CORROSION OF EPOXY-COATED REBAR IN A MARINE ENVIRONMENT

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In 1986 the first signs of corrosion of epoxy-coated rebar were observed in the Long Key Bridge Substructure. Further investigations revealed extensive corrosion of epoxy-coated rebars in four of the five major structures in the Florida Keys. A Task Force was established to investigate the problem by conducting in house research, contract research and a statewide survey of bridges with epoxy-coated rebar substructures. As a result of the investigation it was concluded that epoxy-coated rebar is unsuitable for marine splash zone corrosion protection.

INTRODUCTION

In 1976 a technical group composed of members of the Florida Department of Transportation (FDOT) and the Federal Highway Administration (FHWA) established criteria for corrosion protection for bridges constructed in the Florida Keys. At that time the FHWA was investigating corrosion of reinforcing steel and suggested that epoxy-coated rebars be considered along with other protective measures on federally funded projects. The technical group's resolution was that epoxy-coated rebars should be used throughout the structures built in the Florida Keys since these structures would be located in a corrosive marine environment. The first use of epoxy-coated reinforcement in Florida was on the 17th Street Bridge over Indian River at Vero Beach in October 1977. Two other bridges followed, one at Destin over East Pass in December 1977, and the other at Ormond Beach over Halifax River in May 1981.

In 1981, the FHWA adopted epoxy-coated steel reinforcement as the primary means of corrosion control in bridge decks. As a result, epoxy-coated steel became the primary protection method for all bridge reinforcement in the State of Florida. The FDOT specification for epoxy-coated rebar was fashioned after prevailing ASTM and AASHTO standards. The specifications allow two holidays per 30.5 cm (2/ft) at the production line and 2% damage per 30.5 cm (2%/ft) at the construction site.

Inspection of epoxy coating by the FDOT has always included an initial plant approval and an approved quality control plan. The majority of all epoxy-coated rebars used on FDOT projects was shop inspected by FDOT personnel or by commercial testing laboratories. Job site control has been accomplished through visual examination by construction personnel. Since 1986, FDOT has performed full-time in line inspections at a local epoxy-coated rebar facility to insure compliance with existing specifications. The FDOT has always followed and implemented the national standards and recommendations for the manufacture control and use of epoxy-coated rebar. In 1986, however, the substructure of the Long Key Bridge in the Florida Keys began to show signs of corrosion only six years after construction *(1)*.

KEYS BRIDGES FINDINGS

An investigation was conducted on seven structures in the Florida Keys. Five of these are major structures with lengths greater than 610 m (2,000 ft) *(2,3)*. Significant corrosion of the epoxy-coated rebars was found in four of the five major bridge substructures. The corrosion found in these four bridges was limited to 0.6 to 2.4 m (2 to 8 ft) above the mean high water mark on the substructure (marine splash zone). The bridges and approximate number of piers exhibiting corrosion are shown in Tables I and II.

Corrosion was found in both fabricated and straight epoxy-coated rebar, Figure 1. Visual inspection indicated that corrosion may have started in the fabricated rebars and then progressed to the straight bars. Underneath the coating, water with a pH of 5 was commonly found, indicating that acidic conditions had developed. Cores taken from the structures on opposite sides from the corrosion spalls indicate that corrosion had progressed beyond the spalled area into sound

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Table I THE FIVE MAJOR FLORIDA KEYS BRIDGES

Bridge	Construction Period	No. of Piers In Water	First Signs of Corrosion
Long Key	1979-1981	101	1986
Seven Mile	1979-1982	263	1988
Niles Channel	1981-1983	37	1988
Channel Five	1981-1983	34	None
Indian Key	1979-1981	18	1990

concrete.

The spalled areas were larger than those previously experienced with bare rebar. For example, spalls as large as 0.6 x 1.2 m (2 x 4 ft) have been observed in locations where corrosion was confined to a length less than 30 cm (12 in) of rebar. Some spalls occurred in areas deficient in concrete clear cover and where the concrete components segregated during construction. However, the majority of the corrosion was observed in locations containing sound concrete with up to 10 cm (4 in) of cover. Large delaminations of concrete were observed in areas without visible cracking, indicating advanced stages of corrosion of epoxy-coated rebar.

Determining the initial condition and the original quality of the epoxy coating was difficult. Samples of epoxy-coated rebar were extracted from 2.4 m (8 ft) above the mean high water mark for investigation. Inspection of these samples indicated complete coating disbondment from the substrate. The coating itself appeared to be of adequate quality. Coated rebar samples taken from the Long Key Bridge and analyzed by a producer of epoxy powder were said to be of "good quality." Damage of the epoxy-coated rebar during construction could not be quantified, but appeared to be less than the 2% allowed by specifications.

Table II PROGRESSION OF CORROSION IN FOUR KEYS BRIDGES BY NUMBER OF PIERS AFFECTED

Bridge	1986	1987	1988	1989	1990	1991
Long Key	1	3	17	--	31	31
Seven Mile	--	--	8	--	58	60
Niles Channel	--	--	17	*	17**	17
Indian Key	--	--	--	--	2	2

* All corrosion spalls repaired.
** New corrosion spalls.

RESULTING INVESTIGATIONS

On February 1, 1990 the Department established a Task Force to investigate the epoxy-coated rebar problem statewide. The objectives of the Task Force were:

- Determine the extent of the problem.
- Define causes.
- Define short term solutions.
- Develop long term solutions.
- Develop standards and design criteria.

This report discusses the first two objectives. Discussions on the other objectives can be found elsewhere *(4,5,6,7,8)*. To accomplish the above objectives, in-house research, contract research and a statewide survey were initiated.

IN-HOUSE RESEARCH

In-house research consisted of 1) a laboratory study to evaluate fabrication and damage effects, 2) a field study of test piling, and 3) documentation of the life cycle of an epoxy-coated rebar from coating plant to construction site.

Fabrication And Damage Effects

Fabricated bare, pre-fabricated epoxy-coated and post-fabricated epoxy-coated rebar samples were cast into structural quality concrete and exposed in a high chloride solution for 30 months *(9)*. The samples were characterized according to producer and coating quality. Quality was based on the performance of the coating in the standard bend test. Resistance measurements, voltage potential and visual inspection were used to evaluate the performance of the coating for each specimen.

Figure 1 Typical corrosion deterioration common to Seven Mile Bridge observed in 1987.

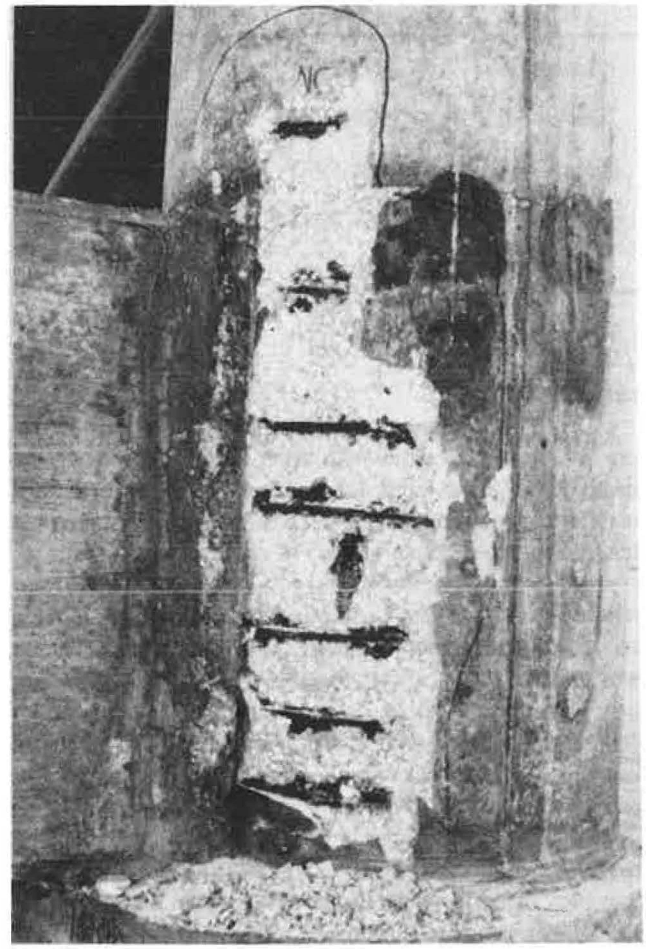
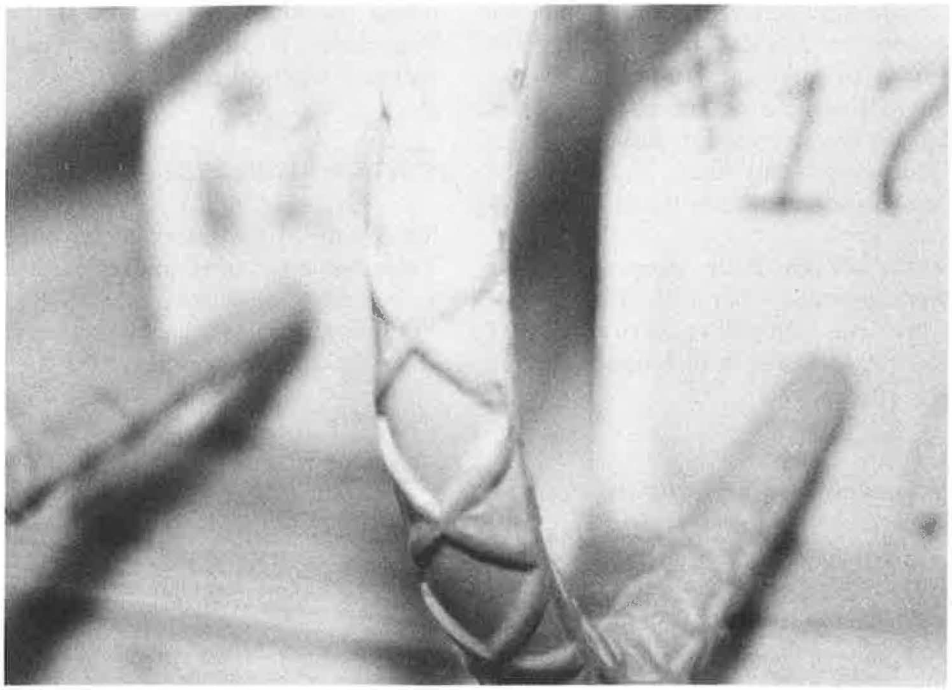


Figure 2 Typical corrosion deterioration common to Niles Channel Bridge observed in 1987.

The results of this investigation showed that coating after fabrication did not significantly improve corrosion resistance. Disbondment occurred in "perfect" condition bars and in the bars coated after fabrication, Figure 2. Coating disbondment can lead to serious problems since the initial passivating effect of the concrete is isolated from the rebar. The disbondment of the epoxy allows the chloride laden electrolyte to reach and progress along the rebar surface. The corrosion observed in these tests was not as severe as noted in the Florida Keys structures. This is believed to be due to the sample configuration that allowed a large anode to small cathode ratio and the short exposure period.

Field Study At Matanzas Inlet

A test site established at Matanzas Inlet (Intracoastal Waterway) on the east coast of Florida was used to evaluate epoxy-coated and bare rebar test piles *(9)*. The test piles were installed in 1979 in the corrosive marine environment, Figure 3. After approximately nine years of exposure, three test piles were removed for examination, one with epoxy-coated steel rebars, one with bare rebars and one with galvanized steel. The epoxy-coated rebar pile outperformed the bare rebar piling. However, the epoxy-coated rebars used in this study were not typical of those supplied to construction projects. The



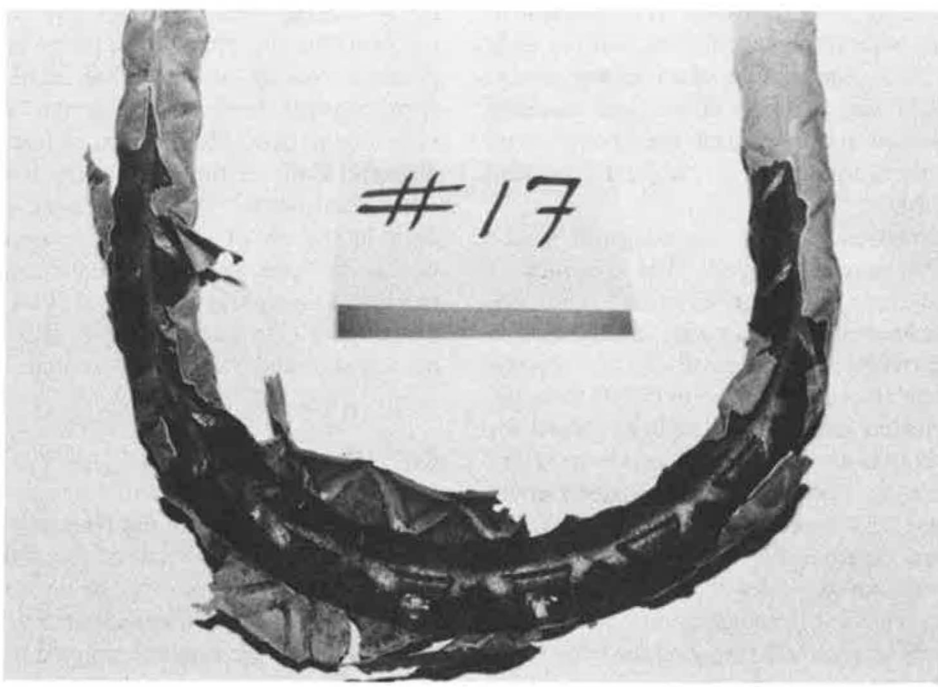


Figure 3 Sample #17 with small defects present before test (top) and extreme disbonding, localized and general corrosion after test (bottom).

epoxy-coated rebars used in this study were "laboratory perfect" bars. "Laboratory perfect" bars may be useful for establishing baseline data but results from these should not be used to imply performance in actual usage. Conditions such as pre-exposure (ultra-violet rays or salt spray), fabrication, and damage during construction were not addressed in this study. The galvanized rebars showed no corrosion and only traces of zinc oxide.

The results of this study compared to the performance of epoxy-coated rebar in the Florida Keys emphasized the problems with past research conducted. These results lead to a change in direction for future research on epoxy-coated rebar.

Life Cycle of an Epoxy-Coated Rebar for a Construction Project

Documentation was made of the life of an epoxy-coated rebar from plant to finished structure. An epoxy coating plant was visited where careful handling and rigid inspection by the manufacturer and FDOT personnel were exercised. Blasting operations, temperature measurements, coating process, curing, holiday detection and adhesion testing were all followed in accordance with an existing quality control plan. All handling was done by padded straps and wood cribbing to minimize damage. The cutting and fabrication were handled in the same manner with all damaged areas and cut ends immediately patched. Each bundle of rebars was placed on wooden pallets and carefully lifted onto shipping vehicles with padded straps. When the epoxy-coated rebars left the plant, they were in excellent condition with minimal damage.

A construction site that was using this plant's epoxy-coated rebar was also visited. The condition of the epoxy-coated rebar was quite different. The construction site was located on a causeway crossing Tampa Bay, a highly corrosive marine environment. Epoxy-coated rebars were stored less than 9 m (30 ft) from the saltwater. Fabricated rebars that had been stored for over a month showed small corrosion products at the root of deformations, Figure 4. Epoxy coating could easily be removed with a pocket knife along the fabricated (bent) areas, Figure 5. Fabricated units were seen on barges that were on the water for six weeks. Epoxy coating on rebars stored at the construction site for over a year, could easily be removed revealing the beginnings of corrosion products. All the epoxy-coated rebars examined were within specification requirements of 2% damage per 30.5 cm (2%/ft). These findings at the construction site showed that even epoxy-coated rebar within specifications will incur sufficient damage and degradation of bond such that the long term performance is highly questionable.

STATE-WIDE SURVEY

To determine the extent of the problem statewide, a listing was made of all bridges constructed using epoxy-coated rebars since the Keys Bridges were built. From this information, bridges were selected for investigation using the following criteria:

- Bridges constructed since 1979,
- Bridges five years or older,
- Bridges with substructures located in marine waters, and
- Bridges with pier-type substructure foundations.

A total of 29 bridges were selected for investigation. Bridge number and site number for the 29 bridge sites are shown in Figure 6. A typical inspection summary is shown in Figure 7. At each bridge site, cores of concrete and epoxy-coated rebar samples are extracted for examination and testing. To date, 14 sites have been inspected. In all but one instance, gross disbondment of epoxy coating from the rebar was reported. In each instance, the disbondment appears independent of the chloride content at the rebar level. No significant corrosion has been noted on the additional bridges inspected to date. However, in all instances thus far, the chloride levels at the rebar were not high enough to initiate corrosion. Since the epoxy coating disbonded early in the life of the structure, corrosion is likely to initiate as soon as chloride levels at the rebar depth increase to a significant amount (0.71 kg per m^3 or 1.2 lbs per yd^3). The causes of rebar disbondment are being investigated under contract research.

CONTRACT RESEARCH

A research contract with the University of South Florida (USF) under the direction of Dr. Alberto Sagüés was initiated. This research is being conducted in close coordination with the statewide survey. Samples extracted from the bridge sites are shipped to USF for detailed examination. The primary objectives of the research are to define the cause of corrosion of epoxy-coated rebar and aid in short and long term solutions to the problem.

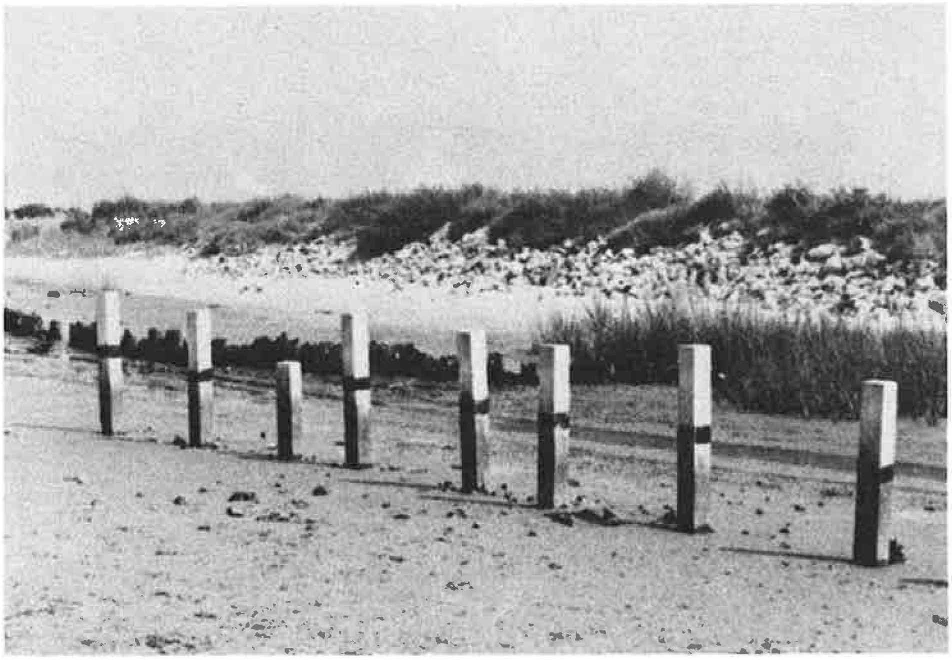


Figure 4 Matanzas Inlet test site after placement of test pilings in 1979 with application of coal-tar epoxy bands around areas containing the rebar support chairs.

These are being accomplished by investigating the corrosion mechanism, parameters affecting the corrosion, and causes and effects of coating disbondment. The results of this research are reported elsewhere *(4,5,6,7)*.

IMPLICATION AND CONCLUSIONS

The investigations conducted to date have convinced the Florida Department of Transportation that epoxy-coated rebar is inappropriate for marine corrosion protection. The disbondment of the epoxy coating from the rebar in the absence of chlorides is the most significant and compelling finding in this investigation. Epoxy-coated rebar is intended to protect against corrosion by providing a thin barrier film. If the bond is lost, the protection characteristics are diminished.

To date, research has not found that the manufacturing process of epoxy-coated rebar was improper or out of specification for any of the FDOT bridges examined. There appear to be no significant differences between present day coating technology and standards and those employed for the Florida Keys Bridges. Due to the severe disbondment problems observed, bolstering of the specifications is not considered an appropriate solution to preventing the corrosion of epoxy-coated rebar. FDOT has concluded that epoxy-coated rebar will not provide suitable long term protection against corrosion in a marine splash zone environment.

In December 1988, FDOT stopped specifying the use of epoxy-coated rebar in bridge substructures. At that time, alternatives such as penetrant sealers, high range water reducers, specification improvement for the quality control of concrete, and certain design features were implemented. Silica fume concrete, coated prestressed strands and ground slag cement were incorporated on a limited experimental basis. Further research was required so protective measures such as stainless steel rebars, galvanized rebars, fiberglass rebars, latex modified concrete, calcium nitrite, and new organic coatings could be evaluated.

In July 1992, the Florida Department of Transportation discontinued the use of epoxy-coated rebar in all construction. Investigations and research conducted since 1988 has lead to the experimental implementation of silica fume concrete for substructures and calcium nitrite for superstructures located in extremely aggressive environments. It is anticipated that these alternative corrosion control features will be adopted as FDOT's standards for long term corrosion control in the marine environment.

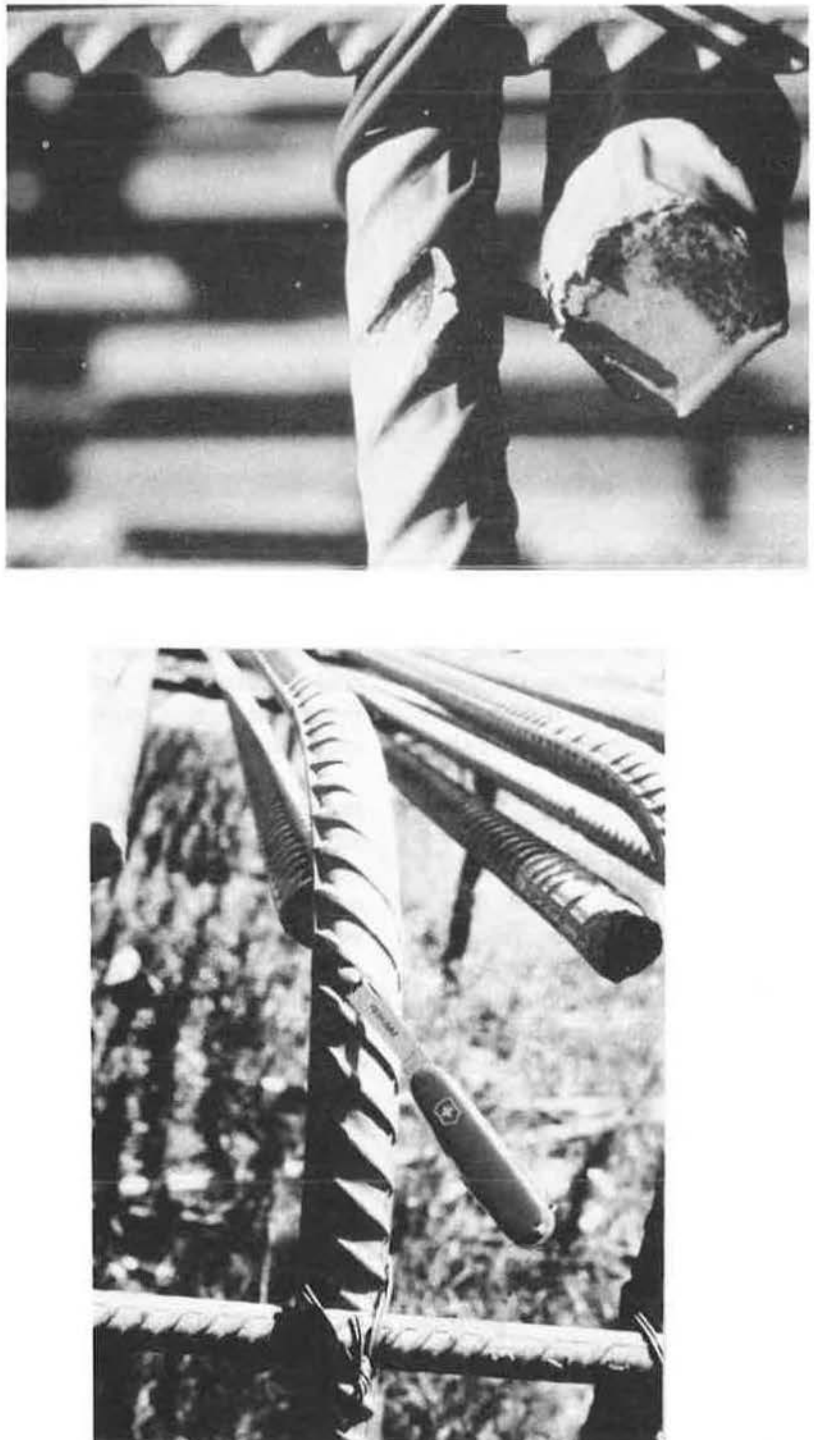


Figure 5 Epoxy coating easily removed with pocket knife along fabricated (bent) areas.

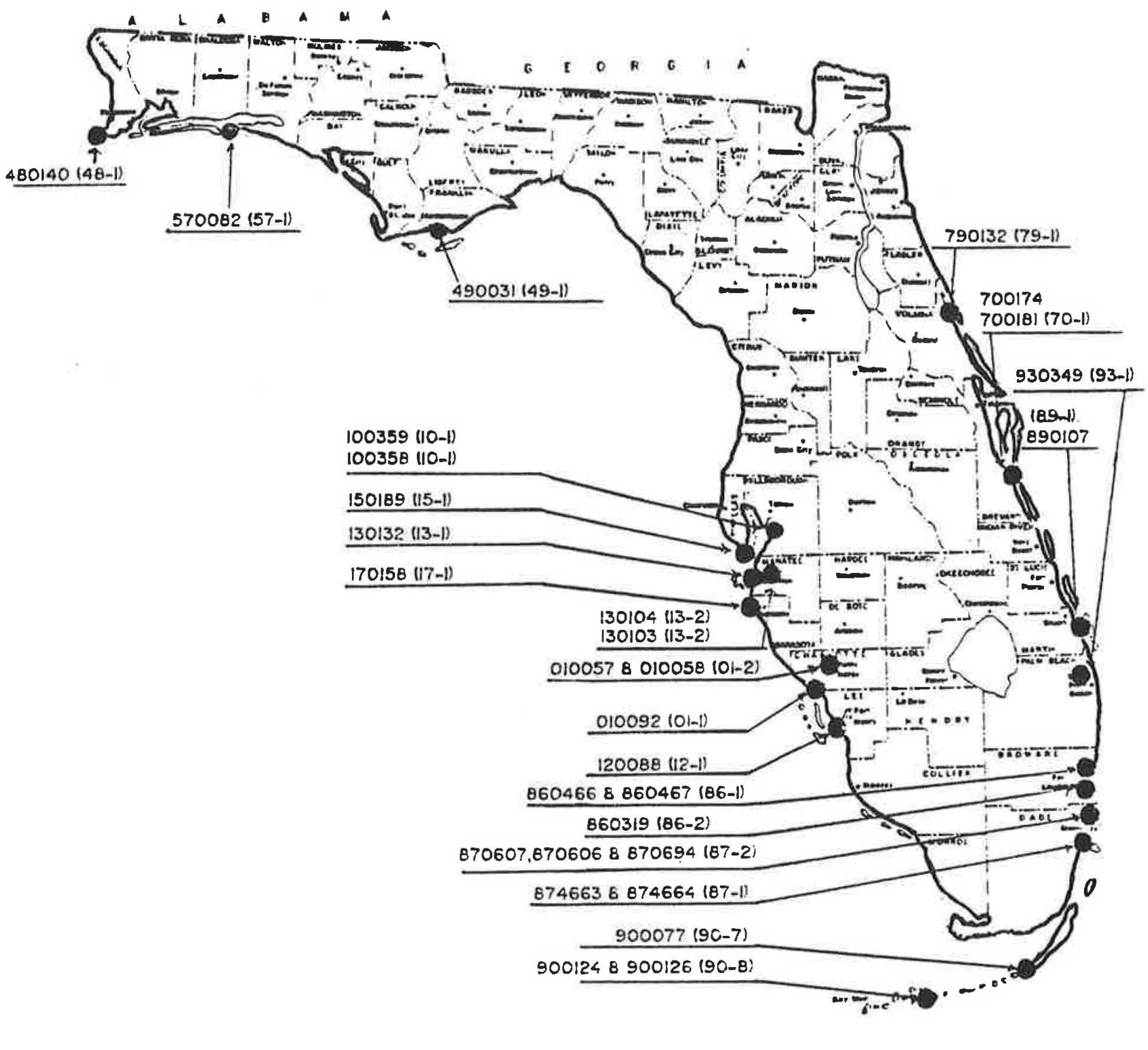


Figure 6 Bridge and site numbers for the 29 bridges selected for the epoxy-coated rebar investigation.

FLORIDA DEPARTMENT OF TRANSPORTATION
EPOXY-COATED REBAR INVESTIGATION
INSPECTION SUMMARY

DATE 05/22/91 **TEMP.** ____________
BRIDGE # 790132 **R.H.** ____________
CONSTRUCTION DATE 1986
LOCATION (SR#, CITY) SR-40 in Volusia County (City of Ormond Beach)
CONDUCTED BY: Lasa, Langley, Cerlanek, and Petrin
SUBSTRUCTURE DESIGN Round columns bearing on square footers
SUBSTRUCTURE REBAR Epoxy (brown color)
CONSTRUCTION QUALITY Good
NO. OF PIERS EVALUATED Three

NO. OF CORES OBTAINED	PIER NO. 5	PIER NO. 13	PIER NO. 17	PIER NO. ---
FOOTER	1	1	1	---
COLUMN	5	5	5	---
STRUT	---	---	---	---

CONCRETE RESISTIVITY (COLUMN)
LOWER LEVEL 13.6 kΩ **MID-LEVEL** 14.1 kΩ **UPPER LEVEL** 20.2 kΩ
CHLORIDE CONTENT AT REBAR COVER (SPLASH ZONE) ____________
NUMBER OF REBARS EXPOSED 15
TYPICAL REBAR COVER 9 to 14 cm (3-1/2 to 5-1/2 in)
NUMBER OF REBAR SAMPLES OBTAINED 6 pieces (2 each column)
REBAR CONTINUITY (%) 80%
AVERAGE REBAR RESISTANCE ____________
NO. OF LINEAR POLARIZATION TEST CONDUCTED: 3
MAX. CURRENT 6 mA **MIN. CURRENT** 20 μA
$CuSO_4$ POTENTIAL: LOWER COLUMN -.600 v **UPPER COLUMN** -.068 v

MACROCELL TEST	PIER NO. 5	PIER NO. 13	PIER NO. 17	PIER NO.
10 SEC.	Continuity	5.5 mA	53 mA	---
10 MIN.	Continuity	1.3 mA	10 mA	---

AVERAGE EPOXY BOND Disbonded
BRIDGE CONDITION SUMMARY This bridge is located on SR-40 over the Intercostal Waterway. The pH of the water is 7.8 and the resistivity is 34 ohms and the chloride content is 10, 493 ppm. The bridge was built in 1986 (5 years old). Concrete resistivity falls in the low-medium range and in some instances few high half cell potentials were observed (-.600 v). Linear polarization tests do not indicate any serious corrosion activity. Continuity was observed in 80% of the bars tested. Rebars had adequate cover and construction quality is average. No cracking, or spalling was found. Epoxy disbonding from bars on all tested samples.

Figure 7 Typical FDOT Epoxy-Coated Rebar Investigation inspection summary.

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