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Article *in* Materials performance · October 2002

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Performance of a 60-Year-Old Concrete Pier with Stainless Steel Reinforcement

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A 60-year-old concrete pier, constructed with stainless steel reinforcing bars (rebar) and exposed to a tropical marine environment, has shown good performance during its service life. This article describes the tests carried out on the pier during this investigation. The tests included visual inspection, chloride content determination, and concrete resistivity as well as electrochemical measurements to the rebar. The authors also discuss durability issues on the pier, based on the results obtained.

The good condition of a concrete pier in the Port of Progreso de Castro in Yucatán, Mexico (Figure 1) has aroused international interest. The pier was built from 1937 to 1941 by a Danish contractor,[1] who presented the winning design to the Mexican government based on the use of 9-m free span concrete arches. The pier dimensions, obtained from a recent survey performed by the Mexican Secretariat of Communications and Transportation (SCT), appear in Figure 2.

The pier (1,752 m long and 9.5 m wide) consists of 146 hinged arches 12-m center-to-center span and 1.6-m high (Figure 2). Each arch is supported at the ends by reinforced concrete girders, each resting on two massive concrete piles. One of the reasons why this design was selected was to eliminate conventional carbon steel reinforcing bars (rebar) by using massive concrete in the substructure. The Mexican authorities wanted to build this pier having low or no corrosion risk, thus avoiding the severe corrosion problems that had developed in several other marine structures in Mexico. This innovative project utilized type 304 stainless steel (SS) (UNS S30400) for girder reinforcement and, in the long term, for corrosion protection. To do so, 220 tons (199,584 kg) of 30-mm-diameter SS, nondeformed bars were used.[1]

The pier shows no visible sign of deterioration after 60 years of service,

FIGURE 1
General view of the Progreso pier.

even though the structure has received no maintenance during this period of time, according to port authorities.[2]

Using modern techniques (mechanical, physical, and electrochemical), several actions have been taken to verify the actual state of the pier to outline maintenance actions to extend the pier's service life. A full-pier examination, based on the preliminary inspection discussed in this article, is scheduled in the near future. This article presents the results of the preliminary inspection as well as the current actions taken as a result of the inspection. This preliminary investigation included a visual inspection of the pier substructure and an assessment of chloride penetration and electrochemical parameters on only one girder reinforced with SS rebar.

Experimental Procedure

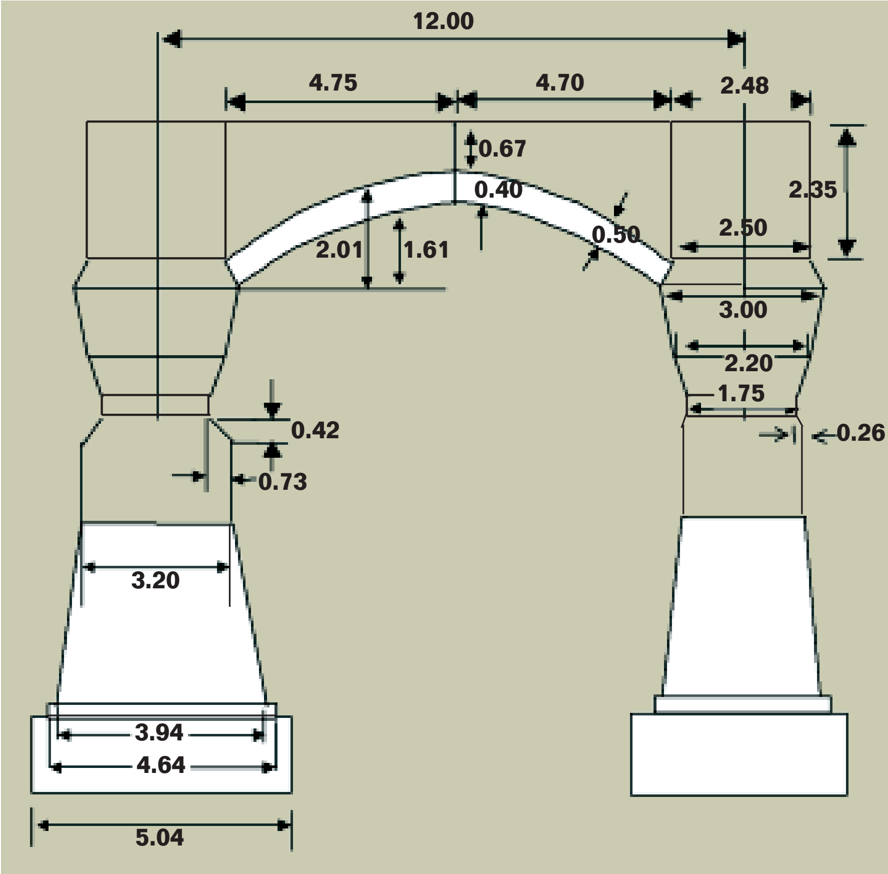
Initially, a complete visual inspection was performed along the 2-km pier and the wharf substructure, followed by a more detailed inspection. The following tests were performed in order to obtain quantitative information on this pier:

- Concrete: carbonation front, electrical resistivity, and chloride profile.
- Reinforcement: electrochemical potential (E_{corr}) and apparent corrosion rate (I_{corr}).

The girder located at the shoreline was selected to perform these tests. Figure 3 shows the location of the core extractions and electrochemical measurements.

Concrete cores, 50 mm in diameter, were obtained from each girder's edge surfaces to test for carbonation depth, chloride content, and concrete porosity and density. In addition, an SS bar sample was analyzed to determine the chemical composition. Some cores were extracted at specific locations near areas where the reinforcement was exposed from a previous inspection. This allowed investigators to verify the position and condition of the SS reinforcement. The total chloride content was estimated from a dry powder concrete sample using an acid-digestion extraction, followed by a potentiometric titration determination according to well-established methods.[3]

FIGURE 2



Longitudinal section of the pier.

E_{corr} and I_{corr} values were obtained using a commercially available linear polarization instrument with a guard-ring electrical confinement array. The sensor was placed on top of the longitudinal SS bars of girder #9, with one rebar facing the sea (north face), and the other facing inland (south face) (Figure 3). In the same manner, resistivity measurements were performed using a four-point Wenner array.

Results and Discussion

VISUAL INSPECTION

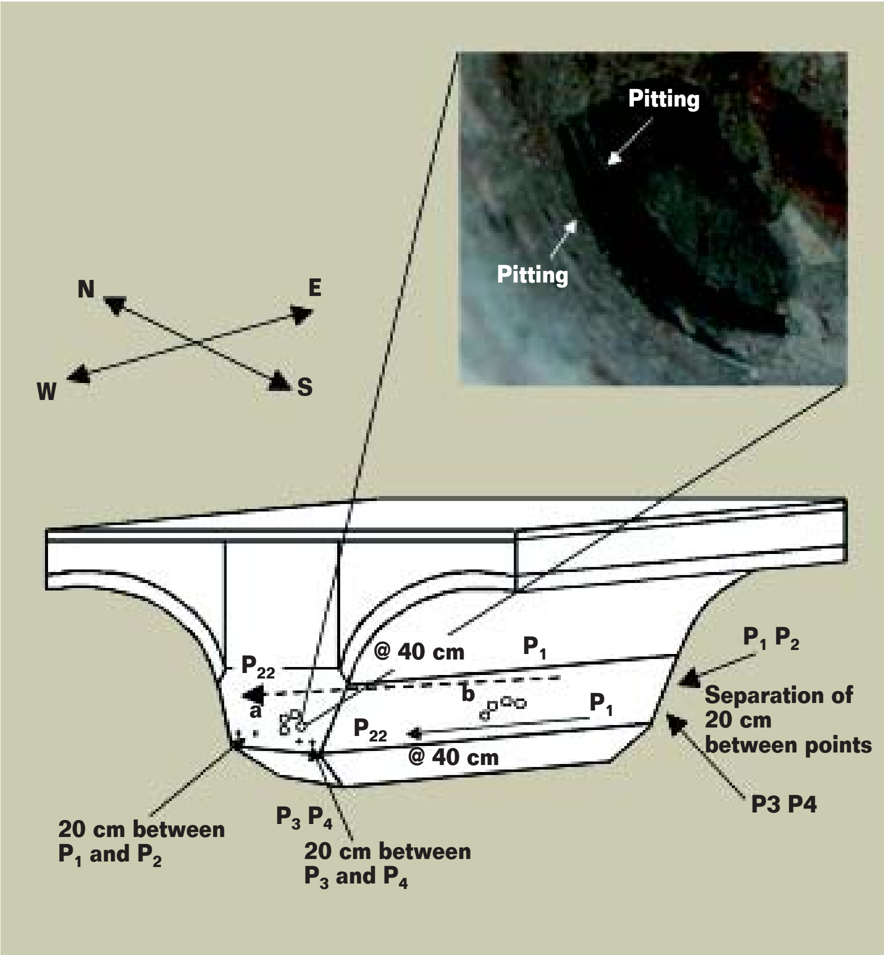
Of the 146 arches, ~100 were visually inspected and few cracks were observed. Only six arches presented 3-mm-wide cracks. A total of 15 arches presented narrow cracks, with crack widths in the range of 0.1 to 1.0 mm. As the arches were made of massive, nonreinforced concrete, there is no risk of metal corrosion. A detailed inspection of the damage in the near future was recommended, however.

No corrosion stains or corrosion-induced cracks were observed in the entire pier and wharf substructure. Only a few damaged girders at the wharf showed exposed SS bars—probably caused by ship impact—besides the exposed steel observed in girder #9.

MATERIALS CHARACTERIZATION

The SS was identified as AISI 304 grade (0.08%C, 18%Cr, 8.6%Ni) by energy dispersion analysis (using a scanning electron microscope) in agreement with a previous investiga-

FIGURE 3



Location of the core extractions and electrochemical measurements on the pier.

tion.[4] The microstructure was identified as austenitic with ASTM grain size No. 8.

The fine and coarse aggregate, observed from the extracted cores, consisted of crushed limestone with a coarse aggregate nominal maximum size of 25 mm. The concrete total porosity was estimated using the ASTM C642[5] standard test method. The values ranged from 19 to 24%. The estimated concrete density was 2.2 gm/cm^3. Based on a petrographic analysis from a previous investigation,[4] the water/cement (w/c) ratio was estimated to be in the range of 0.50 to 0.70, with a mean value in the range of 0.55 to 0.60.

The carbonation depth, measured on three of the extracted concrete cores, ranged from 0 to 1.5 mm. These low values, considering the low-quality concrete, may stem from the concrete's high level of chloride contamination.

CONCRETE RESISTIVITY

Resistivity measurements showed values ranging from 0.6 to 2.5 kΩ-cm in the entire girder surface (Table 1). This defines a highly aggressive medium for most metals. Confirming those values in other girders would indicate a high risk of corrosion because the lowest value is similar to the lowest resistivity observed in marine concrete.[6] These low-resistivity values were expected because the reported w/c ratio used in this structure is characteristic of a low-quality concrete.

E_{corr} AND I_{corr} MEASUREMENTS

The E_{corr} and I_{corr} values reported in Table 2 are usually associated with depassivation and corrosion of SS.[7-8] The agreement in the results observed from both tests is a good indication that the tests were not affected by transformations of Fe^{2+} to Fe^{3+}.[9] Usually, the lineal polarization resistance test cannot be used to evaluate corrosion rates if a proximity exists between E_{corr} and the redox potential of another reaction (the results incorporate the effect of all redox processes). In this case, because of the negative corrosion potential measured (~–350 mV vs copper/copper sulfate [$Cu/CuSO_4$] electrode [CSE]), the contribution of the Fe^{2+}/Fe^{3+} current density is not possible (~ +455 mV vs CSE).[9]

According to a previous report regarding this pier,[10] SS bars were directly exposed in the west face of girder No. 9 because of insufficient concrete cover (<1 cm). Because these portions of reinforcement belong to the bended part of end hooks, stress corrosion cracking (SCC) has affected these areas (Figure 4). The SCC was also evaluated in this investigation. At this time, it is unclear whether SCC was an initial or subsequent event: either the chloride ion caused SCC in the embedded steel and then the loss of the concrete cover or the steel was first ex-

TABLE 1

RESISTIVITY MEASUREMENTS IN NO. 9 GIRDER

Resistivity kΩ-cm

	Point East → West		
Face	P_1	P_2	P_3
North	1.63	0.63	0.63
South	2.51	1.57	2.2

	Point North → South		
Face	P_1	P_2	P_3
East	2.2	1.63	1.88
West	0.94	0.63	1.26

TABLE 2

CORROSION POTENTIALS AND CORROSION RATES IN NO. 9 GIRDER

Corrosion Potentials (mV vs CSE) and Corrosion Rates (μA/cm²)

Point East → West

Face		P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}
North	E_{corr}	-278	-276	-276	-272	-263	-280	-283	-283	-283	-290	-291
	I_{corr}	0.067										0.015
South	E_{corr}	-479	-473	-475	-471	-466	-463	-479	-463	-463	-466	-451
	I_{corr}	0.22										0.618

Face		P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	P_{19}	P_{20}	P_{21}		P_{22}
East	E_{corr}	-278	-285	-283	-285	-285	-285	-287	-281	-268	-309		-346
	I_{corr}											0.030	
West	E_{corr}	-452	-452	-447	-446	-443	-444	-445	-440	-439	-441		-441
	I_{corr}											0.1	

Point North → South

Face		P_1		P_2	P_3		P_4
East	E_{corr}	-536		-553	-340		-350
	I_{corr}		0.519			0.306	
West	E_{corr}	-475		-475	-358		-363
	I_{corr}		0.868			0.351	

posed (because of the low concrete cover) and then SCC occurred. By comparing the results from reference (4) with the visual inspection reported here, it is clear that after 3 years the corrosion of the reinforcement has not significantly worsened.

Very severe localized corrosion was observed on the top of an SS rebar located in the east face, however. This rebar was exposed after the previous investigation (December 1998), and it is located in a vertical position with 3 cm of concrete cover. Corrosion was not observed on the bottom of the rebar, where the seawater from the marine breeze tends to accumulate, thereby creating an ideal place for the initiation of corrosion.

In order to verify the validity of the E_{corr} and I_{corr} measurements, the researchers obtained concrete cores from the area above the exposed SS bar. These cores helped to confirm the position of the SS bar inside the girder and the surface condition of the unexposed metal. Figure 3 shows the locations of the extracted cores. The insert shows a small part of the embedded SS bar surface condition exposed after concrete core drilling. A few rusty spots were observed and identified as pitting.

CHLORIDE CONTENT

The tropical marine environment of the northern Yucatan Peninsula has been characterized in terms of its atmospheric aggressiveness as a grade 5 on the International Organization for Standardization (ISO) scale.[11-12] This designation represents the most aggressive marine environment on this scale. As a result of the aggressiveness and the high porosity of the concrete, high chloride concentrations at the rebar level were expected.

Figure 5 shows the chloride profile concentrations obtained from two different cores, one extracted from the west face and the other from the south face. The chloride concentrations at the rebar depth obtained in this investigation are in agreement with those obtained in the previous survey.[10] The maximum chloride concentration obtained was somewhat above the maximum soluble chloride concentration in solutions. This maximum value should not be considered impossible to achieve if one considers that the concrete cores were obtained above the waterline and thus were not saturated. The chloride extraction method was used to obtain total chlorides, and the dry concrete mass was not corrected by water-filled porosity that will decrease the concentration by ~10%.

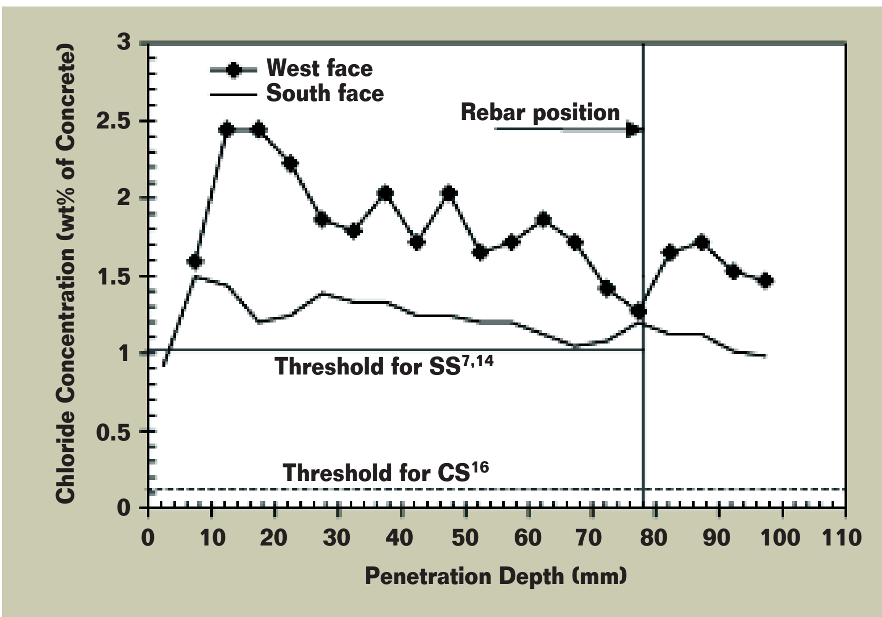
The chloride threshold for AISI 304 was estimated to be between 0.7 and 1 wt% of concrete.[13-14] According to the chloride profiles obtained for the evaluated girder (Figure 5), the chloride content measured at the rebar depth (~1.2 wt% of dry concrete) is above the chloride threshold reported for this type of rebar. However, a higher chloride threshold for AISI 316 and AISI 316 clad bars has been reported elsewhere.[7,13]

The previous results regarding E_{corr}, I_{corr}, and chloride content at the bar depth confirm that the SS rebar at girder No. 9 is in the process of active corrosion. This situation demands a fur-

FIGURE 4

Girder No. 9, where most of the tests were performed. SCC occurred on rebar exposed at this girder.

FIGURE 5



Chloride concentration profiles in girder No. 9.

ther analysis to corroborate—by means of a more extensive and systematic study—if other girders beyond the shoreline are also experiencing corrosion degradation.[15]

STRATEGIES FOR FUTURE DETAILED INSPECTION

As a result of the preliminary inspections already performed on this pier, a detailed inspection program has been presented to the SCT government authorities. The program includes the selection of six bents to perform tests on the piles, girders, and arches. Future testing will include the determination of chloride profiles, carbonation front, concrete resistivity, I_{corr}, E_{corr}, total and effective concrete porosity, and petrographic analysis.

The results of these tests would allow the researchers to determine, with a higher degree of confidence, the chemical and physical characteristics of the pier's materials. Consequently, it would enable them to predict the residual service life of the pier and to outline an effective maintenance program.

Conclusions

A preliminary inspection of the Progreso pier in Yucátan, Mexico, provided enough quantitative information to suspect that the SS bars from the girders are exposed to a high chloride concentration that is possibly causing their depassivation.

A detailed inspection program has been recommended to Mexican government authorities in order to verify this hypothesis.

Acknowledgments

The authors acknowledge partial support from Consejo Nacional de Ciencia y Tecnología (CONACYT) (Mexico City, Mexico), Fondo Nacional de Ciencia, Tecnología Innovacíon (FONACIT) (Caracas, Venezuela), Centro de Investigacíon y de Istudios Avanzados (CINVESTAV) del IPN Unidad Mérida (Mérida, Mexico), Instituto Mexicano del Transporte, and FIUADY for this investigation. The authors are indebted to C. Andrade and A. Sagüés for helpful discussions and to M. Balancán and G. Diaz for performing the tests. The opinions and findings are those of the authors and not necessarily those of the supporting organizations.

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This article is based on CORROSION/2002 paper no. 207, presented in Denver, Colorado.

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