. Doi's comments, see Reference 2, was not known to the author at the time of writing the paper. This again was a bar which was not grouted. In the referenced report on this failure, the Japanese author points out that since the three failed bars were inadvertently not grouted, this could have been prevented with cooperation from the designer, general contractor, fabricator of the post-tensioned member, and by having a proper inspection policy.

Based on these cases, the author must qualify his concluding statement as follows:

"However, over 450,000 metric tons of plain low carbon steel have been successfully used in prestressing applications without any stress corrosion problems being reported in the past 11 years in Japan, *except in several cases of improper construction.*"

It should be understood that these cases were not the low carbon silicon-chrome steel which has improved corrosion properties.

In order to make sure that there is a com-

mon understanding of terms, the author would also like to give his definition of the following terms as related to prestressing steel corrosion:

1. *General corrosion:* Corrosion occurring by oxidation of the steel, stressed or unstressed.
2. *Stress corrosion cracking:* Degradation of the steel basically by intergranular cracking, with or without general corrosion occurring.

The low-carbon silicon-chrome induction heat treated steel has far superior accelerated stress corrosion performance than the plain low carbon induction heat treated steel which has been predominantly used in Japan. The author would only consider the silicon-chrome steel for most applications. Tests of the silicon-chrome induction heat treated steel show stress corrosion test behavior comparable to stress relieved steel. Because this steel is relatively new, it would be desirable to have longer comparative stress corrosion tests. The Neturen Company has these tests under way.

Dr. Doi's greater concern with the smaller diameter bars seems to be contrary to experience in Europe for a totally different type of heat treated steel which has had delayed failure problems with larger diameter bars. It appears to the author that the greater amount of working required to produce the smaller diameter bar would give better surface conditions and less susceptibility to corrosion.

For instance, the maximum surface flaw generally found in hot rolled stretched and stress-relieved bars is up to 0.2 mm, whereas for the cold drawn and quenched bars, surface flaws are up to 0.1 mm. This is particularly true for rolled bars which have been primarily used in the United States. In any case, in the United States, the larger prestressing bars have had excellent performance and have not shown any difference in performance from the smaller bars, to the best of the author's knowledge.

The author, as a structural engineer, has been close to various performance problems of prestressing steel for the last 25 years. The metallurgical aspects of these comments should be the province of metallurgists. However, in studying data reported by Carter,⁴ published in 1969 by the National Association of Corrosion Engineers and work independently done by the Neturen Company, it is

indicated that a dramatic decrease in stress corrosion susceptibility occurs with silicon contents of 1.5 percent and higher.

Dr. Doi's tests tabulated in his comments have low carbon steel with the highest silicon content of 1.03 percent. It would appear that if valid comparisons are to be made, low carbon steel with a silicon content of at least 1.5 percent should have been made.

The accelerated corrosion test using a boiling calcium nitrate solution is the more usual test, though as previously mentioned, no industry standard exists. In order to be responsive to Dr. Doi, Neturen immediately conducted tests on 9.2 mm 130/145 low carbon silicon-chrome steel in a comparable 20 percent solution of ammonium nitrate at 100 C as used by Dr. Doi. Specimens 9.2 mm diameter, with 0.46 percent carbon, 1.75 percent silicon, 0.49 percent chrome and an ultimate tensile stress of 147 kg/mm² (209 ksi) were tested.

Three specimens were tested at a stress of 60 percent of ultimate. There were no failures at 100 hrs when the test was stopped. Three specimens were also tested at 70 percent of ultimate, and failures occurred in 40 to 50 hrs. These tests indicate that a significant improvement results with a higher silicon content. A comparative test on stress relieved steel with the same test setup was not made because of a time limitation.

Neturen plans to perform additional tests comparing stress relieved wire or strand, high strength bars complying with ASTM A722 and various sizes of low carbon silicon-chrome quenched and tempered steel bars, so that a meaningful comparison using the same testing technique can be made.

Fig. A is extracted from Reference 1 (which is coauthored by Dr. Doi) to show the effects of silicon content on the time to failure of quenched and tempered wire. This curve shows the marked improvement with silicon contents in excess of 1.5 percent.

Regarding the fatigue behavior comparison, the conversions from percent of ultimate to stresses, as shown in Dr. Doi's comments, are correct. He mentions that the results of the fatigue tests in terms of percent of ultimate are similar for the helically grooved bars and strand. The comment is that the actual stresses and the stress amplitude for strand are higher. This is correct, and is so because the ultimate stress of strand is higher than that of bars.

Dr. Doi's conclusion is that, "It is clear that stress relieved strand can be used at a higher stress level and with a wider stress amplitude as compared to low carbon silicon-chrome steel." This is true, of course, but this conclusion is not related to how the steel is used in the structure.

Most designs use initial prestress at 70 percent and effective prestress at about 60 percent of ultimate. Design is based on a percentage of ultimate, and sufficient area of prestressing steel is furnished to provide the necessary forces on this basis. When doing this, the upper stress and stress amplitude of the tendons for fatigue loading will be approximately proportional to the ultimate stress of the material chosen.

If there are no other considerations, the cost of the prestressing steel may dictate the choice between the different materials which are available. The economy factor is generally based on cost per pound of effective prestressing force. If the cost per pound of effective prestressing force is about the same for two steels having significantly different ultimate strengths, then the strength of steel is not an issue in economy.

For such a situation, more area of steel of the lower ultimate material would be provided (at equal cost) so that the design factors like initial prestress, effective prestress, upper stress and stress amplitude, would all be about proportional to the ultimate strength. It is for this reason that the comparison between the fatigue properties of helically grooved bars and strand was made on the basis of stresses as a percentage of ultimate.

Regarding Dr. Doi's comments related to Japanese standards, the author is not sufficiently familiar with these standards to discuss their interpretation. The author, however, did contact Neturen Co., Ltd., and their comments were these:

1. In the Japanese Industrial Standards or its supplemental explanation, there is no statement, as mentioned by Dr. Doi, that "the user should carefully select the application of this type of steel" (implying heat treated steel by Dr. Doi).

2. Regarding the Japanese Highway Public Corporation, there is no statement prohibiting the use of heat treated steel.

In order to understand new products, technical data establishing performance should be presented. At the time of the strand short-

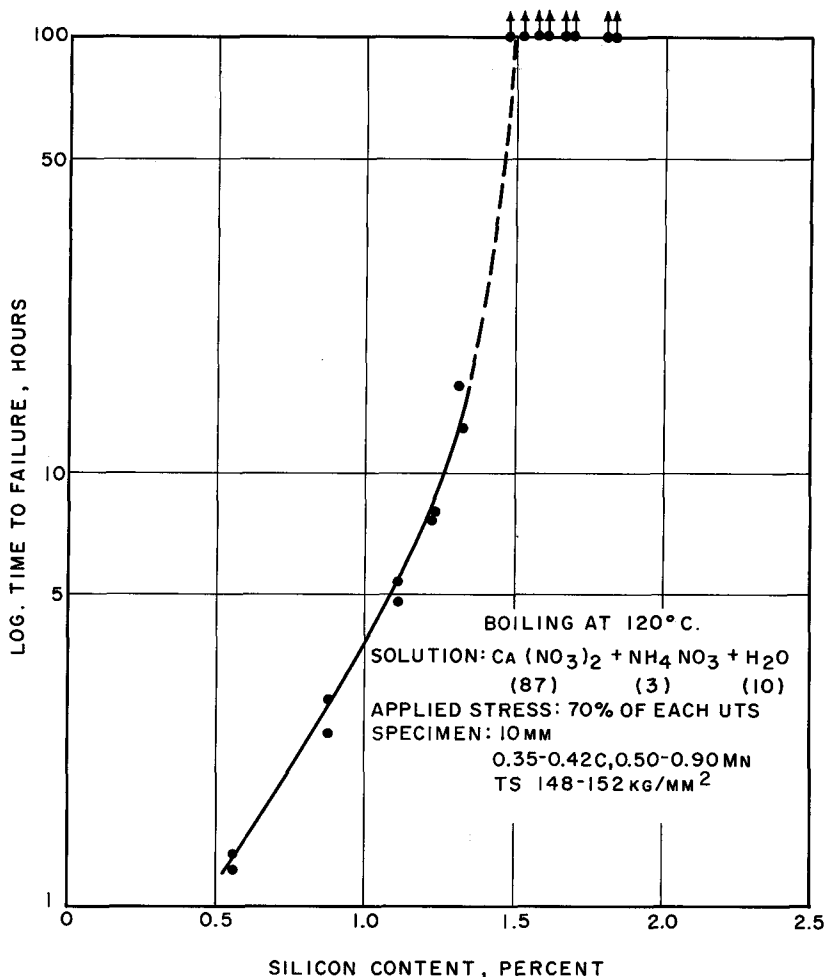


Fig. A. Effect of silicon content on the time to failure of quenched and tempered wire.

age a couple of years ago, there was an urgency in finding alternatives. The low carbon silicon-chrome quenched and tempered steel could possibly be such an alternative. It is necessary to evaluate data with an open mind and not to simply categorize the material as another heat treated steel.

Extensive test data were made available to the author and were carefully considered before presentation. It is hoped that adequate information was presented so that the profes-

sion can reasonably evaluate and judge this relatively new prestressing steel.

References

3. Everling, W. O., "Stress Corrosion in High Tensile Wire," *Wire Products*, V. 30, p. 316, 1955.
4. Carter, C. S., "The Effect of Silicon on the Stress Corrosion Resistance of Low Alloy High Strength Steels," *Corrosion*, V. 25, No. 10, October, 1969.