Discussion Forum

FBEC rebars must not be used

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The problem of early distress in concrete structures, caused by corrosion in reinforcing bars, has led to the development of many different approaches as preventive or remedial measures. One of these approaches is the use of fusion bonded epoxy-coated rebars, known in short as FBECR or ECR. Such reinforcing bars have been widely used in many countries, including India. In spite of many limitations of epoxies as a material, and FBECR as a system of protection against the agents of corrosion, namely, moisture, oxygen, chlorides, etc., a tremendous jump in the use of FBECR is on the anvil in India. It is now time to sound a note of warning.

This discussion records the poor performance of actual concrete structures with FBECR. The structures are located in warm, mild as well as cold climates. In all cases, the FBECR and concrete had satisfied all acceptance criteria and yet the performance of real structures belied the expectations and claims of proponents of FBECR. The major claims of proponents of FBECR are reviewed in the light of poor performance of concrete structures with FBECR.

Origin of FBECR

The practice of providing epoxy coating on rebars possibly had its origin in the reasonable success of epoxy coatings on steel structures. It was, however, overlooked that a steel structure and a reinforced concrete (RC) structure are significantly different in terms of the environment, need for and practicality of application of a protection system. It may be reasonable to provide epoxy-based paints or coating systems on the steel structure, which can be repainted once every few years or whenever required. The same will not be possible in the case of the rebars inside the concrete structure. The other difference lies in the provision of a passivating primer in the case of a steel structure as against the absence of any passivating medium in the case of the FBECR.

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FBEC rebars must be used

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Mitigation of premature deterioration of reinforced structures exposed to corrosive environments resulting from corrosion of reinforcing steel is identified as a major problem all over the world. In fact epoxy coating to reinforcement steel emerged as an effective measure to mitigate rebar corrosion in the mid-seventies because of this dire need. Fusion bonded epoxy is basically a 100 percent, solid finely ground fused powder particles, which when heated, melt to form a continuous adherent film.

It is well known that the reinforcing steel embedded in concrete with high alkalinity gets protected against corrosion in mild environment. However, it is not so in areas which are highly corrosive as chlorides and other corrodants from the environment would find their way to the reinforcement through pores and intrinsic cracks. The nanometer thick gamma Fe_2O_3 film is expansive and highly porous to oxygen and water; and in the type of reinforcement used at sites, a continuous protective film layer of such oxide never develops on the rusted or defective skin of the bar. Whatever little is developed is easily damaged by oxygen and moisture present in different concentrations in the concrete- pore water, incipient cracks , joints, etc. Even if the film is assumed to be uniform the pH of the surrounding concrete has to be above 11.5 or so to maintain its integrity. But ingress of water and oxygen, carbonation and entry of chlorides and other corrodants through the cover concrete, its intrinsic cracks, joints and pore structures, bring down this pH quite fast in an aggressive environment when corrosion is initiated on bared steel. Even a high pH of 12.2 cannot protect the bar with such a fragile film of nano-angstrom thickness against chlorides above 0.4 kg/m^3 or so. In this context, a highly engineered and quality controlled fusion bonded epoxy coating (FBEC) is superior because it is impervious to O_2, H_2O and chlorides. In fact, the chloride ion permeability through the film has to be less than 1×10^{-4} μ (mole per litre), as per ASTM A775/A775M-01,

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Unlike corroding elements of a steel structure, a corroding FBECR exerts lateral pressure to concrete, further aggravating the situation. Any successful application of epoxy coating in an underground pipeline also should not mean that rebars with epoxy coating will be more successful than bare rebars in concrete structures.

Opposition to FBECR

Though the use of FBECR is increasing, the writer believes that any proposition to coat rebars with epoxies is a negation of the basic principles, which make reinforced concrete what it is. The use of FBECR militates against the beneficial effects of interaction between steel rebars and the hydration products of cement in concrete. It introduces a medium of weakness in the path of an intimate bond between the rebar and alkaline concrete.

It is contended that the use of costly FBECR in concrete structures is a retrograde action, which, like the use of cold twisted deformed (CTD) bars, predisposes reinforced concrete structures to early deterioration and distress[1].

Zemajtis, *et al*[2] made negative observations on the performance of FBECR. On the basis of a review of historical performances of concrete structures (both real and laboratory models), specially on the basis of poor performance of forty bridges in the Florida Keys (specially bridge nos. 27,51,52,57) and eighteen structures in northern USA and Canada, Zemajtis, *et al* stated that "These two investigations showed that epoxy-coated reinforcing steel will not provide long time protection against corrosion in severe environments : sea water in Florida and frequent deicing salt applications in northern USA and Canada. Florida investigations showed that application of epoxy-coated reinforcing steel will reduce the time to develop active corrosion by about five to six years in comparison with bare steel."

There are many factors, which play crucial roles in the early failure of FBECR in concrete structures. Some of these factors are given below.

(i) The epoxy coating provides a mere physical barrier, which is permeable and which is further damaged by the time the concreting is done, whereas a bare bar gets an electrochemical protection of passivity through the formation of a γFe_2O_3 layer following the concreting operation.

(ii) The FBECR is deprived of the benefits of the passivation layer of γFe_2O_3 which protects steel against corrosion due to oxidation when oxygen and moisture may be present, as long as an alkaline environment with a pH level of 11.5 or higher is available in the immediate vicinity of the steel rebar.

(iii) In the absence of the protective shield of passivation, corrosion by oxidation takes place easily even before chlorides may reach the FBECR, leading to early debondment of the epoxy coating.

(iv) The debonded coating leads to the creation of an environment where there is an accumulation of acidic fluid (pH of 4.0 to 5.0) behind the coating, thereby accelerating the process of corrosion.

(v) The epoxy coating fails within 45 days in the combined environment of $Ca(OH)_2$ — a product of hydration of cement in concrete — and $CaCl_2$ or NaCl, protection against which is the primary objective of using the FBECR.

(vi) The failed epoxy coating exposes the rebar to the corrosive chloride, the rebar having been deprived of the benefits of a low Cl^-/OH^- ratio.

Some of the other important features, which are overlooked in the use of FBECR, are:

(i) the introduction of a coating between the two media of rebar and concrete creates additional surfaces or zones of weakness

(ii) the epoxy coating material itself may have its own structural or chemical weaknesses

(iii) the life of epoxy itself may not be long enough to help structures have a long life beyond 50 years

(iv) the use of FBECR delays the implementation of projects as the bars are to be repaired/retouched with inferior epoxy upon arrival at site; additional quantities of FBECR are to be procured again to cover any shortfall or new structural requirements, damages are to be repaired again with liquid epoxy, and so on

(v) FBECR costs 30 to 50 percent more than uncoated bars for the same quantity of rebars and additional costs are involved as provisions are to be made to compensate for poorer structural efficiency of FBECR.

The literature on FBECR is replete with the recognition or admission that epoxy coatings are permeable. It is also undeniable that epoxy coatings may have holidays and the coatings may be further damaged during transportation, handling and fabrication at site and during concreting.

The permeable membrane, further weakened by the aforesaid damages or defects, permits the entry of oxygen and moisture underneath the coating. Oxygen may also be trapped underneath the coating during the coating process. Indeed, the well-documented cases of early failures of FBECR in bridge decks in Virginia[2-7], bridge substructures in Florida[2,6], and bridge decks, etc. in Canada and northern USA[2,8] and elsewhere record the presence of acidic liquid underneath debonded coatings and corrosion in the FBECR even before chlorides may reach the FBECR inside concrete structures.

Disbondment, which can occur easily in the FBECR and which lacks the passivation layer of γFe_2O_3, is a precursor to corrosion of the FBECR. Describing his on-field experience in a marine environment, Larry L. Smith reports in the 1993 Transportation Research Board Presentations, Washington, D. C., January 1993[2] : "This bar has not been in the field that long. I was told that it may be out there perhaps 3 months. On closer examination you see there is no evidence of corrosion but there is a disbondment at this time."

The experience with ECR in bridges in Virginia[3] shows that epoxy coatings are permeable. These coatings are debonded, that is, corrosion takes place in ECR, even before the highly damaging chlorides can reach the steel rebars.

It is well known that in a moist environment chlorides can cause corrosion in rebars much earlier and more severely than oxygen does and yet the ECRs in the bridge decks in Virginia started corroding before chlorides could reach the ECRs. In other words, chlorides had no role in the early debondment of epoxy coatings.

Given this inherent limitation of epoxy coatings in protecting steel, and because of the poor performance of concrete structures with FBECR, any success, that is claimed for FBECR, may not be due to the qualities or properties of FBEC but due to good concrete quality and large thickness of cover to rebars. In fact, proponents of FBECR do claim that "fusion bonded epoxy coating is an effective strategy of preventing rebar corrosions in the aggressive environments in combination with good quality concrete and cover along with good construction practices."

The findings on the bridge decks in Indiana[9,10], those of the Canadian Strategic Highway Research Programme study[2,8] (C-SHRP) and all that which transpired at the Transportation Research Board Presentations[2] very clearly show that it is the large cover thickness over 60 mm, preferably 70 to 80 mm, and not the FBEC, which protects the FBECR. In fact, even such cover thicknesses also may not be sufficient to keep FBECR free from corrosion as the seeds of corrosion may be built in by the time the coating is provided. Referring to the observations on bridges in the Province of Ontario, David Manning [2,8,11] said, "And despite the very large amount of cover that was involved, we're looking here at close to 4 inches, there was, in fact, significant corrosion on the reinforcing bars which were exposed……… we became very concerned."

The basic reason for this poor performance of FBECR is that though concrete protects bare steel through the formation of the γFe_2O_3 layer, it cannot do so in the case of an FBECR.

It may not be an exaggeration that FBECR has been used in 100,000 or 200,000 concrete structures. Most of these structures are of very recent vintage.

Numbers may hide the truth. If business success and engineering success were synonymous, CTD bars, commonly known as torsteel, would have been a tremendous engineering success even though the CTD bars can be considered to have made most of the concrete structures in India vulnerable to early deterioration and distress[1,12].

The dismal performance of FBECR in real structures calls for a cautious approach.

Claims of FBECR proponents

Proponents of FBECR cite the number of structures with FBECR as a measure of superiority or usefulness of FBECR in making concrete structures durable. It has been mentioned above that numbers can be misleading.

The proponents of FBECR prefer avoiding any reference to structures where the use of such rebars have led to early distress or to countless structures where plain round bars of mild steel, coupled with OPC, have given concrete structures trouble-free lives of 60-70 years or more.

Keeping in the same vein, proponents of FBECR challenge the whole concept of the nanometer thick γFe_2O_3 layer of passivation which has faithfully protected through the ages and still protects rebars against corrosion. This cannot occur unless one confuses the voluminous $Fe_2O_3H_2O$ (rust) with the γFe_2O_3 layer of passivation which is relatively impermeable to oxygen and moisture and which is formed and sustained when the alkaline pore water in concrete has a pH level at least equal to 11.5.

The proponents of FBECR, while citing the performance of 10-20 year old concrete structures with FBECR, good quality concrete and large cover thickness, as proof of the capability of FBECR in making concrete structures durable, fall shy of recognising that concrete structures with uncoated bars, using concrete of good quality and equally large cover thickness would have performed equally well or better. It has been explained, and examples have been cited which show that the provision of epoxy coating makes steel reinforcing bars specially prone to early corrosion due to both oxidation and chloride attack.

It has already been mentioned, reasons given, and field cases cited in this feature to show that contrary to the claims, proponents of FBECR make, the use of epoxy coated rebars is a retrograde step as it deprives the rebar of the formation of the protective γFe_2O_3 layer of passivation, which has protected all uncoated rebars against early corrosion due to oxidation. Examples show that in the same environment of Florida Keys, where a bridge without any epoxy coating was still in service 60-70 years after construction[2], none of the bridges with FBECR lasted for more than seven to nine years.

Case studies of real structures, which have been cited in this discussion, show that there is corrosion in FBECR even before chlorides can reach the rebar inside concrete.

Examples of field samples and laboratory samples with debondment of epoxy coating within three months and two years, respectively, are on record. In addition, laboratory samples with tests for the real environment of $Ca(OH)_2$ and chlorides have shown loss of adhesion of the coating within 45 days in 100 percent of the test cases (Kenneth C Clear in ref. 2).

So as to compensate for the harm, caused by the use of FBECR, the proponents/users of FBECR today recognise that in order that the life of concrete structures with FBECR may be prolonged, the concrete must be of good quality, the concrete cover to FBECR should be at least 70 mm, the coating thickness should be increased to 175 to 300 μm, and finally the structure should be given a surface protection.

It is a paradox. If FBECR were really capable of fulfilling its objective of making concrete structures durable, special emphasis on quality of concrete, large concrete cover, and above all, surface protection of concrete structures should not have been required.

One fails to follow the logic behind the suggestions of proponents of FBECR that the coating thickness should be upwards of 175±25 μm but less than 300 μm. If 175 μm would be sufficient there should be no need for spending more money on a 300 μm coating. If 300 μm thickness would be necessary, then 175 μm thickness should not have been considered acceptable. The relevant code in India, IS 13620:1993 in its clause 7.1 on coating thickness stipulates "For acceptance purposes at least 90 percent of all coating thickness measurements shall be 0.1 mm to 0.3 mm after curing. The coating thickness limits do not apply to patched areas." When there is so much concern about holidays and local damages, the IS code redefines engineering by permitting 50 μm coating thickness in 10 percent of the areas when 300 μm might be necessary.

It is well known that rebars, without epoxy coatings at additional cost, but with all of the other measures, would have enhanced the life of concrete structures very significantly and that too without any detriment to structural efficiency[13].

Proponents of FBECR never tried to find out what else, other than chlorides, were the causes of early distress in concrete structures of recent construction[1,12,14].

It is recognised that when the causes of a problem are not known, a proposed solution can be worse than the problem. That indeed has been the case with FBECR right from the beginning. With the failure of FBECR to deliver the expected results, the standards of the rebar and those of its use have been upgraded from time to time without achieving the desired result. This did not stop proponents of FBECR claiming the superiority of FBECR over the much cheaper black bars right from the beginning when 100 µm coating thickness and 50 to 60 mm concrete cover were considered adequate and there was no extra emphasis on the quality of concrete and the need for providing any surface protection to concrete structures.

Though proponents claim FBECR to be a solution to all problems of rebar corrosion due to chloride attacks, it is precisely because of the poor performance of the inherently unsound FBECR that research is presently continuing for the improvement of epoxy coating. In the words of proponents of FBECR, "Research that is presently continuing is for the improvement of coating, so that the shortcomings noticed in long term performance after field trials could be taken care of confidently."

The very fact that large scale failures of FBECR have led to special studies and commissions, and also the fact that the performance of FBECR has been found to be greatly dependent upon the vendor and upon a blemishless coating and yet such rebars are used, when the epoxy coatings on rebars are damaged during transportation, site handling and fabrication and during concreting, it should serve as a warning of early failure of FBECR.

Proponents of FBECR cite results of laboratory tests which are at variance with results of field performance of real structures.

Field performance versus laboratory test

In the face of many records of poor performance of real structures with FBECR, proponents have cited short period (generally 1 to 3 years) laboratory tests claiming that the use of FBECR would make concrete structures durable (repair-free life of over 50 years, even up to 100 years) even in marine environments.

It must be emphasised here that when field performance data are available, it is unreasonable to come up with different results through short term laboratory tests and condemn the collection and dissemination of field performance data.

Poor performance of FBECR: Some case studies

Field performances of actual structures are for real. There are well-documented records of poor performance of many structures with FBECR.

The findings, summarised in the following, show that the costly FBECR cannot be relied upon to enhance the life of concrete structures in or away from chloride environments.

Field performance of FBECR in Virginia bridge decks

An extensive survey (approximately 250 samples from 18 bridges, spread over all the nine districts of the State of Virginia, USA) was made on the performance of ECR with 64 mm clear cover depth in bridge decks[2-5]. The bridge decks were in overall good condition with no severe cracking, carbonation, or delaminations. The chloride permeability was low to moderate.

The summary[3] of the findings of the survey are : "The epoxy coating debonds from the reinforcement in as little as 4 years and long before chlorides arrive at the level of the reinforcement. Assuming a debonded coating will provide for little additional service life, ECR should not be used to extend the service life of bridges in Virginia." Other observations from the performance study include:

(i) the epoxy coating debonds in properly constructed bridge decks having good cover over the reinforcement, good quality concrete, and ECR that complies with VDOT's specifications.

(ii) the disbondment was not caused by the presence of chloride ions on the steel surface or excessive coating damages. Instead, the loss of adhesion was related to water penetrating the coating and accumulating at the metal/coating interface, causing peeling stresses exceeding the adhesive bond strength and subsequent oxidation of the steel surface.

Field performance of FBECR in Minnesota bridges

The debondment of FBEC from rebars in Virginia was not an isolated one. For example, "Krass, McDonald, and Sherman (1996) reported on four bridges built between 1973 and 1978 in Minnesota where the overall coating adhesion was considered poor."[2]

Field performance of FBECR in Florida Keys bridges

It is not without reason that the use of FBECR in concrete structures in the middle East and in substructures of bridges in the Florida Keys in the USA led to disastrous consequences. On the basis of experiences with several bridges (the Seven Mile bridge, the Niles Channel bridge and the Long Key bridge) in the Florida Keys, views, similar to those made in the case of bridge decks in Virginia, have been expressed[2] : "Florida's experience indicates that epoxy-coated reinforcing steel, when used in a substructure application and exposed to marine environment, is more susceptible to corrosion than bare steel. This conclusion was based on experience that bare steel will develop active corrosion in about 12-15 years in marine environments, and for epoxy-coated reinforcement this time reduces to 7-9 years."[2,15] In fact, the FBECR in the substructures for bridges in the Florida Keys showed signs of corrosion only 6 years after construction. In other words: "Florida investigations showed that application of epoxy-coated reinforcing steel will reduce the time to develop active corrosion by about five to six years in comparison with bare steel." [2]

As far as debondment is concerned, Sagues, *et al*[16] reported on 30 substructures in Florida's marine environments : "The lack of coating adhesion was widespread and affected virtually all the structures 4 years or older, 29 of 30 bridges."

One notices in the observations that while FBECR would develop active corrosion within 7-9 years, rebars without epoxy coating could give a bridge a life of at least 60-70 years in the same environment. It is quite possible that the other bridge was constructed with OPC and plain round bars of mild steel whereas the newer structures with FBECR had high yield strength deformed (HYSD) bars.

Field performance of FBECR in Canada and northern USA

The experiences with FBECR are not at all encouraging in the warm climates of Florida. The experiences in the moderate to cold climates of Virginia are equally disappointing, and the performance of FBECR in the colder climates of northern USA and Canada is not any better.

The Canadian Strategic Highway Research Programme (C-SHRP) study[2,8] on the corrosion protection performance of epoxy-coated reinforcing steel was started in 1990, as the extremely poor performance of the Florida Keys bridges prompted the proponents of FBECR to suggest that the use of FBECR in as many as 48 bridges in the Florida Keys over a span of a few years was merely experimental and that the extremely poor or negative performance of FBECR in the Florida Keys and in the Middle East was solely due to the warm climates in those areas. Simultaneously, the proponents of FBECR started a campaign of professional vilification of the professors and others who were associated with the study of performance of FBECR in the bridge decks in Virginia.

The C-SHRP project included the evaluation of structures with epoxy-coated reinforcing steel exposed to environments typical for the colder climates of Canada. The study included testing of epoxy-coated reinforcing bars from 12 Canadian and US coaters, seven Canadian and US jobsites, and 19 field structures constructed in Canada and the northern USA between 1974 and 1988. In addition, a 6-month environmental exposure test of epoxy-coated reinforcing bars in Toronto was performed to simulate jobsite conditions.

Some of the conclusions for the C-SHRP study were as follows:

- "The study showed that epoxy-coated reinforcing steel will not provide long-term protection to reinforcement in salt-contaminated concrete."
- "Present and proposed specifications, even if tightly enforced and modified…., will not provide assurance of long-term performance in salt-contaminated concrete."
- "The (sufficient) data indicate that the extended life will be in the range of only one to eight years, …, and will probably average about five years."
- "Therefore, it is recommended that epoxy-coated reinforcing steel should not be used as the primary protective system on highway structures which are expected to experience chloride contamination."

The C-SHRP study was initiated to clear the confusion over the performance of FBECR. The conclusion has been reached that FBECR "will not provide assurance of long-term performance in salt-contaminated concrete." In fact, even on the basis of laboratory tests, which grossly overestimate performances, the conclusion drawn by Don Pfeifer[2] was : "During the continuous ponding the majority of the slabs containing epoxy-coated bent and straight rebar underwent a significant change. Mat to mat resistances were reduced many fold and microcell corrosion currents increased significantly. ...... "Almost complete failure of the corrosion protection properties on many of the coated bars was indicated." The tests were performed using FBECR in pristine conditions at the instance of Concrete Reinforcing Steel Institute, a proponent of the use of FBECR.

The harder one looks the worse it gets with FBECR

There was a time when there was only appreciation for CTD rebars even though those reinforcing bars were causing the considerable damage to concrete structures all over the country. Good words were being said. This went on for three decades in spite of the fact that the CTD bar is harmful for concrete structures[1,12].

It is seen in the performance of concrete structures with FBECR that as in the case of CTD bars, the concept, proposal and use of FBECR defy logic. FBECR should not be expected to provide durable concrete structures as such bars have failed to make concrete structures durable.

Whatever may be the commercial success in propagating and increasing the use of FBECR, whatever may be the position of codes and authorities in power, FBECR is bound to fail as CTD bars have.

The transactions at the 1993 Transportation Research Board Presentations, Washington, D. C., January 1993 may be recalled here. "The mistake that was made in this profession with epoxy-coated bars in the 70's was wishful thinking. What you then say was wishful thinking. You think that your bars are better than my bars or Florida's bars, therefore you are going to use them without other protective systems. I used to think that my bars were better than Florida bars, and therefore I recommended to the world that they use epoxy-coated bars alone. I was wrong when I got in and did detailed evaluation and testing. I must say that I wonder whether you will be wrong when you get in and do the necessary detailed evaluation and testing. If you are, and people have relied on you to build another 100,000 structures that are going to deteriorate prematurely, shame on all of us in my opinion. I think we have to be conservative with these systems, we have a public responsibility …… We're in a situation where the harder we look the worse it begins to appear in my opinion, and I think we have a responsibility to take the conservative path down to the process."[2]

Black (bare or uncoated) steel versus FBECR

It has already been claimed in this discussion that $Ca(OH)_2$ in concrete provides greater protection to steel than fusion bonded epoxy can. If indeed this were true, less costly bare rebars would have made concrete structures more durable than FBECR would. That this in fact is true, can be found in the explicit or implicit expressions of those who undertook the studies of bridge decks in Virginia, bridge and bridge substructures in the Florida Keys and the structures under the C-SHRP program.

Larry L. Smith[2], while making observations on the failure of FBECR in the bridge substructures in the Florida Keys, referred to a much older bridge with black bars thus : "that structure to the right must be close to 60-70 years old."

He further said. "At that time we were using bare tie wires, and if you will note that the bare wire has not corroded except where it comes in contact with the rebar itself." Here rebar refers to FBECR.

Referring to what they had observed in the bridge decks in Virginia, Pyc´, *et al* wrote: "The time from the initiation of corrosion to cracking and delamination in bare reinforcing steel is about 5 years in Virginia (Liu and Weyers, 1998). The epoxy coating debondment identified in this study indicated that the epoxy debonded from the reinforcing steel in bridge decks in as little as 4 years."[4]

The fact that some structures with FBECR have survived for 10 or 20 years cannot be justification for claiming that such FBECR has made concrete structures durable. There is nothing to suggest that black bars would not have performed equally well or better.

Other factors against FBECR

All that have been covered in the preceding relate to corrosion. There are other factors which go against the advisability of using costly FBECR in concrete construction. Some of these shortcomings are listed in the following.

Following the initiation of corrosion in rebars, concrete structures with FBECR have much shorter useful life left compared to cases of concrete structures with initiation of corrosion in black bars.

Structures should have adequate resistance to heat, and IS 456 : 2000 emphasises protection against fire. Epoxies have limited tolerance to freezing temperature and fire. Epoxies soften at temperatures much lower than temperatures at which concrete is structurally degraded or damaged. Unlike bare bars, FBECR is also much more susceptible to damage due to fire during transportation and storage at site.

Of equal or greater suspicion is the durability of epoxy itself which, being of organic origin, has a limited life span; many formulations having life spans of thirty years or less.

One reason the composite reinforced concrete, constructed with the right cement and rebar[1,12], performs without undue problems, is the similarity of the coefficients of thermal expansion of concrete and steel. In contrast, the coefficient of thermal expansion and contraction of epoxy is several times higher than that of steel or concrete. The much higher coefficient of thermal expansion imposes large thermal stresses and many thermal stress cycles in the epoxy coating, leading to its early failure. The findings of Virginia Transportation Research Council on the poor performance of epoxy coated rebars in bridges in Virginia clearly identify premature debonding of epoxy coatings as the cause of poor performance of ECR. Since this debonding of the epoxy coatings took place even before chlorides could approach the rebars, it is possible that differential thermal strains and stresses had a role in causing this disbondment. As it has been mentioned earlier, epoxy coated rebars failed early in the Long Key and other bridges in the Florida Keys as well. Room samples of epoxy coatings were also found to debond within two years. It is possible that low extensibility/flexibility and much higher (compared to those of concrete and steel) coefficient of thermal expansion might be partly responsible for the early disbondment.

As concrete does not bond to the coat of epoxy, it is possible that the fatigue resistance of concrete structures with FBECR will be less than that of a similar structure with black rebars, thereby rendering FBECR unsuitable for the construction of earthquake-resistant concrete structures.

It is well recognised that epoxy coatings, applied with a brush, are much less effective than fusion bonded epoxy and yet damages are repaired at site, many damages to coatings after site fabrication remain unattended, so do all damages during the concreting operation.

In short, the use of epoxy-coated rebars in concrete structures defies logic and common sense. It takes away the benefits concrete imparts to uncoated rebars in RC constructions.

CTD and FBEC rebars are two sides of the same coin

The CTD bars were introduced in India with much fanfare. High expectations were falsely created even though there was no scientific basis to justify even the compatibility of CTD bars with concrete structures. Yet, the harmful CTD bars captured the whole market in the area of steel reinforcing bars[1,12].

FBECR, like the CTD bar, has the potential to degrade concrete structures. Field performance of structures with FBECR is a pointer to such a future for concrete structures which might have been or which may be reinforced with FBECR.

The CTD bars are disappearing from the market. So should FBECR.

FBECR must not be used

The intrinsic shortcomings of FBECR and the consequent poor performance of FBECR in the Florida Keys, in the Middle East, in Virginia and in the cooler climates of northern USA and Canada show that FBECR has the potential to be harmful rather than helpful in making concrete structures durable.

It should not be overlooked here that short-term laboratory tests cannot faithfully model the time-dependent effects of corrosion in rebars in a complex environment and such tests cannot be treated as substitutes for field performances. Thus, whatever laboratory tests of 1-3 year duration may indicate and whatever statutory authorities may dictate or codes may stipulate, experiences with real structures and loss of adhesion within 45 days in 100 percent of the cases, when best samples of FBECR are soaked in solutions of limewater and chloride, should be enough to shatter any confidence in the ability of FBECR to prolong the life of any concrete structure.

Conclusion

There is increasing use of fusion bonded epoxy coated reinforcing bars, specially in areas where chloride attack is a possibility.

The increasing use of FBECR cannot be a basis for claiming superior performance of such rebars in making concrete structures durable. If it would be, then the harmful CTD bar should have been considered to be the most beneficial/technically sound rebar which was ever used in India.

The provision of FBEC on rebars, deprives the rebar of the benefits of the electrochemical barrier which develops when concrete, with its pore water, having a pH level of 11.5 or greater, covers the rebars. The costly FBECR has a physical barrier in place of the γFe_2O_3 protective layer of passivation in the case of an uncoated bar.

The epoxy coating in the form of a physical barrier is debonded early and there is corrosion underneath the coating even before chloride reaches the rebar.

Though the main objective of using FBECR, which costs 30 to 50 percent more than uncoated bar and, which requires more quantum of steel and requires greater management efforts, is to make concrete structures durable by resisting corrosion in rebars in chloride environments, acceptance tests for durability of FBECR are conducted separately for resistance to $Ca(OH)_2$ and NaCl. The discussion records that epoxy coatings fail within 45 days in the combined solution of calcium hydroxide (provided by cement in concrete) and calcium or sodium chloride against which protection is sought.

Short term laboratory tests cannot predict long term performance of structures in the real environment, and yet proponents of FBECR stake their claims on the basis of results of short term unreliable tests.

The feature records the early failure of FBECR in bridges and substructures in the warm climates of Florida Keys, in structures in the warm climates in the Middle East, in bridges in the moderate temperatures of Virginia, in bridges in colder climates of

Minnesota, and in bridges and other structures in the colder climates of northern USA and Canada.

There are reasons for such early failures of FBECR in concrete structures.

The use of costly FBECR in concrete structures is technically unsound. It is wasteful and harmful. The most complimentary statement about FBECR would be that it costs a whole lot of money but it gives no added confidence that its use will make concrete structures any more durable.

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(Continued from page 56)

when tested as per method outlined therein. This is an important acceptance criterion. Increased cover depths, improved cover concrete, admixtures, membranes, surface coatings on concrete and everything else have their limitations needing an additional strategy to complement them.

The first usage of FBEC in the United States where it started as an experimental procedure even before publication of the final reports of FHWA in 1974 was in 1973. It became popular simply because of its effectiveness. With a proven track record of over 30 years on rebars alone, its growth could be judged from the fact that about 15000 t per annum was the consumption of epoxy coated bars in the USA in the seventies and in the year 2002 it has grown to over 900,000 t or about 10 percent of all rebars consumed in the United States. Forty-eight states in the United States specify and use epoxy coated rebars in their works as an effective method of preventing corrosion.

Like any other successful system, it also has its critics and antagonists, largely from business and professional rivals, who search one or two unfavourable reports to condemn the system ignoring a hundred others which testify to its superior performance, when executed properly.

The landmark research initiated by Federal Highway Administration, USA, in 1973 has brought a much better understanding of the problems of premature deterioration of bridge decks in highway structures. The National Bureau of Standards (NBS) that conducted the research had taken into account all possible measures for preventing corrosion including short listing and testing some 47 different coating materials and other strategies. At the end of the research, NBS highlighted the ineffectiveness of several methods in vogue and concluded that epoxy coated reinforcement carried out by fusion bonding process in excess of 102 μ in thickness would be capable of protecting reinforcing steel from corrosion. The thickness is since modified upwards to 175 ±25 μ but less than 300 μ.

The earlier research was primarily focused on the question of whether there is any benefit in using fusion bonded epoxy coating. Research that is presently continuing is for the improvement of coating, so that the shortcomings noticed in long term performance after field trials could be taken care of confidently. Given below is a list of some of the research conducted in this field

Research by Prof RN Swamy

An independent research carried out in Japan and UK in mid-nineties, after 3 to 7 years of field exposure and accelerated tests in the laboratory gave the following conclusions[1,2].

(i) Epoxy coated bars, with a coating thickness of 200-300 microns remained practically unaffected under natural and accelerated exposure conditions, and maintained all the original characteristics of gloss, coating hardness and coating adhesion even with as small a cover as 20 mm in the concrete.

(ii) Even with artificially damaged coatings, the corrosion damage

suffered by epoxy-coated bars was negligible under both natural and accelerated marine exposure conditions. Further, the rate of corrosion damage was far less than that of comparable uncoated and galvanised bars.

(iii) In cracked concrete containing chloride contaminated aggregate and mixed with sea water, epoxy coated bars with undamaged coatings again showed excellent performance and remained in good condition. Damaged coatings in similar conditions showed signs of localised rusting in the vicinity of the cracks with maximum pitting depths only a fraction of those of uncoated and galvanized bars. The rate of corrosion of damaged coatings was far less than that of uncoated and galvanised bars.

(iv) Even under very severe marine exposure conditions, and even with localised coating damages, epoxy coated bars with uniform coating thicknesses and coatings with good impact strength and excellent resistance to salt water spray and alkaline solutions can provide long term protection against corrosion.

Research by S Erodogdu *et al*

Another independent research carried out in Canada deal with the ability of epoxy coated rebars to prevent corrosion more extensively[3,4,5]. The main findings and conclusion from this research programme are as follows.

(i) Time-to-active corrosion initiation for the uncoated rebar exposed to simulated sea water was about 5.5 months according to the criteria quoted in ASTM C.876.

(ii) Long-term open-circuit potentials revealed that epoxy-coated rebar in concrete exposed to simulated marine environment remains passive. This was also confirmed by the linear polarisation measurements as no measurable corrosion was obtained for the entire test period.

(iii) The overall average corrosion current density of the uncoated steel was 2.88 uA/cm^2 (1.33 mm/year) at the end of one year of exposure to simulated seawater, and 10.1 uA/cm^2 (4.65 mm/year) at two years. The average corrosion current densities measured at the end of one year of exposure to a natural marine environment was 0.39 uA/cm^2 (01.8 mm/year), and 1.19 uA/cm^2 (0.55 mm/year) at two years.

(iv) As against above one percent damaged epoxy-coated rebars exposed to a natural marine environment for two years showed a current density slightly higher than the 0.01 uA/cm^2, which is the recommended maximum current density for long-term maintenance-free performance.

(v) After two years of exposure to marine environments in the tidal zone, there was no indication of rust stains or cracks on the surface of concrete slabs due to the corrosion of the epoxy-coated reinforcing steel regardless of the degree of the damage to the coating and exposure conditions.

Research by I L Kondratova

I L Kondratova continued research on this topic under Prof. Bremner during the period 1990 to 1998. Specimens using FBEC were made in poor concrete (w/c ratio 0.6 and concrete cover 20 mm) with coating damaged up to 2 percent deliberately. The specimens were placed in a highly corrosive marine exposure site in the Bay of Fundy, near Eastport, Maine USA— one of the most corrosive sites in the world. Test results after 8 years of exposure indicated that ECR was much more effective in corrosion protection in poor quality concrete with a low cover depth than uncoated reinforcement coating. Adhesion was also not affected excepting on one specimen (out of 5) having 1 percent damaged FBECR and located at 0.5 m below the high tide, which showed some disbondment but no corrosion of the bar inspite of the same[6,7].

In a recent report I L Kondratova *et al* have concluded the following[5,8].

(i) Epoxy-coated bars outperformed uncoated bars in concrete of w/c ratio 0.6 and 20 mm cover tested in the accelerated testing chamber.

(ii) Corrosion inhibitors provided some delay in initiation of corrosion in uncracked concrete specimens, but did not appear to provide significant protection for precracked concrete specimens.

(iii) High performance concrete (w/c ratio = 0.25) provided excellent corrosion protection to the steel reinforcement in uncracked specimens.

(iv) Deep pitting was observed on steel reinforcement in the preformed crack area for specimens with 0.25 w/c ratio.

(v) The best corrosion protection with preformed crack was achieved only by a combined approach to corrosion protection using high performance concrete plus epoxy coated reinforcement.

Therefore, over reliance on concrete alone to protect rebars from corrosion in any corrosive environment would not be prudent for the durability of reinforced concrete structure. This is more so as the paramount need of good compact concrete with a design cover specified on the basis of expected surface chloride concentration, chloride diffusivity of the concrete and desired service life is hardly met in actual practice. A US survey of some recently built bridges observes the value of the concrete cover typically assuming a normal distribution with a standard deviation of the approximately 10 mm. Hence if the design cover is 50 mm, the specified cover should be 67 mm or 73 mm for 95 percent or 99 percent compliance respectively; A major variation affecting cost and technology both! Moreover, such standard of quality control can be possible or justifiable only for special concrete or high performance concrete geared for durability and not on all normal good concrete with codal cover.

Central Road Research Institute, New Delhi

In India, Central Road Research Institute (CRRI), at the instance of Ministry of Surface Transport (Now Ministry of Road Transport and Highway) evaluated the relative performance of anti-corrosive treatments to rebars and concluded after intensive tests in field and laboratory over 3 years that FBEC coating had performed better than other anti-corrosive coatings evaluated[9].

Virginia report

It is interesting to note that the report of Virginia Transportation Research Council (VTRC), claims that epoxy coating does not prevent corrosion of reinforcing steel in bridge decks[10]. It may be mentioned that VTRC is not a statutory body but a team of academicians from Virginia Polytechnic Institute who have been trying to denigrate the achievements and advantages of epoxy coated reinforcement from time to time.

On the other hand the West Virginia Department of Transportation, the division of Highways, a statutory body, in its signed reports to Federal Highway Administration concludes the following:

> "From comparisons based on cracking of the decks it may be concluded that while the use of ECR does not necessarily reduce the number of transverse cracks found in a bridge deck, the damage incurred to the deck allowing water to penetrate through these cracks and accelerating the corrosion of the uncoated steel is greatly reduced, if not eliminated, with the use of epoxy coated reinforcement.
>
> Comparing this (delamination surveys of bridge decks using coated and uncoated rebars) to the uniform absence of any measurable reinforcement-associated delamination in the decks investigated in this project leads to only one conclusion. This conclusion is that the ECR must be directly responsible for the lack of delamination in these decks.

It could be concluded from the data gathered in this investigation that the use of epoxy-coated reinforcement does result in a dramatic reduction of delamination in bridge decks and by inference an increase in the useful life expected of the deck."

FHWA report

The report of Virginia State itself is included in the FHWA Report No RD-96-092. The state report comments[11]:

> "ECR has provided adequate corrosion protection even in areas with chloride concentration up to 2.00 kg/m^3 above the chloride threshold level for initiating corrosion in black steel. These high chlorides areas are at transverse cracks. There were no indications of significant corrosion or coating disbondment even though the initial condition of the coating was poor. Numerous holidays and bare areas were present. The use of ECR in combination with adequate cover has provided effective corrosion protection over 13 years of service with no signs of deterioration of the concrete deck due to corrosion of the reinforcing steel".

The FHWA Report- No. FHWA-RD-96-092, August 96 "Performance of Epoxy – coated rebars in bridge decks", summarising the results of investigations performed by highway agencies in USA, Canada, academia and Canadian Strategic Highway research programme to evaluate the performance of ECR on a total of 92 bridge decks, 2 bridge barrier walls, and 1 noise barrier wall located in the states of California, Indiana, Kansas, Michigan, Minnesota, New York, Pennsylvania and the provinces of Alberta, Nova Scotia and Ontario in Canada in the field and the laboratory, comments as follows:

> "ECR has provided effective corrosion protection for up to 20 years of service with little or no maintenance or repair performed on the decks. No evidence of any significant premature concrete deterioration that could be attributed to corrosion of ECR was found."
>
> Another report of 1998 states:
>
> "The preferred primary corrosion protection system in many states has been fusion bonded epoxy coated reinforcing bars which has been used in approximately 20000 reinforced concrete bridge decks, FBECR has performed very well in alleviating the problem of corrosion under deterioration of concrete bridge decks, It is estimated that its use in the last 25 years had saved the tax payer billions of dollars so far"

In March 2002 FHWA issued a 773-page Report No. FHWA –RD- -01-156 titled "Corrosion cost and preventive strategies in United States": It states FBECR as the preferred protection system — it represents roughly 95 percent of new deck construction since 1980. It also reports about methods used in USA for corrosion control on bridges thus: "For new construction, the preferred primary corrosion protection system is fusion bonded epoxy coated rebars in conjunction with a high quality concrete.

In another Federal Highway Administration Technical note on corrosion protection systems from the office of Engineering R&D puts the current status thus[12]:

> "At present epoxy coated rebar is the most common and very successful corrosion protection system used by forty-eight state highway agencies. To date, there are about twenty thousand bridge decks using FBECR as the preferred protective system. This represents roughly 95 percent of new deck constructions since 1980s.
>
> Today, ECR is specified for new constructions, example parking garages, aquariums, nuclear power plants, coal plants, buildings …. At present there are approximately 100,000 structures containing ECR. Due to tremendous success and confidence gained by using FB ECR over the last twenty years, there are about 35 coating plants employing several thousand people."

A similar report from Minnesota Department of Transportation says on their survey[13]: "The first bridge deck built in Minnesota with ECR shows no signs of distress after almost twenty years of service."

Florida Keys

The Florida Keys, Seven Mile bridge and three sister spans were built in the early 1980s as an experimental design to save money. They started cracking up soon after they were built and a US DOT report in February 1986 noted that deck cracks and expansion joint failures were apparent together with excessive salt penetration into the concrete. Chloride content in sea water here was some 29,000 ppm as against normal seawater content of 17,000 ppm.

This saga of apparent poor quality control and construction practices in the early stages of introduction of FBEC with no system of pre-qualification of coating material, workmanship or vendor in position was reported and analysed and the failure examined mercilessly throughout USA with both designers and construction firms blaming each other.

In 1986 the Florida Department of Transport (FDOT) commissioned Corrosion Research Laboratory to evaluate corrosion aspects of the Long Key bridge. Some of their findings reveal a number of significant factors in relation to the usage of epoxy coated rebar[2]:

(i) Two separate companies carried out the coating; one of that now ceases to exist. No production/quality control records exist for either.

(ii) Significant corrosion of rebar had occurred on three of the four bridges, all limited to within the splash zone.

(iii) Cover to the rebar where corrosion has occurred is down to 25 mm (1 inch)

and below in places and in all cases is below specification.

(iv) Spalling of concrete has occurred in areas with less than specified cover and where the cement matrix was lost during construction.

(v) The FBECR taken to the laboratory showed serious coating fracture and disbondment when subjected to either standard bend tests or fabrication bending.

Aftermath

Subsequent to this incident, coating standards were made much more stringent with the objective of achieving practically holiday-free (three per meter now allowed as per ASTM) coating with insignificant chloride permeability and bond loss compared to uncoated bars limited to only 15 percent[4]. Incidentally, FDOT has more than 26 bridges elsewhere without any corrosion where epoxy coated bars were used. But the performance of these bridges was attributed to good quality of concrete and cover, whereas bad concrete and poor cover were supposed to be made good by the protectiveness of a poorly applied and rather non-standard rebar-coating!

Other independent research and some recent researches

R.N. Swamy *et al* concluded after elaborate research of over a few years with accelerated and with damaged concrete, (partly reported earlier) the following[1,2,9]:

"Uncoated bars showed extensive and deep rusting under natural marine exposure conditions. A concrete cover depth, as high as 70 mm was found to be inadequate to protect the steel under both natural and accelerated corrosion tests. The lower part of the tidal zone was found to be more aggressive than the upper part for such bars.

Epoxy coated bars, with a coating thickness of 200-300 μ remained practically unaffected under natural and accelerated exposure conditions, and maintained all the original characteristics of gloss, coating hardness and coating adhesion even with as small a cover as 20 mm.

Even with artificially damaged coatings, the corrosion damage suffered by epoxy coated bars was negligible under both natural and accelerated marine exposure conditions. Further, the rate of corrosion damage was far less than that of comparable uncoated and galvanised bars.

The data presented here show that even under very severe marine exposure conditions, and even with localised coating damages, epoxy coated bars with uniform coating thicknesses and coatings with good impact strength and excellent resistance to salt water spray and alkaline solutions can provide long term protection against corrosion."

South Dakota DOT study

This South Dakota State Department of Transportation (SDDOT) sponsored a project, which was conducted at the University of Kansas Centre for Research, evaluated the corrosion resistance of three types of steel reinforcing bars – epoxy coated, micro composite, and uncoated[14]. The report's recommendations included the following.

"SDDOT should continue to use epoxy-coated reinforcing bars to provide corrosion protection in bridge decks until such time as a superior corrosion-protection becomes available."

The researchers added: This recommendation is based on superior corrosion performance of epoxy-coated steel as compared to microcomposite steel (Section 5.3) and the superior life expectancy and cost-effectiveness of bridge decks containing epoxy-coated reinforcement compared to the alternatives evaluated in this study.

The report's authors also state: … "Time to first repair for epoxy-coated reinforcement is estimated to be 40 years based on the observation that no bridges built with epoxy-coated bars in South Dakota have required repair …"

Iowa DOT study

Researchers at Iowa State University (ISU) evaluated existing bridge decks to study the impact of deck cracking on durability[15].

In this study, 81 bridges were evaluated. No delaminations or spallings were found in bridge decks constructed with FBECR. The oldest bridge deck was 20 years. No maintenance had been yet performed for those decks constructed with FBECR in Iowa.

The ISU researchers stated the predicted service life of Iowa bridge decks for considering corrosion of FBECR is over 50 years, illustrating that FBECR can significantly extend the service life when compared with bridges constructed with uncoated bars.

The ISU researchers also reported on their study at the Transportation Research Board's annual meeting in January 2003. The TRB meeting is the major technical conference of the transportation community. Attendance at the week-long conference totals over 5,000 people. In their presentation, the ISU researchers contended the service life extension of bridge decks provided by FBECR is in the order of 60 to 65 years.

CRSI study

This three-year research project, which was sponsored by the Concrete Reinforcing Steel Institute, (CRSI), commenced in July 2000. The independent professional research firm, Wiss, Janney, Elstner Associates of Northbrook, Illinois is presently conducting the study.

The research project is nearing completion. A final report is expected to be issued soon. The researchers reported the results of the study at the TRB Annual meeting in January 2003. Their findings correlate well with the results of the Iowa DOT study. In the CRSI research project, when both mats of reinforcement in a bridge deck are epoxy coated, the service life extension is estimated to be in the order of 82 years. For bridge decks in which only the top mat of reinforcement is epoxy coated, the service life extension is estimated to be 40 years.

Permeability of FBEC rebars

Permeability level of chlorides and oxygen of FBEC are very low and many codes provide limits for the same. In fact FBEC is the only coating type wherein chloride ion permeability test is conducted and measured as per ASTM 775 M. Hence the question of oxygen reaching the substrate before chlorides does not arise excepting near undetected holiday and underneath a crack in the concrete – a remote possibility of both occurring together. In fact, Kondratova *et al* studied the corrosivity of epoxy coated bars by embedding U-shaped bars (15 mm deformed) - epoxy coated and surface treated in several different ways, in thin concrete slabs (55 x 200 x 300 mm) with a high water cement ratio of 0.6 and a concrete cover of only 20 mm, to obtain results in a short period[6]. Some of the bars received a primer coating before epoxy application, some had surfaces contaminated with salt (3 percent NaCl) before coating application. Some of the coated bars were intentionally damaged with the damaged area comprising seven 6 x 6 mm square spots – evenly distributed over the surface of the bar. The exposure conditions were a laboratory test chamber in New Brunswick, Canada simulating a marine environment, and a natural marine environment site at Treat Island, Maine under US Army Corps of Engineers. The experimental study was done between 1991 and 1993. The laboratory set up tank assembly activated a two hour wet-cycle at 32 $\pm$ 2°C followed by a four hour dry cycle at 68 $\pm$ 2°C electronically operated by a computer submerging the slab specimens by two thirds during a wet cycle and by one third during a dry cycle. One year accelerated testing in such a laboratory set-up corresponds to approximately 5-8 years of natural marine exposure at Treat Island. The conclusion of this test regime clearly demonstrated the superiority of even a bar with damaged coating over an uncoated bar, the corrosion current flow with the former being 10 percent of the latter after an equivalent of 20 years of the cycle. The experiment was also continued in the Maine Island natural marine environment which is amongst the most corrosive in the world, for a long time. An observation after 8 years, in 1998 found no de-bonding, no delamination excepting in one out of 5 samples. The performance in normal marine environment and compact good concrete is expected to be much better.

Fusion bonded epoxy coating in a factory, has high degree of impermeability to chlorides, oxygen or moisture. The few reported instance of water vapour permeability or disbondment occurred in highly porous poor concrete with shallow cover near holidays or defects in the coating, and often in highly aggressive chloride environment going upto 4.5 kg and even 11.9 kg/m3. Even in the C-SHRP study of Canada, "The Ontario ministry of transportation reported that corrosion on the extracted ECR segments was more severe at a location of heavy cracking, shallow concrete cover of 15 mm and a high chloride concentration of 9.4 kg/m^3. This ECR segment was extracted from a noise barrier wall panel that had significant corrosion-induced concrete distress. The concrete in this barrier wall was also very permeable – 21,293 and 22,722 Coulombs. A typical bridge deck does not have such a low concrete cover and/or highly permeable concrete.

Resistance to heat

Concrete itself is a very poor conductor of heat. So to assume the bar temperature as 800-900°C (When most of non ferrous metals starts melting) is totally unrealistic. At and above 400°C yield point of reinforcement steel drops to less than half in the case of CTD bars and in the case of TMT this is around 600°C and therefore no coating is expected to perform at 800 to 900 °C as this is not going to serve any purpose. Thermal conductivity of the coating varies widely, a median value of which is 6×10^{-4} cal/s/cm^2/°C/cm — a very low figure indeed. Coefficient of thermal expansion varies from 72 to 160×10^{-6} mm/mm/°C depending on the types of powder and curing as against 70 to 120×10^{-6} in same unit for concrete. Difference is not substantial.

However, it is to be noted here that ECR is used in safety structures after passing standard fire resistance test as per American standards. For instance, NASA's rocket fuel plant, that is, manufacturing facility for ammonium perchlorate when reconstructed in 1988 after the plant was destroyed in an explosion the designers preferred to use all concrete reinforcement steel with epoxy coating. This is a fire-rated structure too and NASA's acceptance should itself be considered as certification.

Regarding the lifespan of epoxy, ASTM supports and provides a working life for epoxy from 30 to 90 years. It is believed that fusion bonded epoxy being a thermosetting powder can last more than 75 years as that is also extensively used in the petroleum-carrying pipelines for more than 50 years, without distress.

Field handling of epoxy coated rebars

Epoxy coated bars can be transported without any film damage with the kind of care taken at the time of loading in the epoxy coated plant. Regarding touch-up epoxy on the damages or on cut ends, it is absolutely possible to repair satisfactorily as well as use them within a few hours. In any case a very good guidance is available in ACI 301-96[16]. Regarding bad construction practices at the site, there are well laid out standards and guidelines of good practices even in the ACI code. The workmen, foremen and inspectors have to be trained properly in transportation, handling, storage and fabrication of the coated bars and then during placement and consolidating of concrete using FBECR such that there is no metal to bar contact during any such working. This means padded contact during bundling, lifting and storing, neoprene sleeved mandrel during bar-bending and jacketing vibrating needle with pvc/neoprene sleeve. Pumped concrete will be an obvious advantage. The need of the hour is a strong QCI system from the clients right from the powder selection to placement of coated bar in the forms so as to achieve practically holiday-free coating of the specification drafted as per latest international standards (ASTM, EURO, BIS etc.) as Indian Standard has outlived its life. This along with dense compact concrete well cured and with codal cover should be able to give a durable structure in extreme and severe environments. High performance concrete as in Bandra Sewage outfall tunnel lining will be an added insurance towards long life, as in such well engineered designer concrete cracking will be less and chloride diffusion reduced by several degrees.

In India, FBECR has been increasingly used in pre-cast concrete of M40, M45, M60 and various other strengths. In many situations requiring repetitive and fast production steam curing has been adopted as in Bandra sewage out fall undersea tunnels and underground collector sewerage tunnels on land in highly aggressive environment, designed and engineered by British consultants and constructed by national and multi-national agencies. Chance of any damage to rebar coating during placement is further reduced to practically nil by pumping concrete and consolidation concrete, by form and surface vibrators. With the advent of many more modern technologies in placement and compacting concrete like, slip form, self compacting concrete etc., damage to coating during concrete placement is almost nil and the assumption of coating damage upto 0.50 percent of total surface area in corrosion study has become a reality, though upto 1 percent damage is permitted for patchwork in the latest ASTM and ISO codes.

CTD rebars are different from FBEC rebars

As is well known, cold-twisted deformed (CTD) or thermo-mechanically treated bars (TMT) are products for improving the tensile strength (yield/proof) and bond strength of the rebars for withstanding heavier loads compared to traditional mild steel or black steel (42/44) and only now durability and ductility considerations have been incorporated to obtain CRS/HCR variety. That the corrosion resistance of this variety of bars is some 1.4 -1.8 times that of mild steel or carbon steel is another issue and is not a point of discussion here. The fusion bonded coating will coat whatever the steel surface is, provided the surface is free from scabs, millscale, undulations and other imperfections and in case of deformed bars, the deformations are free from re-entrant angles, acute angles and as per relevant codal provision. In fact coating of uniform thickness is much easier on plain steel bars than on deformed bars.

Some other factors

Epoxy resins of various formulations have been used both in pure solvent-free form and along with fillers, sand, mortar or concrete for strengthening and repairing concrete, grouting and leak-proofing, other than surface coating and now re-bar coating. Formulation in each case is such that the differential strain between the matrix or the concrete and the resin whether dispersed or in the form of a film during shrinkage, temperature movement, etc. is kept to the minimum. It is necessary to differentiate between liquid epoxy and epoxy powder, as liquid epoxies are not made or cured through the same polymerisation process. Infact, cured solventless epoxy or FBE do not shrink. No report of de-bonding or de-lamination due to any differential strain between coating and concrete is available. It is highly cross-linked, inert and insulation polymer material with an irreversible polymerisation process and chance of its degradation in a further-embedded concrete environment is extremely remote. The film does not also affect the ductility of the bar. The film itself goes through a dynamic impact test, though no cyclic loading test excepting thermal shock for this has been done so far. In any case during a seismic incidence there will be many more important causes that will give rise to any failure in the structure and not merely this epoxy coating on the re-bar. There has not been so far any single structure that has used ECR and fallen prey to seismic activity due to such use.

Conclusions

Fusion-bonded epoxy coating is an effective strategy of preventing rebar corrosion in the aggressive environments in combination with good quality concrete and cover along with good construction practices. The usage is now spread all over the world including Asia with plants in almost all major areas of Gulf, China, Indonesia, Malaysia and India. In 2003 industry estimates, its use would be well over two million tonnes all over the world. What started primarily as an important requirement for bridge deck construction is now used in all types of structures including marine structures, multistorey buildings, car parks, fresh and waste water facilities, nuclear power station water system and so on.

In India itself there are more than 3000 structures — flyovers and bridges in coastal area (covering almost the whole coastal strip upto 50 km from the high tide line), off shore structures and jetties, sewage out fall tunnels and conduits, water treatment and waste water plants, building foundations in coastal environment and aggressive soils, nuclear power plant intake structures and so on, covering more than a million ft^2 of rebar surface, using this coating since its introduction here is early nineties. A leading coating company has done rebar coating of around 250 structures recently.

This is the only coating — eco-friendly and cost-effective — which is done with continuous and substantially on-line quality control right from the coating material selection stage so that all vital and environmental parameters for coating performance like thickness, continuity, adhesion, flexibility, resistance against abrasion, impact, disbondment, salt spray and usual corrodant chemicals, chloride permeability, cathodic disbondment and so on, can be tested and accepted as per international standards formulated in this regard.

The industry of coaters and powder manufacturers are professionals in the field of corrosion with responsible behaviour, unlike many involved in promoting other types of techniques with no common standards of acceptability — either national or international, and very little research. The short-comings observed in field study globally are being continuously attended to by improving specifications, standards and techniques internationally, unlike any other system in this regard. It is indeed a reliable corrosion engineering technique of global standards and wide use that saves billions of dollars around the world every year by saving repairs or replacement of reinforced concrete structures.

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