Chapter

Rebars for Durable Concrete Construction: Points to Ponder

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Abstract

Reinforced concrete is the number one medium of construction. It is important to have good quality concrete and reinforcing bar (rebar). It is equally important to have competent bond between rebar and concrete. About six decades ago ribbed rebars of high strength steel started replacing plain round bars of mild steel, the use of which had made reinforced concrete constructions durable. It was overlooked that ribbed rebars of carbon steel would be highly susceptible to corrosion at accelerated rates. That would not only make reinforced concrete constructions reach states of distress early, that could also destroy or reduce bond between ribbed rebars and concrete. The continued use of ribbed rebars of high strength carbon steel demonstrates a widespread lack of understanding of the phenomenon of bond between rebars and concrete. This lack of understanding of bond has led to the introduction of epoxy coated ribbed rebars, ribbed stainless steel bars and glass fiber reinforced and granite reinforced polymer rebars, all of which permit reinforced concrete carry static loads because of engagement between such rebars and concrete. But the load-carrying capacity of reinforced concrete elements is impaired, and such elements become vulnerable to local or even total failure during vibratory loads. The use of PSWC-BAR, characterized by its plain surface and wave-type configuration, permits the use of medium strength and high strength steel. In the absence of ribs, the rate of corrosion is greatly reduced. The use of PSWC-BARs, at no added effort or cost, in lieu of conventional ribbed bars, leads to enhancement of effective bond or engagement between such rebars and concrete, thereby leading to increased load-carrying capacity, several-fold higher life span, ductility and energy-absorbing capacity, and great reduction in life cycle cost and adverse impact of construction on the environment and the global climate. In keeping with a lack of understanding of bond between rebars and concrete, there is arbitrariness in the selection of the required level of percent elongation and ductility of rebars.

Keywords: bond, corrosion, deformed bar, durability of concrete constructions, percent elongation, PSWC-BAR, reinforcing bar, ribbed rebar

1. Introduction

Reinforced concrete is the number one medium of construction, in which reinforcing bar (rebar) is one of the two component elements; the other element being concrete.

It was in the mid-nineteenth century when builders in different countries experimented with concrete, reinforced with steel elements of different types.

Easy availability of the component materials, easy formability, rigidity, strength, safety and durability of reinforced concrete construction made more and more people interested in such constructions.

Plain round bars of mild steel became the standard rebar.

The time-dependent performance of concrete structures, reinforced with such bars, set the standards of performance in the context of durability.

Besides the external elements, e.g., water/moisture, oxygen, carbon dioxide, chlorides, sulphates, alkalis, and other deleterious materials, which can have destabilizing effects on concrete constructions, it cannot be overlooked that the intrinsic properties of the two principal constituent materials, viz., concrete and rebars, have much to do with durability of reinforced concrete; Kar [1].

Besides concrete and rebar, "bond" between concrete and rebar, though not a material by itself, and though no one buys it or pays for it like they buy or pay for concrete and rebar, is a property that is no less important than concrete and rebar are in the context of reinforced concrete construction.

Very little consideration has been given to what leads to good "bond", and what can prevent "bond" between concrete and reinforcing elements. Also important can be the selection of an appropriate percent elongation, better still, ductility, of the material of the rebar.

In the context of "bond" and its influence on the performance of reinforced concrete, Kar [2] has suggested three terms, viz., "bond", "effective bond" and "engagement". While the last two are synonymous, that cannot be said of "bond".

Kar [2] has shown that the quality of "engagement" between rebar and concrete can greatly influence the performance of reinforced concrete elements and structures.

Buoyed by the performance of reinforced concrete, with plain round bars as rebars, engineers thought of making reinforced concrete constructions more economical by using rebars of higher strength steel.

Gradually, many different types of round reinforcing bars were introduced; Abrams [3].

Forgetful of earlier unsatisfactory experiences in the nineteenth and early twentieth century with bars, having different types of protrusions on the surface, engineers decided that the use of high strength steel would be possible by increasing the bond between rebar and concrete by providing ribs on the surface of such rebars.

Plain round bars of mild steel thus gave way to rebars of high strength steel wherein the bars are characterized by the presence of ribs on the surface (**Figures 1** and **2**). Ribbed bars were introduced in the belief that ribbed surfaces would increase bond between rebars and concrete.

The provision of ribs on the surface of rebars of high strength steel was facilitated in 1947 by ASTM International [4] publishing ASTM A305, that provided Specifications on rebar deformation patterns.

Contrary to the beliefs and expectations that (a) the presence of ribs on the surface of rebars of steel would increase the "bond" between rebars and the surrounding concrete, and (b) there would be no detrimental effect of the ribs on the performance of concrete constructions, which may be reinforced with ribbed rebars, the presence of ribs on the surface of rebars may create void spaces, at isolated locations, between rebars and concrete, thereby decreasing "bond". However, the wedge action of ribs, together with the reduced "bond", may (or may not) lead to an increase in the "engagement" between rebars and concrete.

No thought was spared as to the likely consequences the use of bars, with surface deformations or ribs, could have on the long term performance, or even on the immediate performance and load-carrying capacities of reinforced concrete constructions; Kar [1, 2, 5].

Figure 1.
Typical cold twisted deformed (CTD) rebar, with lugs and protrusions on the surface and stresses beyond yield on the entire body, which replaced plain round bars starting the decade of the 1960's.

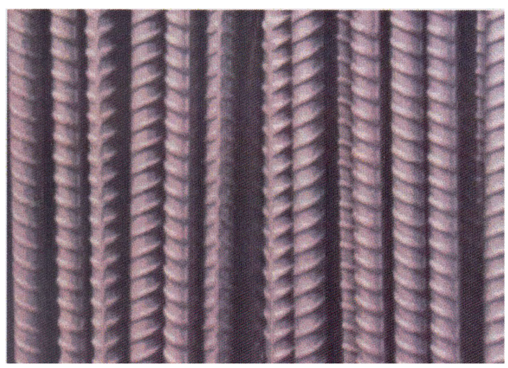


Figure 2.
Typical high strength TMT rebars with surface deformations, which replaced plain round bars starting the decade of the 1960's.

Engineers and manufacturers of rebars blindly followed the lead of ASTM International. The Bureau of Indian Standards (BIS) in India published the Standard IS 1786 on High Strength Deformed Steel bars and Wires for Concrete Reinforcement --- Specification [6].

Though plain round bars, as in IS 432 (Part I) [7], and Grade A bars in IS 2062 [8] were available, gradually plain round bars gave way to ribbed bars where the strength of steel in rebars was increased artificially by twisting the bars beyond yield at a cold state, giving rise to CTD bars (**Figure 1**).

With time, manufacturers of rebars in India and elsewhere adopted the technique of increasing strength through the centuries-old practice of quenching, couched in diplomatic language as thermomechanical treatment, giving rise to TMT bars (**Figure 2**).

During the last sixty years or so, almost all reinforced concrete constructions worldwide have been with ribbed rebars of high strength steel, whether of the CTD or TMT type or not.

The time-dependent performances of concrete structures (**Figures 3**–**5**), reinforced with these later day rebars, failed to match the time-dependent performance of concrete structures, which were reinforced with plain round bars of mild steel.

The relatively poor performance of concrete structures since the introduction of high strength rebars, with surface deformations, has caused worldwide concern.

Figure 3.
Distress in staging of overhead water reservoir due to corrosion in rebars.

Figure 4.
Abandoned hospital building a decade after construction in the new township of Salt Lake City, Kolkata.

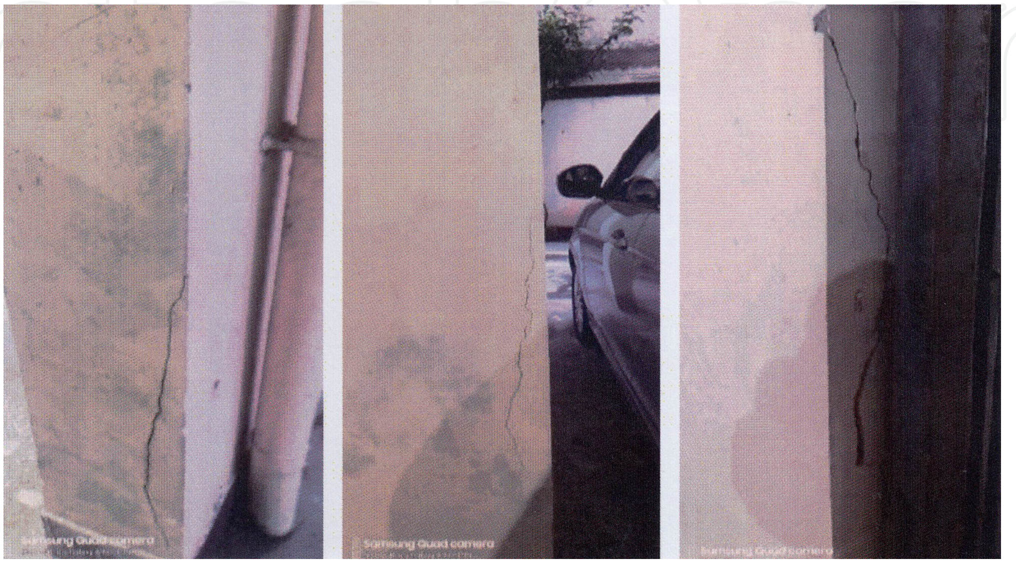


Figure 5.
Typical distress in ground level columns caused by rust in ribbed TMT bars in a 10 year old building in Kolkata.

There had to be reasons, and the reasons were not unknown; Alekseev [9, 10], and Kar [1, 5, 11–17]. But engineers and manufacturers of rebars paid no heed.

The rebars, with surface deformations, are today covered by the Indian Standard IS 1786 [6] for high strength deformed steel bars. The Standard covers both CTD and TMT bars. ASTM International in the USA published quite a few Specifications

(a) : Conventional rebars with plain surface as used to be used decades earlier; also as in PSWC-BAR

(b) : 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)

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

(d) : Fresh ribbed TMT bars (IS 1786) showing start of corrosion at ribs

(e) : Corroded TMT rebars (IS 1786) in pier under construction for flyover; products of corrosion streaking down faces of pier

(f) : 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)

(g) : Loose rust led to greatly lowered "engagement", i.e., "effective bond", causing 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 manufacturer, top contractor and quality monitoring agent) in 2011

(h) : The underside of Bridge No. 1014 up (before repairs) between Khurda Road and Palasa Stations under East Coast Railway, India

(i) : The underside of a bridge between Khurda Road and Palasa under East Coast Railway, India

Figure 6.
A collection of plain bars free from rust and ribbed CTD and TMT bars with various stages of corrosion.

on ribbed rebars of high strength steel. The most commonly used rebars are covered in ASTM A615/A615M [18].

In terms of durability, the structures may be adversely affected because of the inability of concrete to stand up to the external elements, e.g., chlorides, sulphastes, etc. or even to water as its presence may permit alkali-silica reaction in concrete in certain cases.

Most often, the durability of concrete constructions is adversely affected by corrosion in the steel rebars in the case of reinforced concrete (**Figures 3–6(h)** and **(i)**), and by corrosion in the wires and strands of steel in the case of pre-stressed concrete.

Though less frequent, corrosion in ribbed rebars (**Figure 2**), used as secondary reinforcement in prestressed concrete constructions, can trigger unacceptable conditions of distress in prestressed concrete constructions.

The focus here is on rebars and durability of reinforced concrete constructions, as influenced by rebars.

2. Observations following

2.1 The use of ribbed bars

Following the use of ribbed bars of high strength steel, the world has seen a significant fall in the long term performance of reinforced concrete constructions. Sights of decay and distress in concrete constructions, reinforced with ribbed rebars of steel, became inescapable (**Figures 3**–**5**) within years of their construction.

A 1999 survey of bridges and buildings of reinforced concrete construction in the public domain in and around Kolkata, India revealed that while none of the structures, built since the 1940s with plain round bars of mild steel, showed any sign of distress, all the structures built with ribbed bars (**Figure 1**) in the 1970s and 1980s were showing signs of distress; Kar [11].

In a 1991 article in ACI Materials Journal, American Concrete Institute, Papadakis, Vayenas and Fardis [19] wrote: "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 in 2007, Swamy [20] from UK was more forthright in his expression when he wrote in the Indian Concrete Journal: "The most direct and unquestionable evidence of the last two/three decades on the service life performance of our constructions and the resulting challenge that confronts us is the alarming and unacceptable rate at which our infrastructure systems all over the world are suffering from deterioration when exposed to real environments."

An analysis of the observations by Papadakis et al. [19], by Swamy [20] and by others leads to the recognition that the relatively poor performance of reinforced concrete constructions followed the start of use of ribbed rebars of high strength steel.

Figure 5 shows typical conditions of concrete columns, reinforced with ribbed rebars (**Figure 2**), ten years after the construction of a building in Kolkata. All the columns at the ground level of the building suffered a similar fate.

The findings of the 1999 survey as well as the structures in **Figures 3**–**5** show clearly that compared to concrete structures, reinforced with plain round bars of mild steel, concrete structures, reinforced with ribbed bars of medium strength and high strength steel, reach states of distress much earlier.

This excessive corrosion in ribbed rebars of carbon steel suggests that the susceptibility of ribbed rebars to corrosion at accelerated rates is an intrinsic nature of ribbed rebars of carbon steel.

However, there had been hesitation by engineers in recognizing that today's ribbed bars were highly susceptible to corrosion at accelerated rates, and this excessive corrosion in today's rebars is due to.

a. the damages caused to the ribs at the time of provision of ribs on the surface

b. the damages caused to the ribs at the time of transportation and handling of rebars

c. the presence of ribs on the surface of today's rebars.

The hesitation to recognize ribs as a principal cause of excessive corrosion in rebars led not only to the continued condemnation of all new reinforced concrete constructions to early decay, distress and failure, but also to ASTM International, BIS and such other organizations publishing multiple Specifications/Standards on rebars as imagined solutions to the problem of early distress in reinforced concrete constructions, e.g., ASTM International publishing A775 [21] for epoxy coated ribbed bars, and on its failure to solve the problem, ASTM International A955/A955M for Deformed and Plain Stainless Steel Bars [22], and when that did not work, ASTM International published A1055 [23] for zinc (first coat) and epoxy (2nd coat), which too has serious limitations, as epoxy coating prevents the all-important "bond" with concrete (**Figures 7** and **8**).

The lack of "bond" can have serious consequences: (a) cracks in structures (**Figure 6(g)**), (b) lowered load carrying capacities (Kar [2]), and (c) chunks of concrete falling (**Figure 9**) or even structures collapsing (**Figure 7**).

Like epoxy coated bars, stainless steel bars too fail to solve the problem, as ribbed bars of stainless steel too may corrode under conditions of exposure of concrete structures to chlorides, and additionally such bars may not bond or may not bond well with concrete.

Failing to recognize that the problem of early distress in today's reinforced concrete constructions is due to the use of ribbed rebars of steel as in the Indian Standard IS 1786 [6], BIS published the Indian Standard IS 13620 [24] for Fusion Bonded Epoxy Coated Reinforcing bars.

Just as BIS failed to recognize that the problem of early distress in reinforced concrete constructions started with the use of ribbed bars as in IS 1786, BIS also

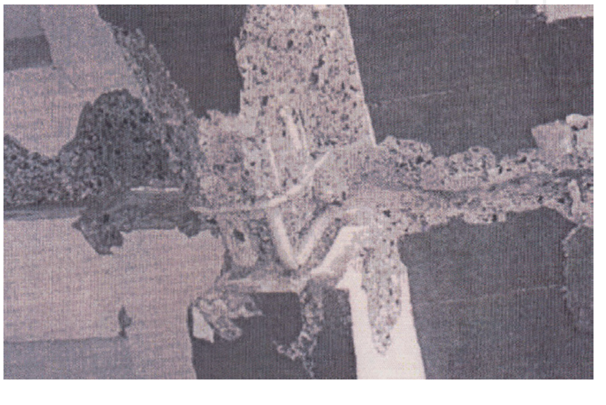


Figure 7.
Concrete easily separates from epoxy coated rebars under vibratory loading conditions whereas all structures are required to resist vibratory loads due to earthquakes; separation led to failure of buildings.

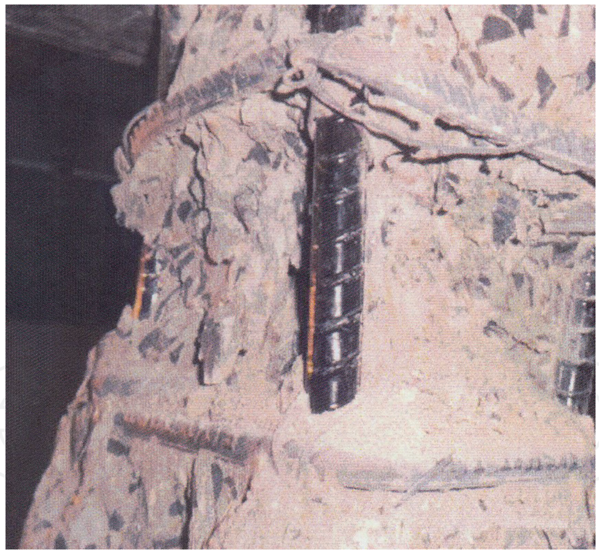


Figure 8.
The bond between epoxy coated rebar and concrete will be negligible, as seen in a column; the ribs on the surface of rebars engage the concrete up to a limit and that too when the loading is monotonous; absence of bond led to lower load-carrying capacity.

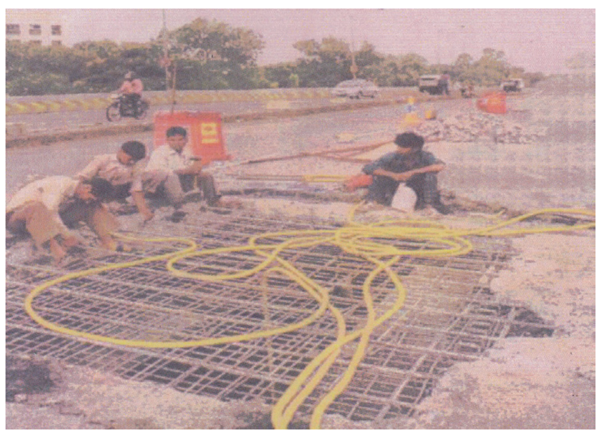


Figure 9.
A view of the deck of the Jogeswari flyover in Mumbai seven years after construction; concrete separated from rebars with poor bond qualities.

failed to recognize that, as cautioned in SubSection 5.6.1 of its Standard IS 456 [25], epoxy coated bars would not bond with the surrounding concrete, whereas the availability of the required "bond" is an essential requirement for reinforced concrete.

Similarly, as ASTM International published Specifications on epoxy coated bars and stainless steel bars, without a recognition or understanding of the basic cause(s) of early distress in reinforced concrete constructions of recent decades, and the significance of "bond" between rebars and the surrounding concrete, BIS in India followed suit by publishing the Indian Standard IS 16651:2017 on High Strength Deformed Stainless Steel bars and Wires for Concrete Reinforcement Specification [26].

The story is the same in many other countries.

It is recognized here that:

a. corrosion in rebars is greatly influenced by the intrinsic nature of the particular rebars; e.g., stainless steel bars will not generally corrode whereas mild steel and medium tensile steel bars will corrode, and high tensile strength steel bars with higher carbon contents will corrode more and at faster rates

b. the surface conditions/features on the rebar influence the rate of corrosion; the provision and the presence of ribs, as in bars conforming to IS 1786 [6] and ASTM A615/A615M [18] lead to acceleration in the rate of corrosion; Alekseev [9, 10], and Kar [1, 5, 12]

c. the manufacturing process influences the rate of corrosion; by stretching/stressing the bars beyond yield, the CTD process leads to corrosion at accelerated rates; the TMT process too hastens corrosion due to stresses from quenching effort; Alekseev [9, 10], and Kar [1, 5, 11, 12].

3. Intrinsic susceptibility of ribbed bars to corrosion

It has been recognized earlier that the problem of early distress in reinforced concrete structures started showing up following the start of use of steel reinforcing bars with ribs on the surface.

Figure 6(d) shows the start of corrosion at the ribs of TMT bars.

Figure 6(c) shows corrosion all over the surface of relatively fresh ribbed TMT bars.

The four bottom bars in **Figure 6(b)** show the start of corrosion preferentially at the ribs of untwisted ribbed bars while the four top bars show corrosion all over the surface of the ribbed bars as a consequence of stressing the bars beyond yield.

These show that:

a. the provision and presence of ribs invite corrosion

b. high stresses, specially stresses beyond yield, lead to corrosion at accelerated rates.

It cannot be overlooked that the ribs were provided out of a perceived necessity of improved "bond" between rebar and concrete when the rebars were upgraded from low-carbon to medium carbon or high carbon steel for higher strength. The truth is that the presence of ribs on the surface of rebars decreases "bond" between rebars and concrete. But the ribs may provide greater resistance to longitudinal movement of the bars relative to the surrounding concrete. Also, as found in the preceding, the ribs encourage corrosion in rebars; Alekseev [9] and Kar [1, 5].

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. nominal stresses in ribbed rebars 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 Items 1 to 4 approach or reach yield stress or strain levels

6. the 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; Kar [1].

The CTD and TMT processes are in violation of the inherent nature of steel to be ductile and to protect itself; Kar [1].

These CTD and TMT bars of high strength steel have another shortcoming to contend with: "The effect of stresses on corrosion is reflected more distinctly in the mechanical characteristics of the reinforcement, specially of high-strength steels with low ductility." [[10], pp. 203–204].

On the basis of extensive work in Russia, Alekseev [10] 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." [[10], pp. 221–222].

The preceding explains the reasons behind the intrinsic susceptibility of ribbed bars of steel to corrosion at accelerated rates.

It is the effect of this high susceptibility of ribbed bars to corrosion that led to the observations by Papadakis et al. [19] and Swamy [20], and to the types of early distress in reinforced concrete constructions, as depicted in **Figures 3**–**5**.

4. Solutions to early distress in concrete constructions

It has been recognized that rebars with surface deformations corrode excessively, leading to concrete constructions with such rebars reaching states of distress early.

The obvious solution to the problem would have been to use plain round bars as in the past. But engineers, having used in design and construction rebars of medium strength and high strength steel over the decades, would not like to go back to the use of rebars of steel having yield strength of 40 to 50 percent of the yield strength of steel in today's rebars.

Two options are available.

OPTION 1: WATERPROOFING TREATMENT.

In recognition of the fact that the problem of early distress, cited in the preceding, resulted primarily from a combination of two factors:

a. extra susceptibility (compared to that of plain round bars of mild steel) of ribbed bars, high yield strength deformed bars, and ribbed CTD and TMT bars to corrosion

b. availability of a moist environment inside concrete

and in further recognition that the problem of early distress in reinforced concrete structures could be avoided by preventing a moist environment inside concrete, Kar [13, 16, 27, 28] developed effective, practical and durable waterproofing systems and the corresponding specifications for waterproofing treatment to virtually all types of concrete structures, the implementation of which would prevent absorption of water/moisture into concrete, as in the cases of buildings, bridges and similarly exposed structures, or would prevent migration of water/moisture through the treated surface, as it would be in the cases of basements, tunnels, etc.

This waterproofing system has also the capacity to prevent the ingress of CO_2 and O_2 into the structure.

The concept of making concrete structures durable through surface protection in the nature of waterproofing treatment is gradually gaining ground in the USA and in other countries, and BIS, in recognition that concrete constructions with ribbed bars, as in IS 1786 [6], required extra protection against corrosion in the rebars, made waterproofing treatments a requirement for durability. SubSection 8.2.1 of IS 456:2000 [25] partly reads: "The life of the structure can be lengthened by providing extra cover to steel, by chamfering the corners or by using circular cross-section or by using surface coatings which prevent or reduce the ingress of water, carbon dioxide or aggressive chemicals."

It needs to be noted here that the provision of waterproofing treatments to concrete structures became essential because of the failure of the ribbed CTD and TMT bars, conforming to IS 1786 in India, ASTM A615/A615M [18] in the USA or bars conforming to similar other Standards/Specifications in other countries, to make concrete structures as durable as those used to be when the rebars had plain surfaces, and high strengths in the rebar materials were not achieved through the highly detrimental processes of cold twisting beyond yield as in the case of CTD bars (**Figure 6(b)**) or through quenching/thermal hardening/thermomechanical treatment as in the case of TMT bars (**Figure 6(c)** and **(d)**).

Kar's [16, 27, 28] art of making reinforced concrete structures durable through the provision of waterproofing treatment on the surface of such structures is an indirect way of solving the problem that was or that is invited with the use of the potentially damaging ribbed rebars of high strength steel, that was encouraged by ASTM International, BIS, ISO and such other organizations, which recommended and permitted the use of ribbed rebars, with or without the added processes of (a) cold twisting, as in CTD bars, or (b) quenching as in TMT bars, in the false belief or hope that concrete structures, reinforced with such bars, would be at least as durable as concrete structures of earlier era, which were reinforced with plain round bars of mild steel.

Though surface protection systems have worked pretty well, it does have the following shortcomings:

a. this additional treatment requires additional project time and expenditure

b. the materials used, and the specifications followed, may not be appropriate

c. there can be shortcomings in workmanship

d. such external treatments may be damaged or may have limited life spans, requiring repeat treatment

e. it does not solve the problem of excessive corrosion on the surface of rebars prior to concreting (**Figure 6(c)** and **(f)**), leading to reduction or total loss of bond between rusted rebars and concrete whereas the availability of competent "bond" between rebars and the surrounding concrete is a pre-requisite for successful performance of reinforced concrete construction.

In spite of these shortcomings, it is essential that all concrete structures, reinforced with ribbed rebars of steel, as in IS 1786 [6], ASTM A305 [4] or conforming to other Standards, be provided with surface protection in the nature of waterproofing treatment; Kar [12, 13, 16, 27, 28].

OPTION 2: PSWC-BAR AS A SOLUTION.

A better solution to the problem of early distress in reinforced concrete constructions with conventional rebars of medium strength and high strength steel would be to use plain round bars as it used to be before the 1960s or 1970s.

That would have solved the problem of excessive corrosion in rebars, and that would have made reinforced concrete constructions as durable as such constructions used to be in the past.

But the problem is that the requirement of much longer development/anchor length might not have permitted the use of plain round bars of medium strength and high strength steel.

With the innovative concept of PSWC-BAR, Kar [14] provided a direct solution (at no added effort or cost) to the problem of early distress in concrete constructions with ribbed rebars of high strength carbon steel. PSWC-BAR was initially named as C-bar.

Kar [5] explained why PSWC-BAR is the most ideal rebar for reinforced concrete constructions.

The use of PSWC-BAR, at no added effort or cost, not only solves the problem of early distress in reinforced concrete constructions through several-fold enhancement of life span of such constructions, it also enhances several fold the ductility and energy-absorbing capacity of reinforced concrete constructions; Kar [2].

The several-fold enhancement of life span, at no added effort or cost, has the effect of lowering the life cycle cost of reinforced concrete construction to a fraction of what it is today.

The use of PSWC-BAR increases load-carrying capacities of reinforced concrete elements, and through the several-fold enhancement of life span, the use of PSWC-BAR minimizes the harmful effects of construction on the environment and the global climate through considerable lowering of the need for the manufacture of cement, steel, etc. Kar [29].

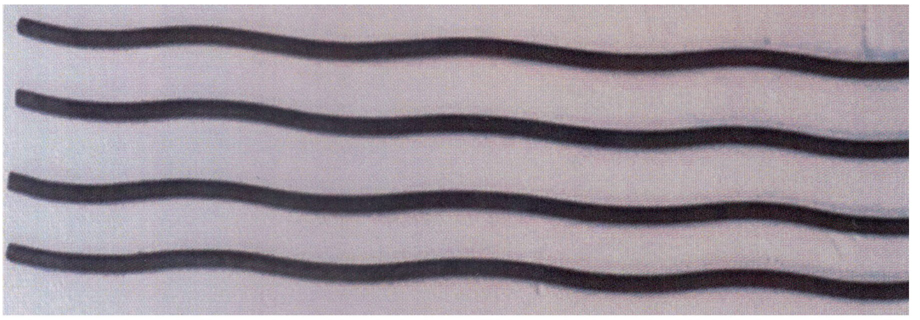
PSWC-BAR, characterized by its **plain surface** and **wave-type configuration** (**Figure 10**), solves the problem of early distress in reinforced concrete constructions that can result from the use of conventional ribbed bars of medium strength and high strength steel, by eliminating initiation of corrosion at the roots of ribs.

PSWC-BAR, because of the absence of ribs or any other special surface feature, if made of the same steel, will not corrode more than conventional plain round bars would do.

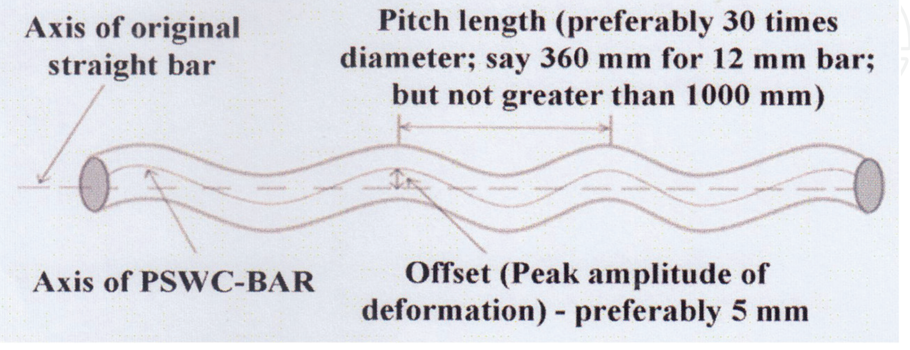
PSWC-BAR, because of its gentle wave-type configuration, enhances "effective bond", i.e., "engagement" between rebar and concrete; Kar [2]. Tests on beams and columns at different universities have shown that, among all types of rebars, PSWC-BAR, with its wave-type configuration, provides the best "engagement" between rebar and concrete, leading to significant enhancement of the various positive attributes of reinforced concrete; Kar [2, 17, 30, 31] and Varu [32].

While the test for loose rust and bond, or say, loss of bond, may lead to disqualification of most or all ribbed bars, conforming to IS 1786, and such other Standards, numerous tests on beams and columns have consistently shown that among rebars of steel, the use of PSWC-BAR, free from the ill effects of ribs, and if manufactured as Grade A of Hot Rolled Medium and High Tensile Structural Steel, as in IS 2062 [8], or conforming to appropriate Standards for plain round bars, can lead to the best load-carrying capacities, ductility and energy-absorbing capacity; Kar [2], indicating thereby that the "effective bond" is the best in the case of PSWC-BARs.

Besides these big fundamental differences between today's ribbed bars, as in IS 1786, and PSWC-BARs (**Figure 10**) as in IS 2062 [8], there lies the undisputedly



(a)



(b)

Figure 10.
PSWC-BAR of steel, characterized by plain surface and gentle wave-type configuration. (a) typical PSWC-BARs of steel, characterized by plain surface and gentle wave-type configurations. (b) schematic view of a typical PSWC-BAR.

stark difference between the very poor time-dependent performances (durability) of concrete structures, reinforced with ribbed bars, as in IS 1786 [6], ASTM A615/A615M [18] and such other Standards/Specifications elsewhere and the time-dependent performances of concrete structures, reinforced with hot rolled plain round bars with wave-type configuration, which are characteristic of PSWC-BARs.

There are various other advantages of using PSWC-BAR as rebars in reinforced concrete construction. A comparison of the load–displacement plots in **Figure 11(a)** and **(b)** show clearly that:

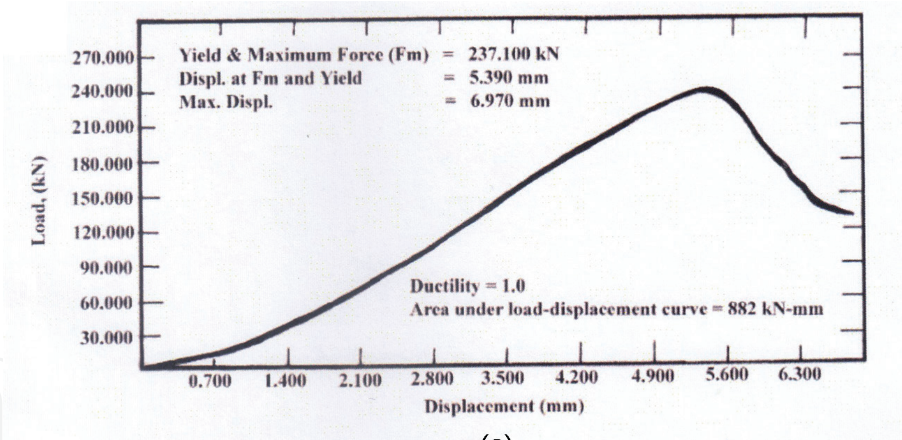
a. because of several fold higher ductility and energy-absorbing capacity, the use of PSWC-BARs as rebars has the potential to prevent structural failures and catastrophes during earthquakes

b. because of several times higher deflection (displacement) of flexural elements, there can be visible warnings before failure, thereby saving lives.

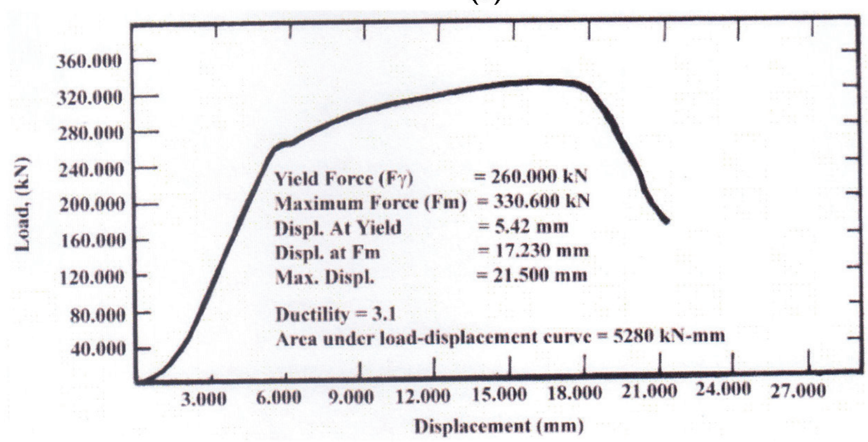
c. load-carrying capacities of reinforced concrete elements increase when PSWC-BARs are used.

Recommended mechanical properties of PSWC-BAR for durable and earthquake resistant concrete constructions are provided in **Table 1**.

Kar [5, 14–17] has written extensively on PSWC-BAR, and, encouraged by the many benefits, which the use of PSWC-BARs can provide, students at different universities have written a number of theses on the relative performances of concrete elements, reinforced with PSWC-BARs and conventional rebars.



(a)



(b)

Figure 11.
Ductile response of beam reinforced with PSWC –BAR. (a) Load–displacement plot of beam with conventional rebars showing failure as the stress in rebars reached the yield stress level. (b) Load–displacement plot of beam with PSWC-BARS showing failure as the stress in rebars went past yield and approached the ultimate. Note: The two plots in (a) and (b) are drawn to different scales.

Sl. No. (1)	Property (2)	Fe 415 (3)	Fe 500 (4)	Fe 550 (5)
i)	yield stress, *Min*, N/mm^2	415.0	500.0	550.0
ii)	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]	≥ 1.15 - ≤ 1.40	≥ 1.15 - ≤ 1.40	≥ 1.15 - ≤ 1.40
v)	Elongation, percent, *Min*. on gauge length $5.65\sqrt{A}$, 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 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 1.
Mechanical properties of steel in PSWC-BARs.

5. Bond in reinforced concrete

Bond between rebars and their surrounding concrete is of utmost importance in the context of reinforced concrete.

This bond, when adequately developed, permits composite response of reinforced concrete through effective transfer of forces between concrete and rebar.

Any reduction in bond, below a certain level, will lead to a reduction, or in extreme cases, a total loss of load-carrying capacities of the constructed structures, as it happened during the Bhuj earthquake on 26 January 2001 when three buildings, reinforced with epoxy coated bars, collapsed 300 kilometers away in Ahmedabad, India (**Figure 7**).

In the case of plain rebars of mild steel or carbon steel, when free from the damaging effects of the ribs as well as the CTD and TMT processes, there will be chemical bond between the mortar in concrete and the hard adherent products of very limited corrosion on the steel material, as in the cases of plain round bars of mild steel or, better still, PSWC-BARs, conforming to plain round rods of Grade A of structural steel in the Indian Standard IS 2062 [8], in which case the rods are given the wave-type configuration (**Figure 10**) at the end of the rolling mill process; Kar [14].

Similarly, PSWC-BARs can be made to conform to provisions in existing Standards/Specifications for plain round bars in other countries. Alternatively, Standards may be specifically prepared for PSWC-BARs.

The chemical bond between the mortar in concrete and the hard and adherent products of corrosion on the surface of PSWC-BARs develops shear capacity at the interface of concrete and the rebar for the transfer of forces, through shear, from concrete to rebars.

In the context of reinforced concrete, this is the "bond" engineers have been familiar with.

This should suggest that, technically speaking, there can be no "bond" between concrete and a painted surface, like the surface of an epoxy coated bar (**Figure 8**), or similarly between concrete and a stainless steel bar.

The same situation can develop if there will be loose rust on the surface of rebars as in the case of ribbed CTD or TMT bars (**Figure 6(f)**), as in IS 1786, which are the most widely used rebars in India.

Figure 6(g) shows that the loss of bond rendered the reinforcement, that was provided for load-carrying requirements, insufficient even as minor temperature reinforcements, and thereby led to the development of through-the-thickness shrinkage cracks in the shear walls even though it was a well-engineered project, except that, as per conventional practices in India, ribbed bars, as in IS 1786 [6], are used without the required scrutiny for "bond", that is set in SubSection 5.6.1 of IS 456 [25].

This is what happened in the case of the ribbed TMT bars in **Figure 6(f)** even when the bars were manufactured by a leading manufacturer of rebars and other products of steel in India.

There is more to "bond".

It is recognized that manufacturers/sellers of epoxy coated and stainless steel bars may not agree to the suggestion that there is no "bond" between epoxy coated or stainless steel bars and the surrounding concrete.

In the absence of any reliable test method to measure "bond" or bond strength in the cases of ribbed bars, engineers too tend to agree with manufacturers and sellers of epoxy coated and stainless steel bars, and they might even suggest that their tests have shown that the bond strength of epoxy coated bars is sixty percent or even eighty percent of that of uncoated bars.

The observations by engineers may be right, but their claims on "bond" are wrong. There are various reasons for it.

There is generally no "bond" between concrete and epoxy coated or stainless steel bars (**Figures 7–9**).

Any resistance to pull-out forces in the case of epoxy coated ribbed bars or ribbed stainless steel bars is essentially due to the wedge action of ribs embedded in concrete.

In the present context of bond, the epoxy coating on fusion bonded epoxy coated bars, as in IS 13620 [24], ASTM A775 [21], ASTM A934/A934M [33], ASTM A1055 [23] and similar Standards/Specifications on epoxy coated bars in other countries can be thought of as "coats of paints" as noted in SubSection 5.6.1 of IS 456 [25].

Recognizing that coats of paints, like loose rust, oil, etc. could destroy or at least reduce "bond", IS 456, the basic reinforced concrete code of practice in India, has put words of caution in SubSection 5.6.1 of its Section **5.6 Reinforcement** thus: 5.6.1 "All reinforcement shall be free from loose mill scales, loose rust and coats of paints, oil, mud or any other substances which may destroy or reduce bond. Sand blasting or other treatment is recommended to clean reinforcement."

In construction with fusion bonded epoxy coated rebars in India or elsewhere, no sand blasting or other treatment is provided so as to meet the requirements set in IS 456 or in any other document, and so as to ensure that there would be competent and adequate bond between such bars and the surrounding concrete.

It is possible that in recognition of this reality, IS 456 in its Section **5.6 Reinforcement** did not consider epoxy coated bars, as in IS 13620 [24], or stainless steel bars, as in IS 16651 [26], for possible use as rebars in reinforced concrete construction.

Though IS 456, the basic Indian Standard for reinforced concrete construction, does not approve of the use of epoxy coated bars as in IS 13620 [24] and stainless steel bars as in IS 16651 [26], such bars, which do not bond with concrete, with attended shortcomings in the performance of concrete constructions, do find use in reinforced concrete constructions in India and elsewhere.

In a series of tests by Varu [32] on thirtythree reinforced concrete columns at Nirma University in Ahmedabad, India, nine columns were reinforced with epoxy coated bars; of which three columns were with epoxy coated plain round bars, three columns were with epoxy-coated ribbed TMT bars of the type in IS 1786 [6], and three columns were with epoxy coated PSWC-BARs.

There is no suggestion that PSWC-BARs and conventional plain round bars may ever be given epoxy coating for protection. But in the test program these bars too were given epoxy coating just to have a more comprehensive understanding of the influence of surface coating (see SubSection 5.6.1 of IS 456 [25]) on load-carrying capacities and "bond" or "engagement".

The full details will be found in the thesis by Varu [32]. The observations can also be found in a few articles; Kar [2], and Kar, Dave and Varu [30].

Among other observations, it was observed:

a. unlike in the cases of the twentyfour columns with uncoated rebars of different types, there were clear indications at the failure region of all the nine columns with epoxy coated rebars that there was no bond of concrete/concrete mortar with the epoxy coated bars. A typical case is seen in **Figure 8**.

b. the epoxy coated bars led to failure of the columns at loads which were less than the loads at which the other similarly constructed, but with uncoated bars of same/similar manufacture had failed. It appeared that the coated bars did not participate in sharing loads on the columns; Kar et al. [30].

In the absence of any bond, the use of epoxy coated and stainless steel bars will lead to under-performance of reinforced concrete elements; Kar et al. [30] and Kar [2], and the use of such bars can lead to unacceptable consequences during vibratory loads (**Figure 10**), specially during earthquake events (**Figure 8**), as it happened when several multi-storey buildings in Ahmedabad collapsed on 26 January 2001 during the earthquake at Bhuj 300 km away.

The failures occurred due to separation between epoxy coated rebars and the surrounding concrete (**Figure 7**).

These should be proof enough that any claim of 60–80 percent "bond" between epoxy coated bars and concrete is wrong.

This should suggest that all concrete structures which were constructed with fusion bonded epoxy coated rebars, are suspect. In other words,

a. the margin of safety in structures with epoxy coated ribbed bars is less than what it may be thought to be as per conventional design; Kar [2] suggested modification to current design practices by considering the "effective bond" or "engagement" instead of assuming that there is competent "bond" between epoxy coated rebars and concrete.

b. all concrete structures, reinforced with epoxy coated bars, remain specially vulnerable against vibratory loads, including earthquakes, as evidenced in the failure of structures in Ahmedabad during the Bhuj earthquake of 26 January 2001.

In the cases of rebars, with ribs on the surface, where a certain amount of resistance to slippage is available, it is partly due to "bond" and partly due to the interlocking of the ribs with the surrounding concrete. From an engineering point of view, this resistance to slippage may preferably be referred to as "effective bond" or "engagement", instead of "bond".

Thus, though in the context of reinforced concrete, engineers have traditionally used only one term, i.e., "bond", and though in the context of reinforced concrete, where the rebar is a conventional plain bar of mild steel or carbon steel (**Figure 6(a)**), the use of the term "bond" may not create any confusion, the terms "effective bond" and "engagement" may be the more appropriate terms in the case of ribbed bars (**Figures 2** and **6(b)** and **(c)**) and PSWC-BARs (**Figure 10**), ribbed stainless steel bars, ribbed epoxy coated bars, polymer coated glass fiber reinforced bars, etc.

In the case of a PSWC-BAR, devoid of ribs or any other surface feature, there will be the "bond" on the entire surface, and in addition, the wave pattern along the length of the bar will provide physical resistance to slippage. The sum total of the "bond" and the "physical resistance" in the case of a PSWC-BAR can be termed as "effective bond" or "engagement".

Tests on numerous reinforced concrete beams and columns, with reinforcing bars of different types, at different universities have consistently shown that "the effective bond" or "engagement" is the highest in the case of PSWC-BARs, leading to the highest load-carrying capacities as well as several hundred percent higher ductilities and energy-absorbing capacities compared to the cases of conventional bars without the wave-type configuration; Kar [2].

In the context of reinforced concrete, there should thus be a recognition of "effective bond" or "engagement", and a clear understanding of "bond".

For similar reasons, the use of the term "engagement" will hopefully avoid a false belief that there is bond between stainless steel bars and the surrounding concrete, and it will hopefully avoid the type of collapses of reinforced concrete bridges and buildings that Ahmedabad was witness to during the earthquake of 26 January 2001, 300 kilometers away at Bhuj (**Figure 7**).

There are instances where chunks of concrete fell down from bridge decks which were constructed with ribbed TMT bars as in IS 1786 [6]. **Figure 9** shows one such example.

It should help put a stop to the use of not only the conventional epoxy coated bars, as in IS 13620 [24], but also to bars where the top coat is with epoxy as in

ASTM A1055 [23], and also to stainless steel bars as in ASTM A955/A955M [22] and IS 16651 [26], as, unlike in the cases of low carbon steel bars, stainless steel bars will not develop a thin layer of strong adherent rust on their surface for bonding with mortar in concrete.

Also, these bars stand in the way of composite response of concrete and the embedded bars, because of which even the capacity to carry static loads would be less than those which would have been arrived at on the basis of conventional design practices; Kar et al. [30] and Kar [2].

In the context of bond, besides the information provided hereinabove, Kar [14] had suggested that in the case of ribbed bars, coarse aggregates could in places rest on/against neighboring ribs (**Figure 12**), thereby blocking mortar from bonding with rebars, and also preventing passivation of rebars at such isolated locations. The void spaces aid the cause of corrosion.

In their tests, Mohammed, et al. [34] too observed void spaces beneath ribbed bars, resulting in higher rates of corrosion in ribbed bars than in the case of plain bars.

Whether in India or abroad, it has been the practice to assume that the use of ribbed bars provides the required bond between such bars and the surrounding concrete.

Though the presence of ribs on the surface of bars decreases the "bond", when compared to the cases of plain bars, the presence of ribs on the surface of bars may in some cases increase the "engagement".

Figure 6(g) presents a case where the absence of "bond" led to a decrease in the "engagement" between rebar and the surrounding concrete.

To start with, ribs were provided on the surface of rebars of high strength steel with an intent to increase bond between such rebars and concrete. This act boomeranged as it led to an acceleration in the rate of decay in reinforced concrete constructions.

The high strength in steel was/is gained in some cases either through the twisting of the bars beyond yield at a cold state or through quenching. The provision and the presence of the ribs, coupled with the twisting beyond yield or the quenching, lead to corrosion at unacceptably accelerated rates on the surface of the rebars; Alekseev [9, 10], and Kar [1, 5, 11–17] (**Figure 6(b)** and **(f)**), resulting in reduction or total destruction of the "bond" (**Figure 6(g)**). While the immediate effect of the

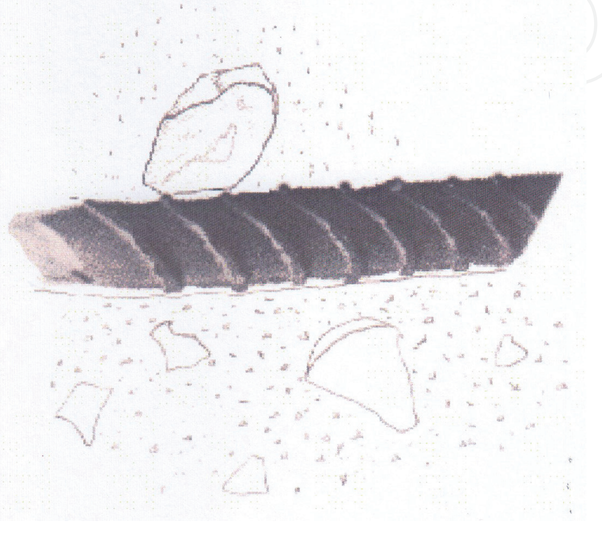


Figure 12.
Barrier effect of ribs, lugs and protrusions on the surface of ribbed rebars of steel preventing cement mortar from coming in contact with rebar.

destruction of "bond" is visible in **Figure 6(g)**, the long term effects are visible in **Figures 3–6(h)** and **(i)**.

Besides questionable "bond", the ribbed CTD and TMT bars, as in IS 1786 [6], meant for use as rebars in reinforced concrete construction, may not be permitted to be used as rebars, as because, such bars, with high susceptibility to corrosion at accelerated rates, will in many or most cases, fail the qualification test for rebars which have been set in SubSection 5.6.1 for reinforcement in IS 456 [25].

An example will be found in **Figure 6(g)** where it is seen that in the construction of six 48–52 storeyed buildings at a site, the shear walls, which in the absence of columns, were reasonably reinforced, developed through-the-thickness shrinkage cracks, about a metre apart as excessive loose rust on ribbed TMT bars (**Figure 6(f)**), prevented/destroyed "bond" between concrete and the highly rusted fresh rebars.

Visits to construction sites revealed that easily visible through-the-thickness shrinkage cracks in new constructions were very common. This lack of "bond" can lower the load-carrying capacities of such constructions.

The bars, conforming to IS 1786, were thus unfit for construction, at least in the light of the requirements in SubSection 5.6.1 of IS 456.

In the face of all the problems of insufficient "bond" in the case of ribbed rebars of high strength steel, epoxy coated ribbed bars, ribbed bars of stainless steel, and unacceptably high rate of corrosion in rebars, conforming to IS 1786, PSWC-BAR of medium tensile and high tensile steel (**Table 1**), conforming to IS 2062 [8], or to any other appropriate Standard/Specification for plain round bars of carbon steel of high strength steel, stands out as the only bar of high strength steel that is free from the varied problems of all other bars of high strength steel.

PSWC-BAR, endowed with the property of best "engagement", i. e., "effective bond" with concrete, also stands out as the only bar, the use of which, besides several-fold enhancement of life span, increases, by several hundred percent ductility and energy absorbing capacity of reinforced concrete construction (**Figure 11**) and Kar [2].

It is apparent that there has not been a clear understanding of the phenomenon of "bond" between rebar and concrete, what creates this "bond", what can affect the development of "bond", and what are its roles in the performance of reinforced concrete.

It is because of this lack of understanding of "bond" and its significance that made manufacturers and sellers of rebars, designers of reinforced concrete structures, construction engineers, and officials of BIS and such other organizations, who put the stamp of approval on ribbed rebars, overlook all these years the reality, the cautions in text books and Standards which read something like: all reinforcement shall be free from loose mill scales, loose rust and coats of paints, oil, mud or any other substance which may destroy or reduce bond.

It is this total failure to recognize the many significances of "bond" in the realm of reinforced concrete that facilitated the unchecked use of ribbed bars in reinforced concrete construction all these years, and in the process caused very significant losses to property owners, and great harm to the national wealth of countries, as well as to the environment and the global climate.

The facts, that (a) ribbed bars, conforming to IS 1786 and to Standards/Specifications on ribbed bars in other countries, are highly prone to the development of loose rust on the surface of such rebars, (**Figure 6(f)**), (b) this rust can "destroy or reduce bond" between concrete and rebars (**Figure 6(g)**), (c) without competent bond between rebar and concrete there cannot be reinforced concrete in its true sense, and (d) the loose rust will prevent any possible passivation of rebars by the alkaline pore water in concrete, and thus stand in the way of protection of rebars against corrosion unless concrete constructions will be given surface protection in the nature of waterproofing treatment, have not sunk into the minds of all those who should have known, are obvious from the continued poor performance of the structures in **Figures 3**–**6(h)** and **(i)**, and uncounted other structures which have been and are being constructed with ribbed bars.

Kar [2] has shown that besides success and failure, and besides the issue of durability, the "effective bond" or "engagement" between rebars and the surrounding concrete may influence the load-carrying capacity, ductility and energy-absorbing capacity of reinforced concrete elements.

6. Percent elongation of rebar

Percent elongation is an important measure of ductility of rebars, that can influence the performance of the rebar and in turn the performance of concrete elements under load as well as under exposure to the environment; Kar [14]. The percent elongation is of course a very important property that may greatly influence the survivality of reinforced concrete constructions during earthquake events.

In recognition of the fact that the changing material compositions and manufacturing processes, as well as the increasing yield strengths of rebar materials during recent decades, are generally associated with decreasing percent elongation, the Specifications of ASTM International and the Standards of BIS allow/permit the use of rebars with smaller percent elongation properties with increasing yield strength of the rebar material.

It is recognized here that there are certain differences between the gage/gauge lengths in the ASTM and BIS test specimens. However, these differences do not substantially affect the following observations on percent elongation.

ASTM A615/A615M [18] of 12 Jan, 2016 has set the minimum percent elongation of rebars for Grades 75, 80 and 100, i.e., yield strengths of 520 MPa, 550 MPa and 690 MPa, to 7 percent for rebars having diameters up to 25 mm, and an even lower 6 percent for rebars having diameters greater than 25 mm, whereas for Grade 40 (280 MPa) and Grade 60 (420 MPa) bars, ASTM sets the minimum percent elongation at 12 and 9, respectively.

Similarly, IS 1786 [6], through its Amendment No. 03, dated 19-09-2017, has set the minimum percent elongation at 10.0, 10.0 and 10.0 for rebars of yield strengths 600 MPa, 650 MPa and 700 MPa, whereas it has set allowable percent elongations at 14.5 to 18.0 for different varieties of 415 MPa bars, and 12.0 to 16.0 for different types of 500 MPa bars.

Several questions arise, viz.,

a. if once it is recognized that the percent elongation of the steel material for rebars is an important and thus an inviolable property, that is to be set for acceptability of rebars, then why smaller percent elongation properties (as 6 in ASTM A615/A615M [18] and 10 in IS 1786 [6]) be considered permissible for higher yield strength materials, but not for smaller yield strength materials?

b. or, are the percent elongation properties, set in the Specifications/Standards violable, and the set properties merely represent values which certain manufacturers can achieve in the cases of bars they make?

c. how is it that when the achievable (with reasonable effort) percent elongation gets smaller and smaller with increasing yield strength, ASTM A615/A615M

[18] has set the same elongation at 7 percent or 6 percent for steel having yield strengths of 520 MPa, 550 MPa and 690 MPa?

d. If 6 percent elongation is considered acceptable for 690 MPa steel, then why should such a low percent elongation be not acceptable in the cases of rebars with steel of lower yield strengths?

e. how is it that, when the achievable (with reasonable effort) percent elongation gets smaller and smaller with increasing yield strength, IS 1786 [6] has set the same figure of 10 percent for rebars having yield strengths of 600 MPa, 650 MPa and 700 MPa?

f. how is it that when ASTM A615/A615 M [18] finds it difficult to achieve percent elongation greater than 6 for 600 MPa hot rolled bars, IS 1786 finds a 10 percent elongation achievable for 700 MPa TMT bars, when it is known that, compared to hot rolled processes, as in the USA, the TMT process, as in India, leads to hardening and lowering of ductility and percent elongation properties?

There needs to be a clear understanding of the significance of percent elongation and or ductility of rebars in the context of performance of reinforced concrete elements.

It may be desirable to set, irrespective of the yield strength of steel, a single value, below which the percent elongation or ductility will not be acceptable in the cases of rebars of steel.

In view of the fact that virtually all structures in India and in many other countries are required to be earthquake resistant, a reasonably high value may have to be set for the required percent elongation or ductility of rebars.

In this conflicting scenario, with a view to minimizing the rate of corrosion and also to improve ductility and energy absorbing capacity, PSWC-BAR, conforming to IS 2062, and possessing the property of improving "effective bond" over and above the normally available "bond", with a minimum percent elongation of 16, is recommended as the rebar of choice. The yield stress will be limited to a maximum of 550 MPa, preferably to 500 MPa; Kar [5].

Greater details on the development and mechanical properties of PSWC-BAR, together with design aid, so as to take advantage of the power of PSWC-BAR to enhance load-carrying capacity, as well as ductility and energy-absorbing capacities of reinforced concrete elements, are provided in the article: The Search for an Ideal Rebar for Durable Concrete Construction Leads to PSWC-BAR; Kar [5].

7. Ductility ratio

A better measure of the mechanical property of a rebar, and that of the performance of a concrete flexural element, reinforced with such a bar, would have been the ductility ratio rather than the arbitrarily selected percent elongation.

Assuming that the percent elongation will be at least large enough to ensure that the specified yield strength and the specified ultimate strength of the bar will be achieved, the only other useful information that a percent elongation may provide is a vague understanding that the bar may not break during necessary bending.

That should suggest that vaguely specified percent elongation is an unnecessary specification when separate tests for bending of bars are specified.

In contrast, while tests for yield and ultimate strengths (stresses) will ensure the said strengths (stresses), the information on ductility and the shape of the load-deformation plot of the bar beyond yield will provide important information on an idea about the bendability of a rebar. And in addition, the ductility ratio, coupled with a plot of the load-elongation curve of the bar will provide a great deal of information about the performance of a flexural element beyond the yield stress level of the rebar, provided that the rebar will have the requisite "engagement" with concrete, and it happens best in the case of PSWC-BARs; Kar [2].

8. Summary

Reinforced concrete is the number one medium of construction. Besides strength, easy formability and availability of the constituent materials, trouble-free long term performance, i.e., durability of concrete structures, constructed with plain round bars of mild steel, having yield stress of around 250 MPa to 280 MPa, had helped reinforced concrete attain this position.

It has been suggested that, in the context of reinforced concrete, besides concrete and rebars, "bond" between such rebars and the surrounding concrete deserves equal consideration.

Engineering practice shows that though there is a need for a clear understanding of "bond", and though the ensurement of adequate "bond" is an essential necessity, these are almost totally neglected.

Similarly, the important property of percent elongation or ductility of the rebar has not been considered with the thoroughness it deserves.

With time, besides significant changes in properties of cement, a constituent component of concrete, the reinforcing bar (rebar) was gradually changed from plain round bars of mild steel to plain round bars of medium tensile steel (yield stress of about 350 MPa) and then on to today's ribbed rebars of high strength (yield stress 415 MPa to about 700 MPa) steel.

The use of ribbed rebars of high strength steel, susceptible to corrosion at accelerated rates, led to concrete structures reaching states of distress early.

In consideration of durability, ribbed bars, as in IS 1786 in India, and ASTM A615/A615M in the USA and as in such other Standards/Specifications elsewhere, should thus be avoided.

The high susceptibility of ribbed rebars to corrosion may in cases destroy or reduce "bond" between concrete and ribbed rebars of high strength steel.

Such bars may not stand scrutiny for eligibility for use as rebars for reinforced concrete construction. It has been shown that PSWC-BAR, characterized by its plain surface and wave-type configuration, is the most ideal rebar for reinforced concrete construction.

While the plain surface of PSWC-BARs would ensure that the susceptibility of such bars to corrosion will be several orders of magnitude less than the susceptibility of conventional ribbed bars of high strength steel, the wave-type configuration of PSWC-BARs ensures that the "bond" or "engagement" between such bars and the surrounding concrete is no less than the "bond" between ribbed rebars and concrete.

Numerous tests on concrete beams and columns, reinforced with PSWC-BARs, and with ribbed bars, conforming to IS 1786, have consistently revealed that the "effective bond" or "engagement" between PSWC-BARs and the surrounding concrete is greater than the "effective bond" between concrete and ribbed rebars, conforming to IS 1786.

It is this greater "effective bond" that increases the load-carrying capacity, ductility and energy absorbing capacity of concrete elements, reinforced with PSWC-BARs.

The use of PSWC-BAR, characterized by its plain surface and wave-type configuration, at no added effort or cost, can solve the worldwide problem of early distress in reinforced concrete construction.

Besides several-fold enhancement of life span, with many added benefits, like greatly reduced life cycle cost, the use of PSWC-BAR increases by several hundred percent the ductility and energy-absorbing capacity of flexural elements of reinforced concrete. It may thus prevent catastrophes during earthquakes.

Recommended mechanical properties of PSWC-BARs for durable concrete constructions are provided.

In consideration of requirements for durability and resistance to earthquake forces, the yield stress of steel in PSWC-BAR is recommended to be limited to 550 MPa, and preferably to 500 MPa.

The several-fold enhancement of life span of concrete structures, with the use of PSWC-BARs, instead of conventional ribbed bars, can prevent staggering financial losses to property owners and to national economies of all countries as well as great harm to the environment and to the global climate.

An alternative way to enhance the durability of reinforced concrete construction is to provide, at additional cost, surface protection in the form of waterproofing treatment to concrete structures.

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