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## Impact and corrosion resistances of duplex epoxy/enamel coated plates



Fujian Tang, Yi Bao, Yizheng Chen, Yan Tang, Genda Chen\*

Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO 65409-0030, USA

### HIGHLIGHTS

- Duplex coating consists of outer epoxy and inner enamel with epoxy-filled pores.
- Duplex coating changes impact failure from delamination/flaking to indentation.
- Corrosion resistance of duplex coating exceeds 180% that of individual coatings.
- Damage reduces the resistance of duplex coating by 10 times in  $\text{Ca}(\text{OH})_2$  solution.

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### ABSTRACT

The microstructure, impact resistance, pull-off adhesion strength, and corrosion resistances of duplex epoxy/enamel coating applied on steel plates are investigated experimentally. In comparison with those of individual epoxy and enamel coatings, the duplex coating has lower adhesion strength, higher impact resistance, higher short-term and long-term corrosion resistances both in 3.5 wt% NaCl solution and saturated  $\text{Ca}(\text{OH})_2$  solution with various chloride concentrations. This is because the outer epoxy fills the micro pores in the inner enamel. Impact induced damage significantly reduces the corrosion resistances of epoxy and duplex coatings but has little effect on the corrosion resistance of enamel coating.

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### 1. Introduction

Reinforced concrete (RC) structures in highway bridges, buildings, dams, and tunnels often undergo physical and chemical deterioration when exposed to aggressive environments. Corrosion of steel reinforcement is one of the most important causes of RC structural deterioration. It is usually caused by either carbonation of concrete cover or penetration of chloride [1,2]. Carbonation of concrete cover changes the concrete environment from alkaline ( $\text{pH} = 13$ ) to a neutral level or an unfavorable condition for the formation of passive film on the surface of steel reinforcement. Penetration of chloride breaks down the passive film and then initiates steel corrosion in the presence of moisture and oxygen. Once initiated, corrosion can cause concrete cover cracking [3,4] and steel section reduction [5], resulting in degraded bond behavior

between the steel reinforcement and its surrounding concrete [6] and reduced capacity of structural members [7,8]. In 2002, the annual direct corrosion cost for replacement and maintenance of U.S. highway bridges was approximately \$13.6B, and the indirect cost of corrosion due to traffic delay and lost productivity was estimated to be as high as 10 times that of direct corrosion costs [9].

Prevention of steel reinforcement corrosion in RC structures can be achieved either by modifying the properties of concrete cover or using corrosion resistant bars. For example, the properties of concrete can be modified by applying inhibitors [10,11], reducing water-cement ratio, adding high performance admixtures [12–14], and optimizing aggregate gradation. Corrosion resistant bars include non-metallic bars such as fiber reinforced polymer (FRP) bars [15,16], stainless steel bars, stainless steel or copper clad steel bars [17], and coated steel bars [18,19]. Coating is one of the most effective methods to protect steel bars from corrosion by establishing a chemical and physical barrier between the steel and its corrosive environment. Two of the most widely used coatings are fusion bonded epoxy (FBE) and zinc (galvanized). One of the major problems for epoxy coated bars is the debonding caused by pene-

\* Corresponding author at: Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 328 Butler-Carlton Hall, 1401 N. Pine Street, Rolla, MO 65409-0030, USA.

E-mail address: [gchen@mst.edu](mailto:gchen@mst.edu) (G. Chen).

tration of potassium, sodium ions, and water (humidity), resulting in under-film corrosion due to weak bond with substrate steel [20,21]. When the pH value of concrete pore solution is higher than 13.2, zinc dissolve accompanied by release of hydrogen gas [22,23]. The generation of hydrogen gas increases the porosity of surrounding concrete, resulting in a reduction of steel–concrete bond strength.

Porcelain enamel, as an inorganic coating material, not only provides an aesthetic exterior of industry products but also provides excellent engineering properties, such as abrasion, corrosion, and heat resistances [24]. It is widely used in chemical reactors, heat exchangers, or food-processing vessels due to their excellent chemical stability and workability in harsh environments [25]. The corrosion performance of enamel coating applied on reinforcement steel bars has been investigated in our previous studies [26,27]. The effects of bar deformation, external damage, coating thickness, and corrosive environments on the corrosion resistance of enamel steel bars were thoroughly studied. Enamel coating is chemically reacted with both concrete and steel and thus provides a smooth transition zone at the concrete-steel interface. Enamel coating can prevent the so-called under-film corrosion that has been associated with the fusion bonded epoxy (FBE) coating. However, while it can increase bond strength between steel bars and concrete, enamel coating mixed with calcium silicate has lower corrosion resistance than that of the enamel coating itself. The mixed enamel is also brittle and susceptible to impact damage during shipping and handling. Even intact enamel coated steel bars are less corrosion resistant than intact FBE coating due to micro pores in enamel coating.

In this study, a duplex epoxy/enamel coating is developed and its microstructure, impact resistance, adhesion strength, short-term and long-term corrosion resistances are characterized. It consists of an outer layer of epoxy and an inner layer of enamel. The outer epoxy was used to increase the impact resistance to external damage and provide an additional barrier to corrosion. The inner enamel was intended to chemically bond with the substrate steel, preventing under-film corrosion. For comparison purposes, both epoxy and enamel coated specimens were also prepared and tested. The microstructures of coatings were examined using scanning electron microscopy (SEM), the impact resistance was investigated by impact test, and the adhesion strengths were determined by pull-off test. The corrosion performance was investigated with electrochemical impedance spectroscopy in 3.5 wt% NaCl solution for 1.5 h and in simulated concrete pore solutions with various chloride concentrations for 31 days. Effect of impact damage on both the short-term and long-term corrosion resistances was also assessed.

## 2. Material and methods

### 2.1. Preparation of enamel and epoxy coatings

Enamel is a silicate-based material that can be applied to steel surface using either a wet or dry process. In this study, enamel mixed with calcium silicate is coated on steel specimens in the wet process of enamel slurry application. The enamel slurry was prepared by mixing water, enamel glass frit, cement, clay and borax according to a proportion of 1.00:1.20:1.20:0.17:0.01 by weight. The chemical composition of the glass frit is given in Table 1. Type I Portland cement was used and its chemical composition was determined and listed in Table 2. The glass frit and cement were added first to water and mixed for 20 min, and then clay and borax as suspension agents were added and mixed again for 3.5 h.

Carbon steel plates, 76.2 mm × 38.1 mm × 3.18 mm (length × width × depth), were prepared for various tests. The chemical composition by weight is: 0.27% C, 0.28% Si, 1.03% Mn, 0.05% S, 0.03% P, and the balance Fe. Enamel was coated on the steel plates by Pro Perma Engineered Coatings (Rolla, MO, USA). Prior to coating, all steel plates were sand-blasted and cleansed with a commercially available cleaning solvent. Each cleaned plate was dipped into the enamel slurry, and heated for 2 min at 150 °C to drive off moisture, then moved into a gas-fired furnace at 810 °C for 10 min, and finally cooled to room temperature. The heat treatment melted the glass frit and bonded the enamel to the substrate steel.

Epoxy was directly sprayed on the surface of cleaned steel plates at room temperature. It is a commercially available product 156 Rebar Green Epoxy Coating (Aerove Industries Incorporated, USA). It is composed of 35% hydrocarbon propellant, 35% *n*-butyl acetate, 29% acetone, and 1% aliphatic petroleum distillates by weight. For duplex coating, the enamel coating was applied first to the cleaned steel plates and the epoxy was then sprayed on top of the enameled plates.

To study the impact resistance of coatings and the effect of impact-induced damage on the corrosion resistance, some coated steel plates were pre-damaged using an impact test apparatus designed according to the ASTM Standard G14 [28]. The apparatus consists of a 0.91 kg steel rod with a circular flat head, a vertical section of hollow aluminum tubing to guide the rod, and a horizontal section of steel angle to position the coated steel plate. The weight rod was dropped from a height of 45.7 cm to damage the coating.

### 2.2. Characterization of coatings and pull-off test

Microstructures of the epoxy, enamel and duplex coatings were examined with scanning electron microscopy (SEM; Hitachi S4700). A small piece of coated steel plate was cut across the cross section and cold-mounted with EpoxyMount. The cross section was then ground with silicon carbide papers to 1200 grit. The ground samples were rinsed with deionized water, cleansed with acetone, and finally dried prior to SEM imaging.

The adhesion strength of coating with its substrate steel plate is determined following ASTM D4541-09 with an automatic PosiTest pull-off tester [29]. To reduce the risk of adhesive failure, the bottom face of a 14-mm-diameter dolly was slightly abraded with sandpaper, cleansed with acetone, and adhered to the surface of coated steel plate with Araldite multi-purpose adhesive. After the adhesive was cured for 24 h, scoring around the perimeter of the dolly was employed and the dolly was pulled-off perpendicular to its interface with the coated steel plate at a stress rate of 0.41 MPa/s. The maximum strength of each coated steel plate was recorded.

### 2.3. Electrochemical corrosion tests

Fig. 1 shows the dimensions of each steel plate specimen for electrochemical corrosion tests. For each coated steel plate, one corner was ground off to expose the steel for soldering with a copper wire for electrochemical measurements. All four side edges and the back face of the steel plate were covered with EpoxyMount (ALLIED). Therefore, only the center portion on the front face of all steel plates, approximately 12.5 cm<sup>2</sup>, was potentially exposed to the test solution. To quantify the variation of test data, three identical specimens were prepared and tested in each condition, including a combination of three coatings (enamel-EN, epoxy-EP, and duplex coating – DUP), two damage levels (undamaged – U and damaged – D), and two corrosive environments (3.5 wt% NaCl solution and saturated Ca(OH)<sub>2</sub> solution). For comparison purposes, six uncoated steel plates (UN) were also prepared and tested. Therefore, a total of forty-two specimens were tested. In the following presentation, UEP stands for undamaged epoxy coating, UEN and DEN represent undamaged and damaged enamel coatings, UDUP-EP and DDUP-EP denote the outer epoxy of undamaged and damaged duplex coatings, and UDUP-EN and DDUP-EN are the inner enamel of undamaged and damaged duplex coatings.

Two types of solution used in this study are 3.5 wt% sodium chloride (NaCl, Fisher Scientific International Inc.) and saturated calcium hydroxide (Ca(OH)<sub>2</sub>, Fisher Scientific International Inc.). The NaCl solution was made by dissolving NaCl powder into distilled water that was used to test the short-term corrosion resistance of steel plates. Open-circuit potential was recorded immediately after steel plates were immersed in the salt solution for up to 3400 s, and then electrochemical impedance spectroscopy (EIS) was performed. The saturated Ca(OH)<sub>2</sub> solution was prepared by mixing certified Ca(OH)<sub>2</sub> powder into distilled water that was used to simulate the concrete pore solution and investigate the long-term corrosion resistance [30–32]. The Ca(OH)<sub>2</sub> powder was added into the distilled water until some residue could be observed at the bottom of the solution, and the pH value was measured to be 12.5 at room temperature. In order to observe both the passivation and

**Table 1**  
Chemical composition of enamel glass frit.

Composition	SiO <sub>2</sub>	B <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	CaO	CaF <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	ZrO <sub>2</sub>	MnO <sub>2</sub>	NiO	CoO	Total
Amount (wt%)	44.0	19.3	15.8	2.8	0.0	4.7	4.6	5.3	1.5	1.0	0.9	100

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