International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 5.22 (SJIF-2017), e-ISSN: 2455-2585
Volume 5, Issue 09, September-2019

THE SEARCH FOR AN IDEAL REBAR FOR DURABLE CONCRETE CONSTRUCTION LEADS TO PSWC-BAR

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Abstract – PSWC bar of steel, characterized by its plain surface and wave-type configuration, when used as rebars in concrete construction, has the capability to make concrete constructions durable through several-fold enhancement of life span of such constructions. The use of PSWC bar leads to increased load-carrying capacities of reinforced concrete elements, and it transforms traditionally brittle reinforced concrete into ductile reinforced concrete through several-fold increase in ductility and energy-absorbing capacity of flexural elements of reinforced concrete. All of these have many attendant benefits. It is shown in this article that among rebars of carbon steel, PSWC bar is the most ideal one, as at no added cost or effort, the use of PSWC bar endows reinforced concrete constructions with numerous benefits.

Keywords – Concrete Constructions, Concrete Structures, Durability Of Concrete Structures, PSWC-Bar, Rebar, Reinforced Concrete, Reinforcing Bar.

I. INTRODUCTION

Widespread problems of early decay and distress in concrete structures came to the fore following the start of use of ribbed rebars of high-strength (yield strength greater than 250 MPa, or say, 35000 psi) steel in concrete constructions, which by that time had become the number one medium of construction.

Granted that there are or there may be qualitative differences in the qualities of similar products of different manufacturers, there are some intrinsic problems with ribbed rebars as evidenced, without any dispute, in the relatively poor time-dependent performance of reinforced concrete structures, built with ribbed rebars.

The worldwide problem, created by the use of ribbed bars; whether of the cold twisted deformed (CTD) or thermo mechanically treated (TMT) type or without any such special treatment for increasing the strength of steel, has been aptly summed up by Papadakis, et al. [1], who observed in their paper in 1991: “The last two decades have seen a disconcerting increase in examples of the unsatisfactory durability of concrete structures, specially reinforced concrete ones.”

Sixteen years later, Swamy [2] too remarked that “the most direct and unquestionable evidence of the last two/three decades on the service life performance of present constructions and the resulting challenge that confronts us is the alarming and unacceptable rate at which the infrastructure systems all over the world are suffering from deterioration when exposed to real environments.”

In its Technical Circular 1/99, The Central Public Works Department of the Government of India [3] too observed in 1999: “While works as old as 50 years provide adequate service, the recent constructions are showing signs of distress within a couple years of their completion.”

The observations by CPWD [3], Swamy [2], and Papadakis, et al. [1] are a testament to concrete structures of earlier periods, which were built with plain round bars of mild steel, performing much better than more recent structures with ribbed CTD and TMT bars when such structures may be subjected to the real environment.

A way had to be found to get out of the pitiable condition today’s reinforced concrete structures are in.

II. THE SOLUTION

The first step in a solution to a problem requires identification of the cause or causes of the problem.

2.1 Ribs At The Root Of The Problem

The time periods, referred to by Swamy, Papadakis, et al., and by CPWD, are clearly indicative that the worldwide problem with reinforced concrete constructions started with the start of use of ribbed rebars.

It had to happen that way, as it is an intrinsic nature of ribbed bars that, compared to plain round bars of mild steel of earlier era, such bars corrode very fast.

The four untwisted rebars at the bottom in Figure 1 (a) show the start of corrosion preferentially at the ribs of rebars whereas there is rust all over the surface of the top four pieces when the remaining length of the same bar, that gave the four bars at the bottom, was twisted beyond yield at a cold state as it happens in the case of CTD bars.

CTD bars miserably lack in ductility (Figure 1(b)).

The start of corrosion at the ribs on TMT bars can be seen in Figure 1(c). Extensive corrosion all over the surface of TMT bars can be seen in Figure 1(d).

It cannot be overlooked that the ribs were provided out of a perceived necessity of improved bond or engagement between rebar and concrete when the rebars were upgraded from low-carbon to mid-carbon or high-carbon steel for higher strength. The truth is that the presence of ribs on the surface of rebars may help restrict longitudinal movement of the bars relative to the surrounding concrete, but the ribs encourage corrosion in rebars by decreasing bond and creating gaps between rebars and the surrounding concrete [4].

2.2 Reasons For Intrinsic Susceptibility Of Ribbed Bars To Corrosion

Whether of the CTD or TMT type, or not, the reasons for ribbed bars of carbon steel being intrinsically susceptible to corrosion at accelerated rates are :

1. residual stresses develop at the bases of ribs during the manufacturing stage
2. cracks or surface damages, which trigger corrosion, may develop at the ribs at the time of manufacture, during transportation and handling
3. in the rebar, nominal stresses under load are enhanced in keeping with the phenomenon of stress concentration due to the presence of ribs or cracks
4. additional stresses develop in ribs in a loaded structure due to the wedge action of such ribs against surrounding concrete
5. the sum-total of stresses and strains in 1 to 4 approach or reach yield stress or strain levels
6. rate of corrosion increases with increasing stress levels; the rate accelerates as the stress or strain approaches yield levels, and the surface becomes unstable once at or beyond yield, whereupon the bars become incapable of being passivated and consequently the process of corrosion becomes unstoppable.

The CTD and TMT processes are in violation of the inherent nature of steel to be ductile and to protect itself [5].

These CTD and TMT bars of high strength steel have another shortcoming to contend with: “The effect of stresses during corrosion is reflected more distinctly in the mechanical characteristics of the reinforcement, specially of high-strength steels with low ductility.” [6, pp. 203-204]

On the basis of extensive work in Russia, Alekseev [6] commented on the above scenario thus: “the durability of reinforcement specimens with a stepped (deformed) profile may be roughly an order less than that of smooth specimens since the former have stress concentrators on the surface at the bases of projections, which represent sites of preferential formation of cracks.” [6, pp. 221-222]

Such a big difference, which the presence or absence of ribs on the surface of CTD and TMT bars, with ribs on the surface, can make to the performance of reinforced concrete structures, led CPWD [3], Swamy [2], and Papadakis et al. [1] to make their observations on the performance of reinforced concrete structures.

III. TMT BARS AND THE ASSOCIATED PROBLEMS

A collection of photographs showing plain bars without corrosion, and ribbed CTD bars and TMT bars, with significant corrosion, can be seen in Figure 1.

TMT bars (thermo mechanically treated/thermally hardened/quenched bars) have ribs on the surface. Furthermore, as explained later, the TMT process is a violent one that lowers ductility, leads to residual stress build-up and increase in the rate of corrosion in rebars. Thus, TMT bars, compared to plain round bars of the same material and similar quality of manufacturing, will have much greater susceptibility to corrosion than in the case of plain round bars.

There is another reason behind the excessive rate of corrosion in TMT bars. TMT bars generally contain a little more carbon than the plain round bars of low-carbon mild steel (grade Fe 250 MPa) of earlier periods did.

Figure1(e) shows a palm, covered with rust, when a fresh TMT rebar, sticking out of a shear wall under construction, was gently grabbed and the grip released thereafter. When the other palm grabbed a neighbouring rebar and thereupon released the grip, particles of rust fell on the foundation mat. This happened when the TMT bars were manufactured and supplied by a leading manufacturer of steel in India, and there was quality control at every stage of construction, as recorded in the legend to the photograph.

The presence of rust on TMT bars lowers the bond strength between TMT bars and the surrounding concrete (Kar, et al. [7, Table 1)], Kar [8, Table 2], and Varu [9]), and therewith lowers the performance of reinforced concrete elements under load besides lowering the time dependent performance of reinforced concrete elements dramatically for Alekseev [6], Papadakis, et al. [1], Swamy [2] and CPWD [3] to express their observations the way they did.

Through- the-thickness cracks in a shear wall (Figure 1(f)) show that reinforcement (Figure 1(e)), provided in the shear wall, designed to carry all the vertical and horizontal loads in one of several 52 storey buildings in Kolkata, proved to be inadequate even as nominal temperature reinforcement for concrete construction.

It is for similar reasons that it is not infrequent to see roof slabs, reinforced with TMT bars, developing through-the-thickness cracks within a year of construction.

These are all manifestations of lack of bond between corroded rebars and the surrounding concrete. It is all because loose rust on TMT bars, whether as visible on the palm in Figure 1(e) or whether as loose particles which fell on the foundation mat, prevent or diminish the bond between TMT bars and concrete.

Many such unintended, but real, field tests on the performance of concrete constructions with ribbed TMT bars, within days and months or within a few years of their construction [1, 2, 3], provide enough proof that, unlike in the case of plain round bars, TMT bars may not be depended upon as rebars for reasonably safe and durable concrete constructions.

The unacceptably poor performance of TMT bars is not only because of the provision and presence of ribs on the surface of rebars, but also because TMT bars have to contend with the violent act of quenching, that, besides giving strengths to rebars, hardens the peripheral region of rebars and in the process lowers ductility. The hardening of the peripheral region causes build-up of residual stresses, thereby leading to corrosion at accelerated rates (Figure 1(c), 1(d) and 1(e)) and early distress in concrete structures, and this hardening occasionally leads to cracks in the TMT bars (Figure 2(b)).

The claims by manufacturers of TMT bars, that the TMT process leaves rebars adequately ductile, cannot be true. The ill effects of low ductility on durability had been commented upon by Alekseev [6] and Kar [5]. Evidence (Figure 2(b)) can be found in the work of Pillai and Nair [10].

According to Alekseev, "A high-strength reinforcing rod is characterized by reduced ductility and usually a tendency towards corrosion cracking. Under the simultaneous action of tensile stresses and aggressive media, this specific type of corrosion is manifest as cracks in the steel structure commencing from the surface and macroscopically oriented at a right angle to the direction of tension." [6, pp. 207-208]

Alekseev [6, p. 209] adds: "Susceptibility to corrosion cracking is particularly enhanced by thermal hardening of the type 'hardening plus moderate tempering'." This is what can happen in the case of TMT bars.

Alekseev further adds: "all types of thermally hardened steels of classes At-IV, At-V and At-VI, including thermo mechanically hardened ones with heating in coils, are susceptible to corrosion cracking to a high degree." [6, p. 209]

All of these have been stated also in Ref. [11] : "Vulnerability of steel to stress corrosion is higher, the greater the metastability of phases composing it. The liability to corrosion cracking increases appreciably with the thermal hardening type "quenching plus medium tempering"." [11, p. 250]. This is precisely what can happen in the case of TMT bars.

With all that going seriously wrong with gaining strength through thermal hardening, as in the case of steel rebars, Alekseev made suggestions to retrieve the situation, if indeed it is feasible or practical at all. "The advantage of hot-rolled over thermally hardened reinforcement with respect to stability is evident. In order to enhance the durability of thermally hardened reinforcement to the level of that of hot-rolled reinforcement, the theoretical stress has to be reduced by 1.5 to 3 times. It is obvious that such a measure is of little use although its practical application cannot be ruled out." [6, p. 215]

Alekseev's suggestion on durability of reinforced concrete constructions with TMT bars has been cast aside by manufacturers, leading thereby to the poor state of health of infrastructure in India and elsewhere as commented upon by Papadakis, et al. [1], Swamy [2], CPWD [3] and Alekseev [6, 11].

IV. THE OTHER SIDE OF TMT BAR

Though in India and in many other countries, thermal hardening, through the TMT process, is an accepted way to enhance the strength of reinforcing bars, Alekseev [6] had raised the danger signals years ago.

"Insofar as high-strength reinforcement is concerned, measures should be adopted to evaluate as well as enhance its corrosion resistance under stress since its protection by concrete does not totally exclude the possibility of corrosion damage. The latter, especially localized damage, poses real danger of accidental situations in view of the brittle and usually sudden failure of corroding rods."

"The higher the degree of hardening achieved by thermal treatment, the lower the resistance of the reinforcement against corrosion cracking."

The "difference in stability is associated with the degree of structural in equilibrium which increases with increment in degree of thermal hardening."

"All thermally hardened classes are unstable; protective measures should be intensified as the class of reinforcement rises."

All these should work as danger signals against the use of higher and still higher strength rebars of steel where the gain in strength is achieved through the TMT process.

There is another matter one needs to be concerned about. It is fundamental that more the number of steps/processes involved in the manufacturing of a product, greater are the chances of something going wrong. Thus, in addition to all that has been written above about TMT bars, there can also be the added problems of quality, arising from processes associated with TMT bars (Pillai and Nair [10], Figure 2).

In spite of all these forewarnings, there have been continued efforts in increasing the level of thermal hardening. That is how one finds the raising of the highest grade of steel for reinforcing bars in the Indian Standard IS 1786:2008 [12] to Fe 700 (700 MPa) in Amendment No. 03, and also to 690 MPa in ASTM A615/A615M – 15A[15].

V. OTHER EFFECTS OF USING REBARS OF HIGHER AND HIGHER STRENGTH GRADES

5.1 Decreasing Moment Capacity

The reinforcing bars are meant for use in concrete constructions which include flexural elements, e.g., floor slabs, beams, etc.

Over the years, the compressive strength of concrete for general use has not increased much, whereas the yield strengths of steel for rebars have at least doubled from the earlier yield stress of 250 MPa to 500 MPa and now trebled to 700 MPa.

All of these mean that in a reinforced concrete flexural element, while the rebars of high strength steel will be expected to be strained more in keeping with higher yield strength of steel, and the limiting strain of concrete in the extreme fiber in the compression zone will remain virtually the same, the neutral axis will shift towards the compression face.

The resulting effective area of concrete in the compression zone will be less, and though the internal lever arm between the centroids of the compression and tensile forces will increase, the overall effect will be a fall in the moment capacity. At ultimate condition, the failure may be governed by sudden compression failure of concrete in a brittle manner. Good designers caution against such brittle failures.

Thus, to arrive at the required area of higher grade steel in the case of flexural elements, it will not be appropriate to simply scale down the originally determined cross sectional area of steel of the lower grade by the ratio (lower grade/higher grade).

5.2 Decreasing Savings in Costs

If any decrease in the moment capacity of the flexural element will not be permitted, more rebars of the higher grade steel will have to be provided such that steel will be strained much less than what its yield strength would have normally permitted.

This would minimize any perceived savings in using high strength steel, as there will be a lot more rebar areas strained less than yield. Worse, chances of brittle failure of concrete elements will increase under conditions of overload.

5.3 Widening Cracks in Concrete

The modulus of elasticity of the material remaining the same, if higher strength rebars will be permitted to be strained more, cracks in concrete in the tension face will be wider, facilitating corrosion in rebars.

5.4 Effects of Structures Failing Early

If a durable bridge, with lower grade steel with a plain round surface, and free from the ill effects of CTD or TMT processes, would have a life span of 100 years, and in comparison two or three bridges with high strength TMT bars of high susceptibility to corrosion and thus of shorter life spans would have to be built to have a collective life span of 100 years, as an alternative, the total cost in terms of money, disturbances to the normal activities of the society, and adverse impact on the local and global environment would be several times higher in the second case.

VI. THE SEARCH FOR THE IDEAL REBAR

The preceding shows that the use of rebars of high strength steel, even if it would be free from the ills of corrosion at accelerated rates and loss of ductility, may not be much beneficial in terms of cost of construction and reliability.

Figure 1 shows clearly that while rebars with plain surface are reasonably free from rust before use, TMT bars can have a lot of rust before being put to use. Moreover, it has been explained in **Section 2.2** that TMT bars may not be passivated inside concrete. This has led to the situation that prompted Papadakis, et al. [1], Swamy [2] and CPWD [3] to express their unhappiness. Much earlier, Alekseev [6, 11] had explained the ill effects of ribbed bars and TMT processes.

Given this background, the search for an ideal rebar could benefit from a study of different standards.

6.1 IS 1786 [12]

Today in India though the Indian Standard IS 1786 [12] permits the use of TMT bars with yield strength up to 700 MPa, and though TMT bar is the standard rebar in India, manufacturers appear to have preferred TMT bars of grades Fe 500 or Fe 500D, occasionally going for grade Fe 600.

6.2 IS 13920 [13]

The Indian Standard IS 13920 [13] on Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces, set up to set the right standard for the protection of structures against seismic forces, has expressly permitted the use of "high strength deformed steel bars produced by thermo-mechanical treatment process" when it was a primary requirement that the reinforcing bars for earthquake resistant structures would have to be ductile, and when it was also well known that TMT bars were not known to be reasonably ductile.

The Indian Standard IS 13920:2016 [13] does not permit the use of steel of grades greater than Fe 550, and structures in virtually all areas of India need be designed for seismic forces, generated by earthquakes of different magnitudes.

All of these suggest that it may not be permissible to use steel of grades higher than Fe 550 MPa, and it may not be desirable to use steel according to the provisions of IS 1786 :2008 --- 'High Strength Deformed Steel Bars and Wires for Concrete Reinforcement' --- Specification (Fourth Revision), Amendment No. 3, which permits the use of ribbed bars where the high strength is obtained partly through the TMT process.

6.3 AS / NZS 4671:2001 [14]

It is pertinent to note that being conscious about frequent earthquake events in New Zealand, the Australian/New Zealand Standard AS/NZS 4671:2001 [14] on Steel Reinforcing Materials has permitted the use of rebars only up to Grade 500 MPa, irrespective of the nature of structural need. The earthquake ductility grade rebar is GR 500 E with yield strength 500 MPa, % elongation ≥ 10 and an ultimate strength/yield strength ratio >1.15 - <1.40.

The AS/NZS 4671:2001 [14] has rebars of two other ductilities, viz., normal ductility and low ductility.

Unlike rebars of as many as 6 grades, with further variations, totaling 11 different categories, in IS 1786 [12], the AS/NZS [14] provides for rebars of only two strength grades, viz., 250 MPa and 500 MPa. With variations in ductility and elongation properties, there are a total of six categories of steel rebars.

The rebar of earthquake ductility is for rebars of only grade 500 MPa. This has been done probably on the recognition that higher the strength of steel, less is the ductility (indirectly expressed in terms of % elongation), and lower the % elongation, lower is the safety margin of structures under conditions of both static loading and dynamic loading.

6.4 ASTM A615 [15]

It is noteworthy that the Standard ASTM A615 [15] covers both deformed and plain carbon-steel bars.

It covers bars from 280 MPa (40000 psi) to 690 MPa (100000 psi). However, consensus design codes and specifications, such as “Building Code Requirements for Structural Concrete (ACI 318)” [16], does not recognize rebars of Grade 100 (690 MPa).

Though for design for shear and torsional forces, ACI 318 [16] continue to limit the yield strength of rebars to Grade 60 (420 MPa), on October 17, 2018, the ACI 318 gave preliminary approval for the use of high-strength rebar in several seismic applications. ACI 318 may approve Grade 80 (550 MPa) reinforcement for both seismic and non-seismic applications. It may also allow Grade 100 (690 MPa) for non-seismic applications.

6.5 IS 2062:2011 [17]

There are many standards which recognize high strength steel with appropriate chemical composition instead of going for the harmful CTD or TMT approaches which would have lowered ductility or % elongation. The Indian standard IS 2062:2011 is one such document for hot rolled low, medium and high tensile structural steel [17]. It provides information on chemical composition and mechanical properties for hot rolled low, medium and high tensile structural steel for yield strength up to 650 MPa.

VII. THE IDEAL REBAR

In the light of the above information, certain decisions can be made on the selection of reinforcing bars of steel for the construction of durable reinforced concrete structures, with a reasonable assurance of survivality of such structures during earthquake events, which is a must in India.

The decisions to be made relate to:

a) mechanical properties
b) manufacturing process
c) surface feature
d) configuration

For any steel, the most important considerations are its :

(a) chemical composition
(b) mechanical properties or performance requirements
(c) cost

It is recognized that the chemical composition is decided upon or arrived at keeping the performance requirements as well as the cost of materials in mind.

It is not uncommon to find (as in ASTM) that a decision on the chemical composition of the material for steel reinforcing bars is left to the manufacturer whose products are to satisfy the set requirements for mechanical properties or performance criteria.

Similarly, no particular chemical composition for the rebars is suggested here.

7.1 Mechanical Properties of the Ideal Steel Rebar

In due consideration of the preceding information, and with a view to making reinforced concrete constructions safe, durable and not overly uneconomical, and also to make matters practical and manageable, only three categories of rebars are proposed, as shown in Table 1.

Limits have been set for the $Y/Y_{specified}$ and $TS/Y_{specified}$ ratios. This is done in recognition of the fact that large $Y/Y_{specified}$ and $TS/Y_{specified}$ ratios may adversely affect the safety of structures during excessive overloads, as may happen occasionally, e.g., during earthquake events. This is because capacity of reinforcement, much greater than the design capacity, may lead to sudden brittle failure of the reinforced concrete elements, initiated by failure of concrete in the compression zone.

Through endorsement of IS 1786 [12], the Indian Reinforced Concrete Code of Practice IS 456[18] permits the use of rebars of 700 MPa, having a low % elongation of 10.0.

It is recognized here that in India virtually all structures are required to be designed for seismic forces. Thus, if one would value the wisdom in ACI 318 [16] and the wisdom in IS 13920 [13], the grade of steel for rebars in India should be limited to Fe 550 (550 MPa), or better still to 500 MPa steel as in New Zealand. This will be closer to 420 MPa as permitted in ACI 318 for shear, and the 500 MPa steel has a minimum percent elongation of 16.0, as shown in Table 1.

It cannot be overlooked here that the contribution of engineers of New Zealand to reinforced concrete design and earthquake engineering is highly regarded in the profession, and the Indian construction practices do not permit segregation of rebars for shear resistance from rebars for other causes.

If one would consider the practical situation from manufacture to design, management at site, construction and availability at all levels, as well as ductility (expressed in terms of % elongation) and resistance to corrosion, it makes practical sense to have just one grade: Fe 500, having properties as in Table 1.

7.2 Manufacturing Process

It has been recognized in the preceding that subjecting rebars to the CTD or the TMT process leads to loss in ductility, excessive corrosion in rebars, and early decay and distress in concrete constructions.

Rebars should thus be hot rolled according to standard practices. There shall be no cold working, e .g., in the CTD process, and there shall also be no quenching, e.g., in the TMT process for purposes of increasing strengths of rebars.

7.3 Surface Feature

It has been recognized in the preceding that the provision and presence of ribs on the surface of rebars cause excessive corrosion in rebars, and early decay and distress in concrete structures.

The rebars should thus be free from any surface protrusions or features of any type. Ideal rebars of steel shall thus be characterized by their plain surface without any protrusions, recesses or sharp features, which could lead to stress concentration and localized gaps between rebar and concrete, thereby increasing the susceptibility of rebars to corrosion.

7.4 Configuration

The ideal rebar should have a configuration that would provide engagement with concrete better than what a straight rod or even a ribbed bar would provide.

Logically, a rebar with a gentle wave-type configuration (Figure 3) could be expected to do that [8].

7.5 PSWC Bar

With a view to minimizing corrosion by eliminating ribs, and yet ensuring the required bond or engagement between rebars and the surrounding concrete, Kar [19] proposed the PSWC bar (initially named as C-bar) in 2010. Subsequently, the bar was re-christened PSWC bar in 2014 defining the bar fully where P stands for plain, S stands for surface, W stands for wave-type and C stands for configuration.

PSWC bar (Figure 3) of steel (yield stress preferably not greater than 550 MPa) is characterized by its plain surface and a gentle wave-type configuration. Its steel material is not limited to any specific chemical composition, as long as it satisfies the mechanical properties, set in Table 1.

Tests at several universities in India showed that the use of PSWC bars as rebars in concrete construction leads to :

a) improved load-carrying capacities of concrete flexural as well as compression elements [7, 8, 20, 21, 22, 23,24]
b) several-fold enhancement in ductility and energy absorbing capacity of concrete flexural elements [8, 20, 21].

It was consistently found that even in the absence of any rib or any other surface feature, the PSWC bar, characterized by its plain surface and a gentle wave-type configuration, performed the best among rebars of different types. This is in addition to the fact that as the PSWC bars have a plain surface, the life spans of constructions with such bars will be several times higher than the life spans of constructions with ribbed CTD or TMT bars [6,11]. And this by itself has many attendant benefits [8, 9, 19, 20,23].

The PSWC bars have gentle and uniform wave patterns along the length as in Figure 3, where the offset in the deformed configuration will be 4 mm to 6 mm (5 mm for standardization), and the pitch length will be 20d to 30d (preferably 30d for standardization), where d is the diameter of the rebar.

Compared to the cases of conventional plain or ribbed rebars, this configuration in PSWC bars led to the best effective bond or engagement between rebars and the surrounding concrete even when there was no rib on the surface of PSWC bars [7, 8, 9, 19, 20, 21, 22, 23, 24].

The TMT process is done away with, as the TMT process hardens rebars, lowers ductility and resistance to corrosion, and as furthermore, it is possible to make the required and desirable high strength steel [Table 1] without resorting to the TMT process, as shown in the Indian Standard IS 2062 Hot Rolled Low, Medium and High Tensile Structural Steel, Bureau of Indian Standards [17].

The combination of the wave-type configuration and the absence of ribs has done wonders [7, 8, 9, 19, 20, 21, 22, 23,24].

At no additional cost or effort, the use of PSWC bars, in lieu of conventional plain, CTD or TMT bars with ribs, leads to the following benefits:

a) several-fold longer life span of concrete structures
b) greater load-carrying capacities of reinforced concrete elements
c) several-fold increase in ductility and energy-absorbing capacity of concrete flexural elements
d) greater safety during earthquake events
e) greatly diminished damages to the local and global environments
f) greater sustainability on many counts, viz., greatly reduced life cycle cost, greater safety during earthquakes, reduced disruption to the society, greatly reduced demand on nature resources, and approximately 5% reduction in the total global emission of CO_2 from all sources.

7.6 Making of PSWC bars

PSWC bars can be given their wave pattern (Figure 3) at the last stand of the rolling mill process, or such bars can be cold formed, as the information, depicted in Figure 4, and the corresponding digitized information in Table 2 show that the cold forming of PSWC bars from hot formed conventional bars do not lead to significant changes in mechanical properties. In other words, unlike in the CTD process, cold forming of PSWC bars does not require significant straining.

There shall thus be no perceptible differences between the corrosion properties of hot formed PSWC bars and cold formed PSWC bars from hot rolled conventional plain bars.

VIII. DESIGN OF CONCRETE STRUCTURES WITH PSWC BARS

8.1 References 7, 8, 9, 19, 20, 21, 22, 23 and 24 show that the use of PSWC bars leads to considerable enhancement in load-carrying capacities and ductilities of concrete elements reinforced with PSWC bars.

Tests at different universities have shown improved performances of beams and columns, when reinforced with PSWC-bars of gentle wave-type configurations. Expectedly, enhancement in performance is sensitive to the offset and pitch length in the configuration pattern of PSWC-bars.

As an interim and a conservative measure, it is suggested that all the tables and provisions/ recommendations in ACI-318, IS 456 and other similar or related standards/guides/ handbooks/books be followed for the design and construction of reinforced concrete elements and structures while using PSWC-bars, except that

1. The ultimate strength in flexure in beams/slabs, etc. can be considered to be 10.0% (ten percent) higher when constructed with PSWC-bars
2. The available shear and torsional strength can be considered to be 5.0% (five percent) higher when constructed with PSWC-bars
3. Capacities of columns can be considered to be 5.0% (five percent) higher when constructed with PSWC-bars
4. For the design of flexural members, subjected to vibratory, impact and impulsive loads, advantage may be taken of the idealized load-deformation curve as shown in Figure 5.

IX. CONCLUDING REMARKS

1. Early decay and distress in reinforced concrete constructions of recent decades have been a matter of worldwide concern. In most cases, this early decay is due to corrosion in today's ribbed rebars (CTD or TMT) of steel.

2. At no added effort or cost, the use of PSWC bars, characterized by their plain surface and gentle wave-type configuration, can enhance the durability of reinforced concrete elements several fold, thereby significantly lowering the life cycle cost of construction and reducing demands on nature resources, including construction quality water.

3. Along the way, as the rate of decay and signs of distress in infrastructure are delayed very significantly, needs for repair, rehabilitation and renewal work will naturally be greatly delayed with the use of PSWC bars as rebars. The use of PSWC bars will thus minimize disruption to normal urban life in congested areas and will cause no frequent inconvenience, disturbance, and hardship to residents and commuters. Further, the use of PSWC bars will help avoid great expenses as cost of repair is much higher than the cost of normal constructions.

4. Compared to the cases of beams, columns and other constructions with conventional rebars, the use of PSWC bars raises the load-carrying capacities of all such constructions very significantly. It raises the ductility and energy absorbing capacities of flexural elements by several hundred percent, thereby offering the potential to save lives and properties during earthquakes.

5. The yield strength of steel for reinforcing bars for flexure and compression should be limited to 550 MPa, preferably to 500 MPa, and not to 700 MPa which has been shown in the Indian Standard IS 1786 [12].

6. Standard provisions in codes can be followed in the design and construction with PSWC bars; however, advantage can be taken of the increased load-carrying capacities, ductility and energy-absorbing capacity of reinforced concrete elements which will be constructed with PSWC bars.

7. PSWC bar perfectly satisfies the sustainability requirements of concrete constructions, as its use as rebars, at no added effort or cost, can (a) enhance the life span of concrete structures and other concrete constructions several fold and thus lower the life cycle cost to a fraction of what it is today, (b) increase the load-carrying capacities and therewith safety of reinforced concrete elements, (c) enhance ductility and energy-absorbing capacities of concrete flexural elements several fold thereby saving lives and properties during earthquakes, (d) lower very significantly the demands on nature resources that go into the making of cement, steel for rebars, aggregates and water, (e) lower very significantly the negative impact of construction on the local and global environment.

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Table 1 Mechanical properties of steel in PSWC bars

Sl. No. (1)	Property (2)	Fe 415 (3)	Fe 500 (4)	Fe 550 (5)
i)	0.2 percent proof stress/yield stress, *Min*, N/mm^2	415.0	500.0	550.0
ii)	0.2 percent proof stress/yield stress, *Max*, N/mm^2	500.0	600.0	660.0
iii)	$Y/Y_{specified}$ ratio[1]	1.02 -1.2	1.02 -1.2	1.02 -1.2
iv)	TS/ $Y_{specified}$ ratio[2]	$\geq$ 1.15 - $\leq$ 1.40	$\geq$ 1.15 - $\leq$ 1.40	$\geq$ 1.15 - $\leq$ 1.40
v)	Elongation, percent, *Min*. on gauge length 5.65√ A, where A is the cross-sectional area of the test piece	20.0	16.0	12.0

Note :

1) $Y/Y_{specified}$ ratio refers to ratio of actual yield strength or 0.2 percent of yield stress to specified yield stress of the test piece

2) TS/ $Y_{specified}$ ratio refers to ratio of tensile strength to specified yield stress of the test piece

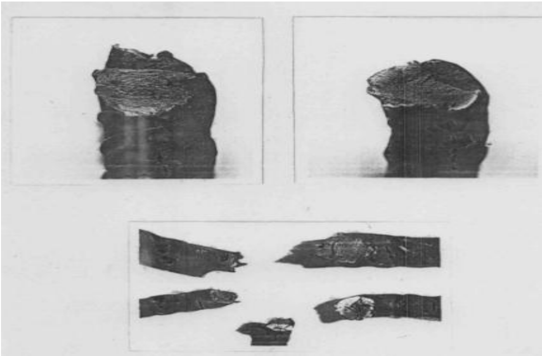
Additional Note :

1) The steel shall be suitable for welding processes

Table 2 Effects of cold forming of PSWC bar from hot rolled plain bar

	Type of Rebar (mm)	Upper Yield Stress (MPa)	Lower Yield (MPa)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
1	Plain	320.74	319.31	323.15	471.14	37.10
2	PSWC Bar	348.41		313.42	459.91	37.10

(a) : Rebars with ribs showing start of corrosion preferentially at the ribs of untwisted bars (four bottom bars) and corrosion all over the surface when the remaining length of the same bar was twisted beyond yield at a cold state (four top bars) (CTD bars)



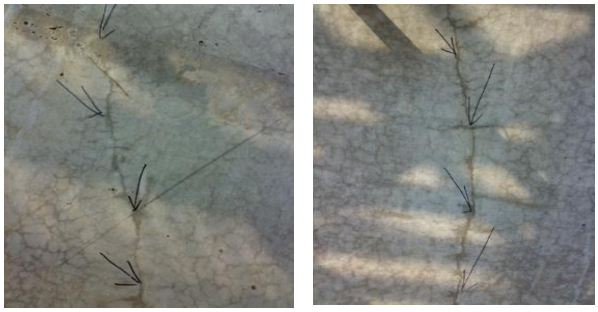
(b) Brittle failures in 8 to 32 mm dia cold twisted rebars with ribs (CTD bars)

(c) : Fresh ribbed TMT bars showing start of corrosion at ribs (three days after ribbed bars reached the construction site)

(d) : Absolutely fresh ribbed TMT bars stacked at the factory before despatch, showing onset of corrosion all over the surface

52-storey buildings under construction

(e) : Ribbed TMT bars coated with products of corrosion even before concreting
(designer one of the top designers in the world • contractor one of India's best •
rebars manufactured by one of India's best known manufacturers • there was quality control by a team of engineers from a university)

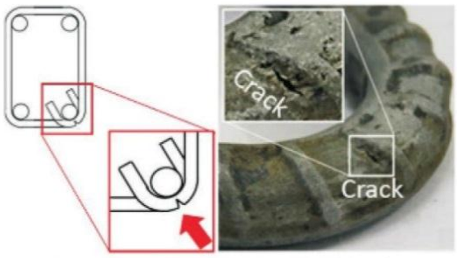


(f) : Through-the-thickness cracks in reinforced (with ribbed TMT bars in the figure above) concrete shear walls for tall buildings in Kolkata even before a floor was completed (project has top designer, proof design consultant, leading rebar maker, top contractor and quality monitoring agent) in 2011

(g) : Conventional rebars with plain surface as used to be used decades earlier; also as in PSWC bar

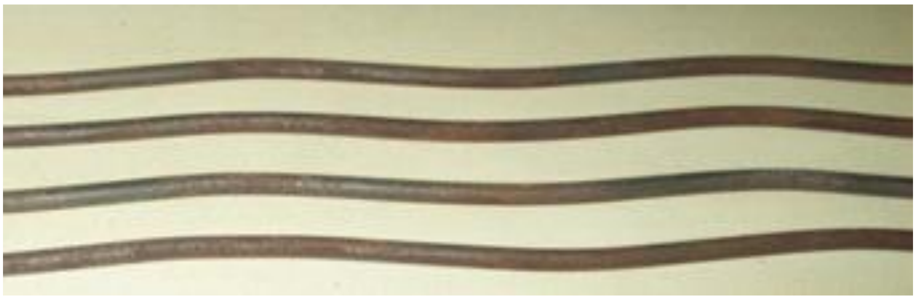
Figure 1. A collection of plain bars free from rust and CTD and TMT bars with various stages of corrosion

(a) : Non-uniform quenching of TMT bars

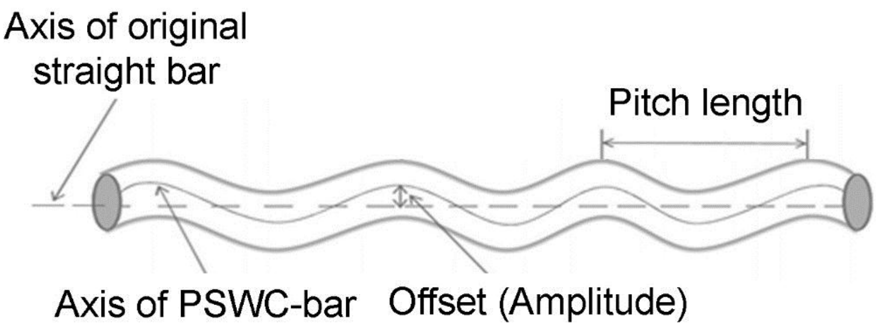


(b) : crack in TMT bars

Figure 2. Lack of quality in TMT bars
[10, R.G. Pillai, and S.A.O. Nair]

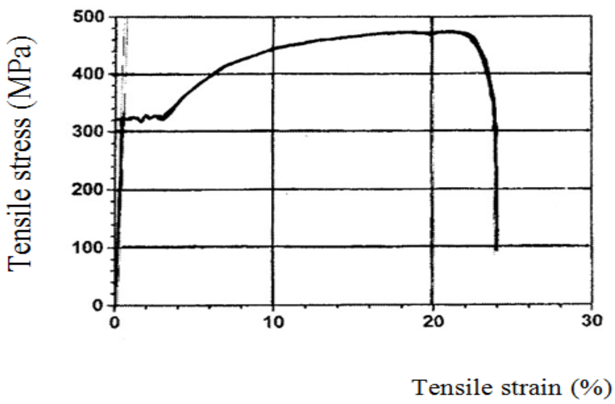


(a) : Elegant PSWC bars characterized by plain surface and gentle wave- type configuration (photograph of actual bars)

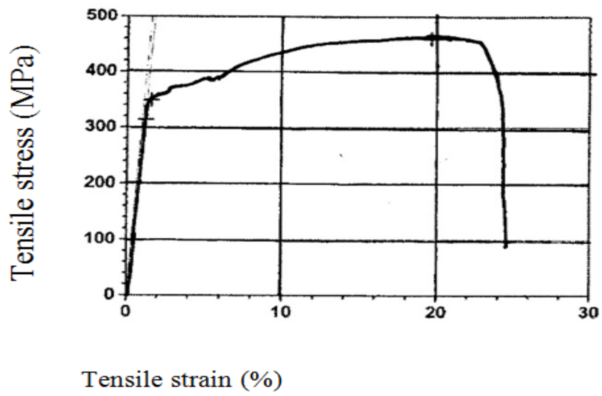


(b) : Defining features for PSWC Bars (schematic view)

Figure 3. PSWC bars



(a) : Stress vs strain of hot rolled plain bar



(b) : Stress vs strain of cold formed PSWC bar from hot rolled plain bar

Figure 4. Stress-strain curves of conventional plain bar and PSWC bar showing close similarities

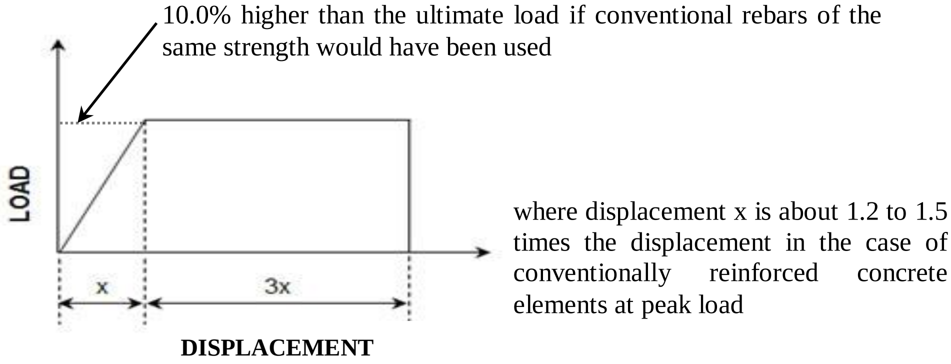


Figure 5. Idealized load-deformation curve for design of flexural elements reinforced with PSWC bars

