

Reinforcement of Old Steel Bars Through Fibers, and its Effects on the Mechanical Properties

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ABSTRACT

The corrosion causes a harmful loss of the mechanical properties of the reinforcing steel, strength, ductility, and service life are reduced consequently. The paper focuses on the viability of reinforcing the naturally corroded steel bars, aged 45-50 years that have been extracted out of a demolition bridge and restoring them using externally bonded carbon fiber (CF) package. This work is in contrast to the majority of other research in which artificial corrosion is employed that may not relate to the natural process that occurs over extended periods, as in real world service. A DMAIC Six Sigma model (define, measure, analyse, improve, control) was used. Three sets of specimens were tested conducting a tensile and bending test of a steel bar that was new, naturally corroded old bars, and corroded bars reinforced utilizing CF. The corroded bars experienced great losses in properties compared to standards where the yield strength, ultimate strength, tensile strength, and elongation of the bar reduced by 17.62, 20.19, and 27.52, and 15.76 respectively, and the diameter reduced by 6.62. CF-wrapping resulted in significant enough gains of yield strength by 40.57%, ultimate strength by 26.60%, tensile strength by 8.47%, elongation by 39.58%, and nominal diameter by 13.83%. Every bending piece sample passed bending test These results indicate that reinforcement imbibed by CF wrapping can be an efficient method of recovery of long-term corroded reinforcement, implying its prospective preeminence as a sustainable type of reinforcement repairing

within the framework of quality enhancement.

Key Words: Corrosion, Yield strength, ultimate strength, tensile strength, mechanical properties before and after implementation of Six Sigma

1. Introduction

The quality improvement approach, Six Sigma aims to improve the quality in terms of mechanical properties, reduce defects and variations in material improvement. For the improvement of quality it uses statistical tools and techniques. This approach not only identifies the defects, but also eliminates in step by step process. For making decision, a data driven approach is used by Six Sigma, to reduce errors and improve the quality improvement process. This approach uses DMAIC (define, measure, analyze, improve and control) method. The quality improvement approach, Six Sigma with DMAIC criteria is vastly used in many areas, such as industries, finance, manufacturing, healthcare and Education. Six Sigma helps to improve the mechanical properties, increases strength and reduces cost. This approach needs time and resources, to get the required benefits. Six Sigma helps to achieve goals, and excellence.

One of the most vital aspects that lead to degeneration of reinforcing steel in concrete structures is corrosion.[1] Long term exposure to aggressive environments results in pitting and cross section loss that reduces yield/ultimate strengths and ductility, reducing service life.[2] The evidence of notable mechanical deterioration compared to the lack of aging of uncorroded steel is supported by the results concerning the samples exposed naturally, where the loss of strength and strain capacity vary with severity and the type of pits formed, depending on the decade under consideration [3]; complementary works on corrosion of specimens in naturally vs. artificially corroded bars report a similar trend but with a distinctive failure behavior .[4]

The past work so far uses accelerated corrosion (e.g., impressed current, chloride spray, carbonation). Scant studies have also estimated the tensile behavior of the dampened reinforcement that has served over a period of decades in the real field, leaving a gap between the laboratory and the field conditions [5].

Fiber reinforced polymer (FRP) retrofits-particularly carbon fiber (CFRP) sheets-are commonly used to reclaim load capacity on corrosion damaged RC elements; nevertheless, there is little direct evidence of restoring the tensile performance of naturally corroded bars. Practical tests on corroded rebar components demonstrate that

CFRP repair can restore stiffness strength and that CFRP can halt the initiation and propagation of damage due to corrosion, whereas recent work on hybrid CFRP/steel bars investigates bar level tensile performance [3], [4], [5]

To measure such recovery, this paper uses the Six Sigma DMAIC (Define-Measure-Analyze-Improve-Control) approach to (i) benchmark the loss of mechanical properties of a naturally corroded reinforcement between 45 and 50 years old, and (ii) determine whether externally bonded CFRP wraps can recover tensile and bending properties [6]

1.1 Research Aim

This paper examines whether carbon fiber wrapping would enable fixing the tensile, bending capability of decades old, naturally corroded reinforcement bars across a context of a Six Sigma (DMAIC) improvement initiative.

2. Literature Review

Reinforcing steel has been a common source of deterioration usually resulting in loss of strength and durability on reinforced concrete (RC) structures. Extensive literature reports have been made on the deterioration in tensile strength, ductility, serviceability because of exposure to the aggressive environments. Corrosion also decreases effective cross-sectional area, forms pits and cracks, and undermines the steel and concrete bond [6]. According to Francois et al. [7], the reinforcing bars obtained at the age of the 27-year-old corroded beams indicated that the strength of the reinforcing bars was considerably reduced in yield strength, ductility and rigidity. Similarly, Ignasi et al., observed up to 35 percent and 45 percent reductions of the yield strength and tensile strength of 30-year naturally corroded bars, respectively [8]. Such results indicate that natural corrosion, in contrast to accelerated testing, may cause the non-homogeneous and sometimes more severe mechanical degradation.

The majority of experimental programs have incorporated accelerated corrosion methods, such as impressed current [9], chloride salt spray [10], carbonation [11], and wetting/ drying [12]. These paths can give quick estimates of mechanical losses and are unlikely to be interfered with by the heterogeneous pit morphologies of natural corrosion. Accelerated chloride exposure was reported to result in decreased elongation and ductility by Apostolopoulos et al., [13] and nominal and residual tensile capacity by Du et al., [14]. Though useful, such as can be artificially induced corrosion can under represent field-aged

steel complexity.

To solve decaying problems, fiber-reinforced polymers (FRP) have been used widely as external strengthening methods. Al-Saidy et al. [15] showed that CFRP sheets were capable of regaining coronated RC beams regaining flexural strength. Wang et al. [16] stated that CFRP strengthening enhanced the stiffness of corroded concrete beams as well as the load carrying capacity, whereas Borrie and Liew [17] highlighted the ability of CFRP to steel systems to resist environmental deterioration. The tensile properties of such CFRP steel hybrid reinforcements were studied by Başaran et al. [18] where fiber wrapping influences graphically. Overall, these experimental data support the basic premise that CFRP retrofits enhance structural performance, though nearly all studies are limited to structural members (beams, slabs) not the mechanical salvaging of individual corroded bars.

The final restriction is that not many studies have assessed naturally corroded reinforcement. Islam et al. [11] documented mechanical degradation after 20 years of salt water durability and Ignasi et al. [8] as well as Francis et al. [7] reported losses in 27-30 year old bars. Even in light of these insights, there is a paucity of systematic reviews of techniques to strengthen naturally corroded rebars. The literature on CFRP strengthening has scant detail on bar-level performance mortality after decades of in-service exposure.

2.1 Research Gap

Previous studies have determined that corrosion conventional deteriorates tensile and ductile performance of reinforcement and CFRP systems can reinforce structural members. However, there is little evidence available on whether CFRP wraps directly recover the tensile and bending strength of naturally corroded reinforcement bars. This paper fills this gap by experimenting on 45-50-year-old bars recovered during the dismantling of a bridge, wrapping them with CFRP and measuring recovery through a Six Sigma DMAIC initiative.

Table 1. Summary of Key Literature and Research Gap:

Study	Corrosion type	Key Findings	CFRP/FRP Strengthening	Gap Highlighted
Apostolopoulos et al. (2006) [13]	Accelerated chloride spray	Reduced yield strength, elongation, ductility	No	Artificial corrosion, not natural
Du et al. (2005) [14]	Impressed current	Losses in elongation and No strength	No	Focus on accelerated corrosion only
François et al. (2013) [7]	27-year natural corrosion	Reduced ductility and tensile properties	No	No strengthening applied
Ignasi et al. (2019) [8]	30-year natural corrosion	35% reduction in yield, 45% in tensile strength	No	Natural corrosion studied, but no CFRP
Islam et al. (2022) [11]	20-year saltwater exposure	Lower stiffness and strength	No	No strengthening
Al-Saidy et al. (2010) [15]	Corroded RC beams	CFRP restored flexural performance	Yes (beam level)	Not at bar level
Wang et al. (2023) [16]	Corroded beams	CFRP improved stiffness and capacity	Yes	Beam focus, not bars
Borrie & Liew (2021) [17]	Review (CFRP–steel systems)	CFRP enhances durability	Yes (hybrid systems)	No natural corroded bar data

Study	Corrosion type	Key Findings	CFRP/FRP Strengthening	Gap Highlighted
Başaran et al. (2023) [18]	CFRP–steel hybrids	Wrapping ratio influences tensile capacity	Yes (hybrid bar)	Limited to lab specimens, not aged steel
Current Study	45–50 years natural corrosion	Quantified losses and recovery with CFRP wraps	Yes (bar level)	Recovery of decades old naturally corroded reinforcement using CFRP

3. Methodology

This study was conceptualized and carried out as part of the Six Sigma DMAIC framework (Define-Measure-Analyze-Improve-Control) [19] that offers a structured mechanism used to define and quantify poor performance, and to verify the validity of the remedial measures. The experimental work was comprised of two types of mechanical tests conducted with three series of the specimens of reinforcing steel:

1. New steel bars ($n = 20$),
2. Naturally corroded old steel bars retrieved in a 45–50 years old abandoned bridge ($n = 15$).
3. Naturally corroded bars which were externally reinforced with carbon fiber (CF) wraps ($n = 15$).

3.1 Define and Measure

The problem that was defined according to the define stage included the loss of mechanical properties in long-term corroded reinforcement. The aim was to assess whether CF wrapping will reinstate these properties. During the measure stage, new bars were subjected along with naturally corroded ones to tensile and three-point bending testing done on the Universal Testing Machine (UTM). Manufacture and sample preparation were done under standard protocols to eliminate source of variation and guarantee comparison.

3.2 Analyze

In the analyzing phase, scuttled bars were also compared with those that had not been scuttled such that sources of attributes loss to natural corrosion could be quantified. Both

datasets were also cross-referenced with international standards- ASTM E8/E8M, ISO 6892-2:2019, EN standards and Pakistan Standards (PS) [19]. This will give a comparative index to assess reliability, validity and the proportion by which the yield strength, tensile strength, elongations, and nominal diameter will be reduced.

3.3 Improve

At the improvement phase, reinforcement of naturally corroded bars was done by externally bonding CF wraps. Re-test of specimens under the same tensile and bending procedures were conducted on the re-wrapped specimens. Comparisons of results with those of the unstrengthened corroded samples were done to quantify recovery and the same international standards against which their compliance with acceptable limits of mechanical properties were compared.

3.4 Control

Lastly, in the control stage validations were verified against the benchmarks. This procedure made it possible to obtain the opinion that the method strengthening could be regarded not only as effective but also as sustainable in practical applications. Recommendations were formulated for maintaining long-term performance and ensuring structural reliability.

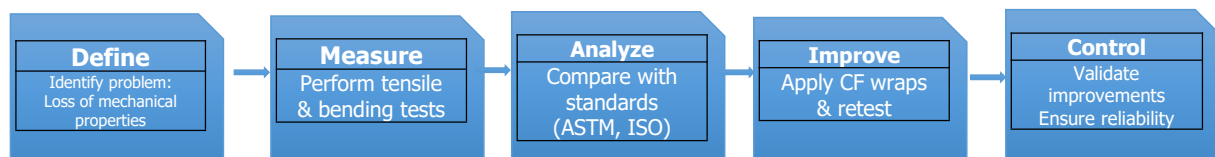


Figure 1: DMAIC Methodology Flow Chart

3.5 Sample Size Justification

The number of specimens used in this study exceeded minimum international requirements. According to ASTM E8/E8M-21 and ISO 6892-1:2019, the recommended sample size is 3–5 for general steels, 5–7 for high-strength steels, and 5–10 for alloy steels [19]. With 20 specimens for new bars and 15 specimens each for corroded and CF-strengthened bars, the dataset provides statistically reliable results suitable for comparative analysis.

3.6 Reliability Statistics

To assure both reliability and validity of the experimental output, all the mechanical properties measured were bench marked against national and international standards. The

national standard used was Pakistan Standards PS 3731 and PS 3714 (2016), whereas, international standardizing was ASTM, EN, and Australian standards [19]. These codes identify given lower and upper control limits on properties like the yield strength, ultimate tensile, elongation and nominal diameter. Individual and mean results that lie within these limits are acceptable and conforming whereas those that lie outside the limits are not acceptable.

Figure 2 shows how the yield strength was different between advancing and naturally corroded reinforcement bars. The values of the new bars are well in the standard range, thus, proving the validity of the test process. The corroded bars display wider downward press, and most of the observations are beneath the lower control limit designating that the yield strength was significantly lowered after prolonged exposure to corrosion.

Figure 3 shows the behaviour of ultimate tensile strength. As in the case of yield strength, the new bars fall neatly within the permissible range and are also in close conjunction to the predicted values in the national and international standards. On the other hand, the corroded samples also do not fall within the lower standard limit again supporting the conclusion that corrosion effects the ability of reinforcement to sustain the maximum tensile forces considerably.

As demonstrated in Figure 4, the results of tensile strength were distributed. Here as well the new bars fall within the standard limits as shown, which indicates compliance and as such affirms the structural sufficiency of the bars. Nevertheless, the corroded ones, and the group mean thereof, are on the side of the lower control border, which confirms the results obtained in Figures 2 and 3. This is a sign of not only reduced tensile capacity, but reliability drift away from settled limits.

Collectively, the three figures highlight a clear trend: while new reinforcement conforms to all benchmark standards, the naturally corroded steel consistently violates lower limits of compliance across yield strength, ultimate tensile strength, and tensile strength. This standards-based evaluation confirms the accuracy of the measurement process while objectively quantifying the extent of degradation in corroded reinforcement prior to strengthening interventions.

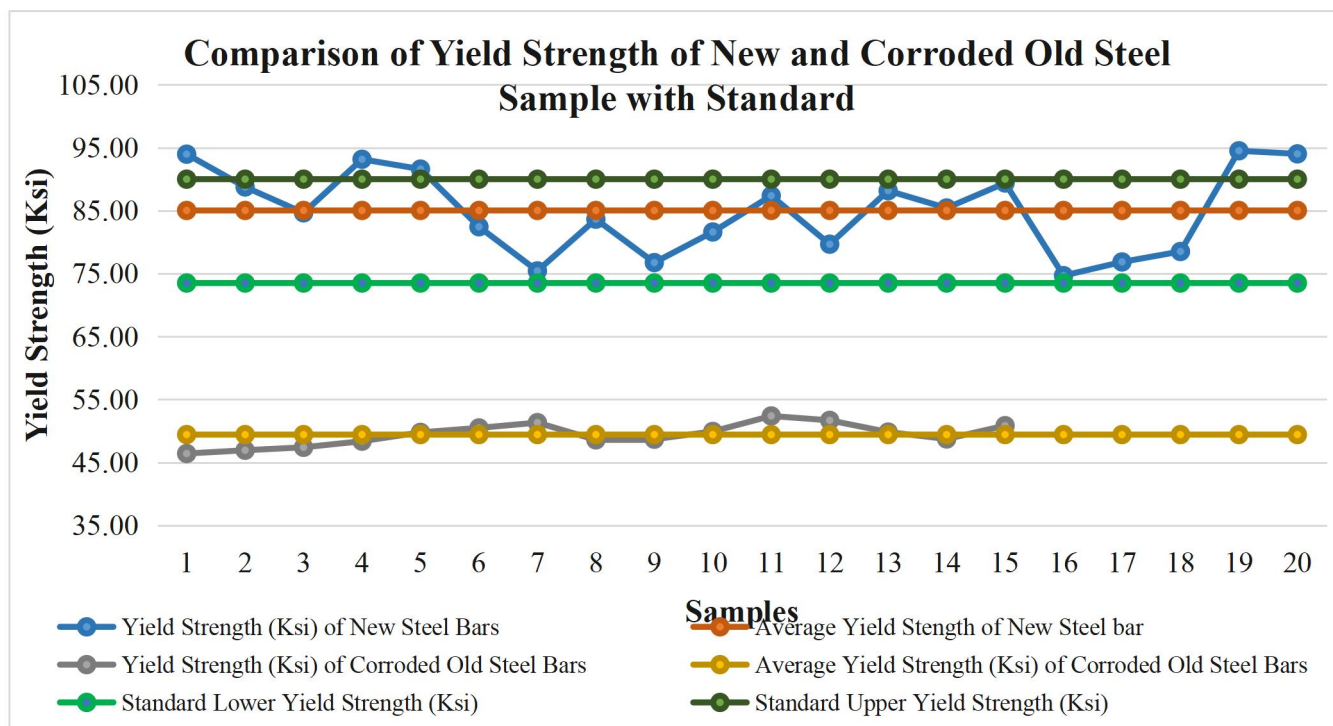


Figure 2: Comparison of yield strength both new and corroded old steel samples with standards.

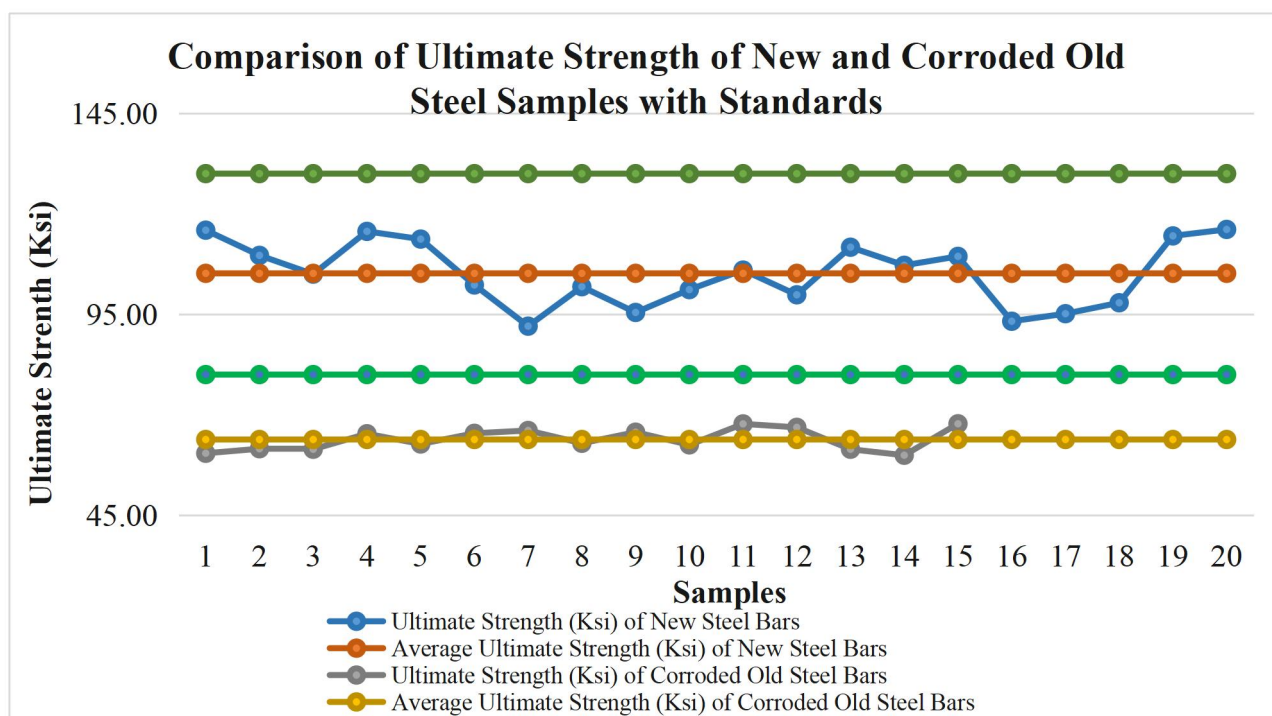


Figure 3: Comparison of ultimate strength of both new and corroded old steel samples with standards.

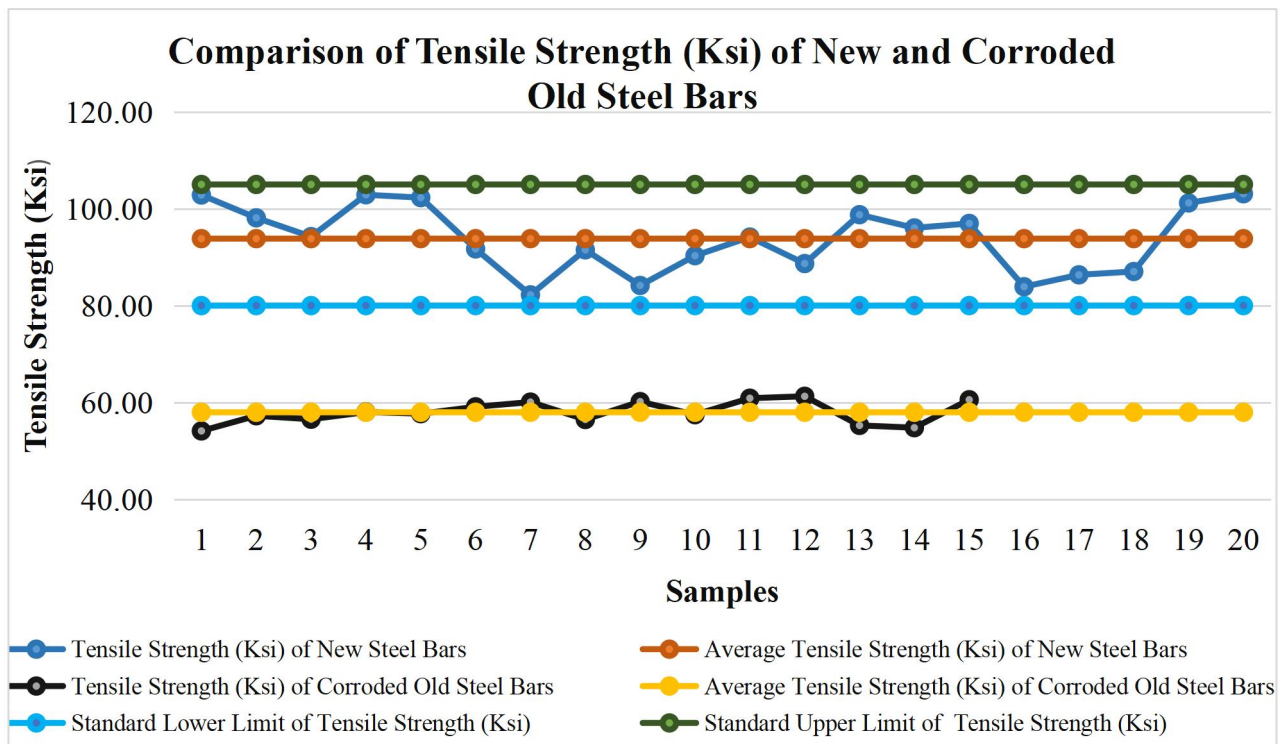


Figure 4: Comparison of tensile strength of both new and corroded old steel samples with standards.

4. Result and Discussion

The DMAIC methodology of the Six Sigma can effectively be implemented in quality improvement of designs and structures. Its implementation requires knowledge of designs, for further improvement.

4.1 Pre-strengthening (Baseline Condition)

Before implementation of Six Sigma, if Figure 5 is examined, the mechanical properties of old steel bars are less than the given lower standards. Even the old steel samples doesn't follow the lower limit of standards. On average, yield strength of old steel bars is reduced to 17.62 percent, ultimate strength is reduced to 20.19 percent, tensile strength is reduced to 27.52 percent, percentage elongation is reduced to 15.76 percent, while the nominal diameter is reduced by 6.62 percent from standard lower limits. The three points bending test is passed.

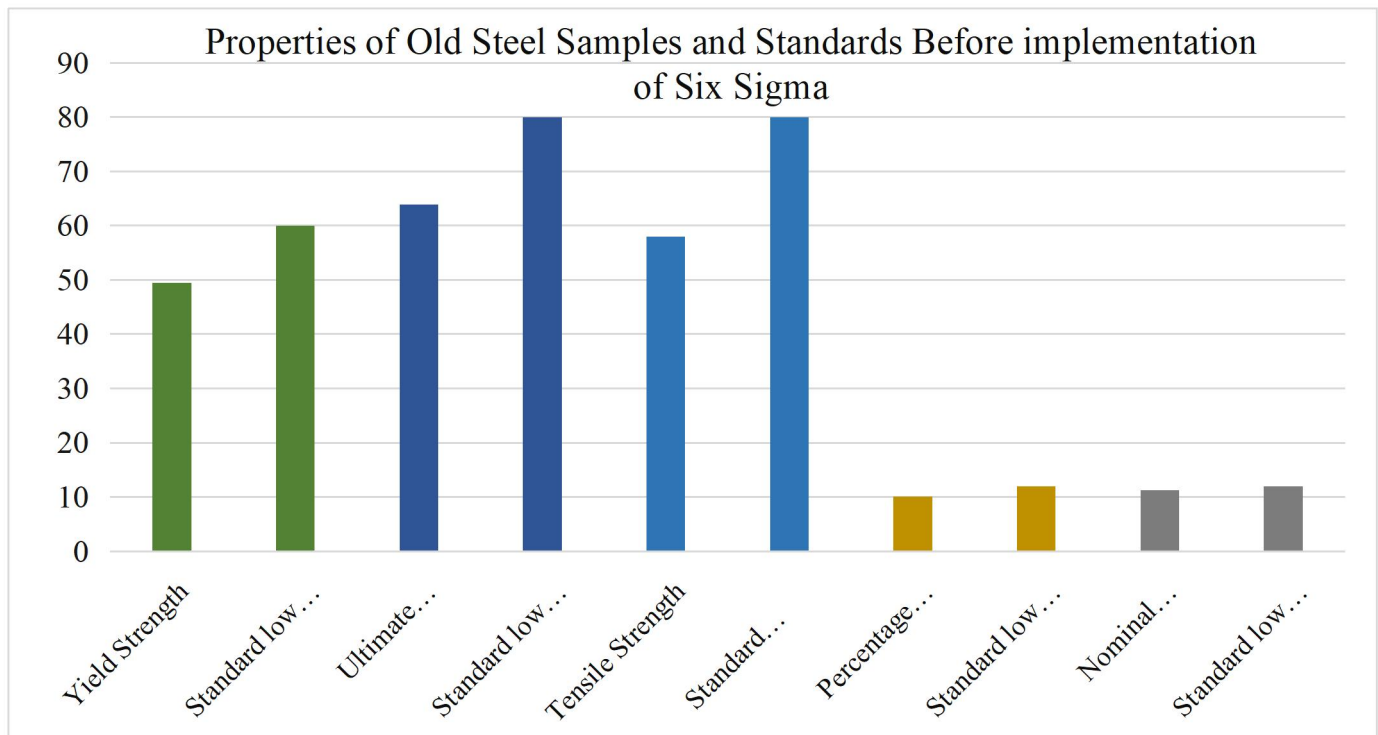


Figure 5: Mechanical properties of old steel bars, and standard lower limits before improvement

4.2 Post-Strengthening (Improved Condition)

Figure 6 shows the mechanical properties of corroded old steel bars after implementation of Six Sigma, DMAIC methodology. Figure 5 shows more improvement as compared to the previous results, before Six Sigma implementation. The mechanical properties are improved from the standard lower limits, and approaches closer to the standard higher limits. Carbon fibers have a very positive effects on the mechanical properties of old steel bars. This graph shows improvement in yield strength, ultimate strength, percentage elongation, tensile strength, and nominal diameter. The yield strength is improved 40.57 percent, ultimate strength is improved 26.60 percent, percentage elongation is improved 39.58 percent, tensile strength is improved 8.47 percent, and nominal diameter is 13.83 percent. Table 2 shows all the mechanical properties, in which improvement are made.

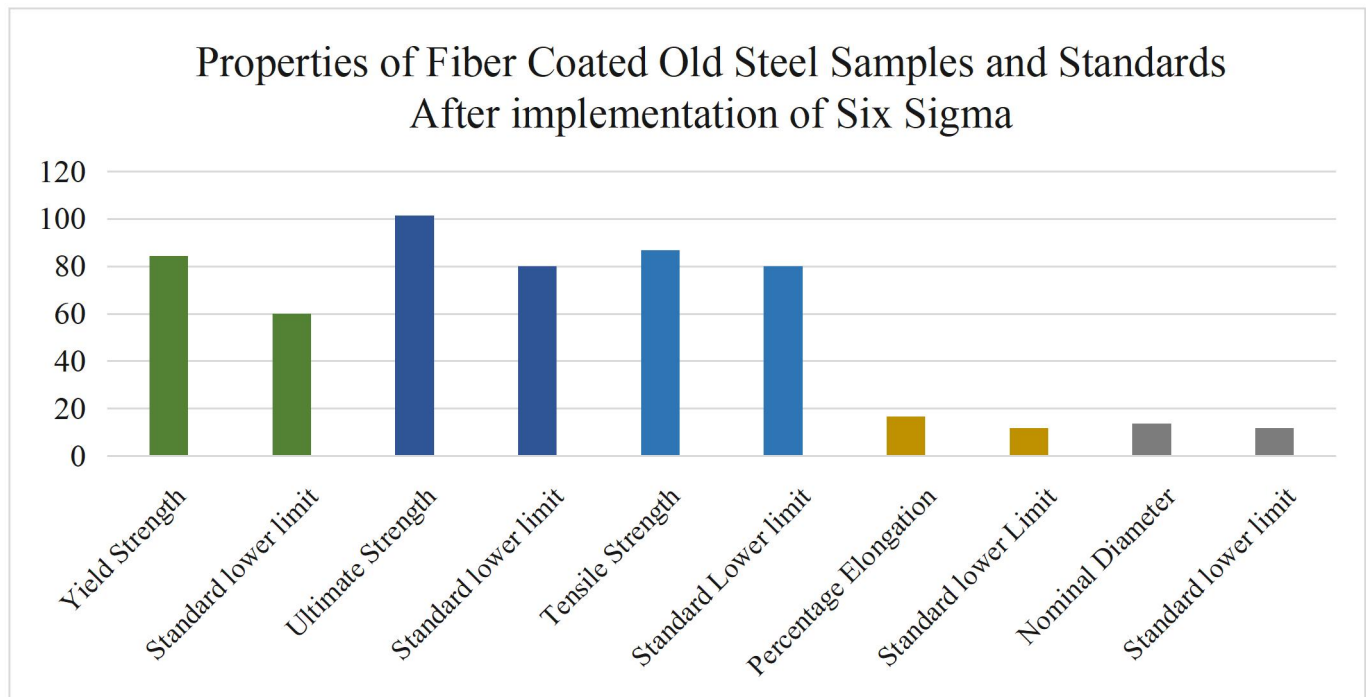


Figure 6: Mechanical properties of old steel bars, and standard lower limits after improvement

Table.2: Mechanical Properties of Corroded Old Steel Bars, which are Improved

S.No.	Mechanical Properties	Fiber Coated Old Steel Samples	Results
1	Tensile Strength	86.77 Ksi	Improved
2	Yield Strength	84.34 Ksi	Improved
3	Ultimate Strength	101.28 Ksi	Improved
4	Percentage Elongation	16.75 %	Improved
5	Nominal diameter	13.66 mm	Improved
6	Bending	Passed	Improved

The findings affirm substantial corrosion-induced losses in reinforcement characteristics with previous research citing 20 - 50 downsides in tensile and yield frenzies following decades of exposure [7,8,13]. More significantly, it shows that carbon fiber reinforcement can regain most of this compromised mechanical strength, an area that has not been amply reported with regards to bar-level reinforcement by naturally corroded steel. The

obtained increases in yield and elongation indicate that CF wraps do not only compensate for the loss of load-carrying capacity but enhance ductility, which is essential to structural resilience.

5. Conclusion

The present analysis showed that natural corrosion reduces reinforcing steels by large magnitudes in terms of yield strength, ultimate strength, tensile capacity, and ductility as earlier presented by extensive field studies in literature [7,8,13]. This kind of degradation highlights the frailty of the aging infrastructure and the need to develop successful rehabilitation measures.

Experimental findings also proved that carbon fiber (CF) wrapping delayed most of the performance loss on the naturally corroded reinforcement bars, which has been not given most attention so far. Remarkably, a 40.57 percent increase in yield strength and 39.58 percent in elongation indicate that CF reinforces the strength and ductility of structures- two key attributes to structural safety and resilience.

Through the application of the Six Sigma DMAIC methodology, this study gave an ordered approach to misdiagnosing deterioration, measuring losses, making upgrades and confirming the results against other worldly directives. This method did not only confirm the success of CF wrapping, but defined a quality-improvement procedure that can be repeated later on other structural materials rehabilitation projects.

The research findings affirm the efficacy and sustainability of the CF wrapping in terms of increasing the service life of preexisting damaged rebar as an alternative to their replacement since the latter is often cumbersome.

Future directions: Studies need also be conducted to explore fatigue behavior and durability in service of CF wrapped reinforcement, bond characteristics with concrete, and its long-life environmental durability to develop a more complete picture of its effectiveness when applied to real-world environments.

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