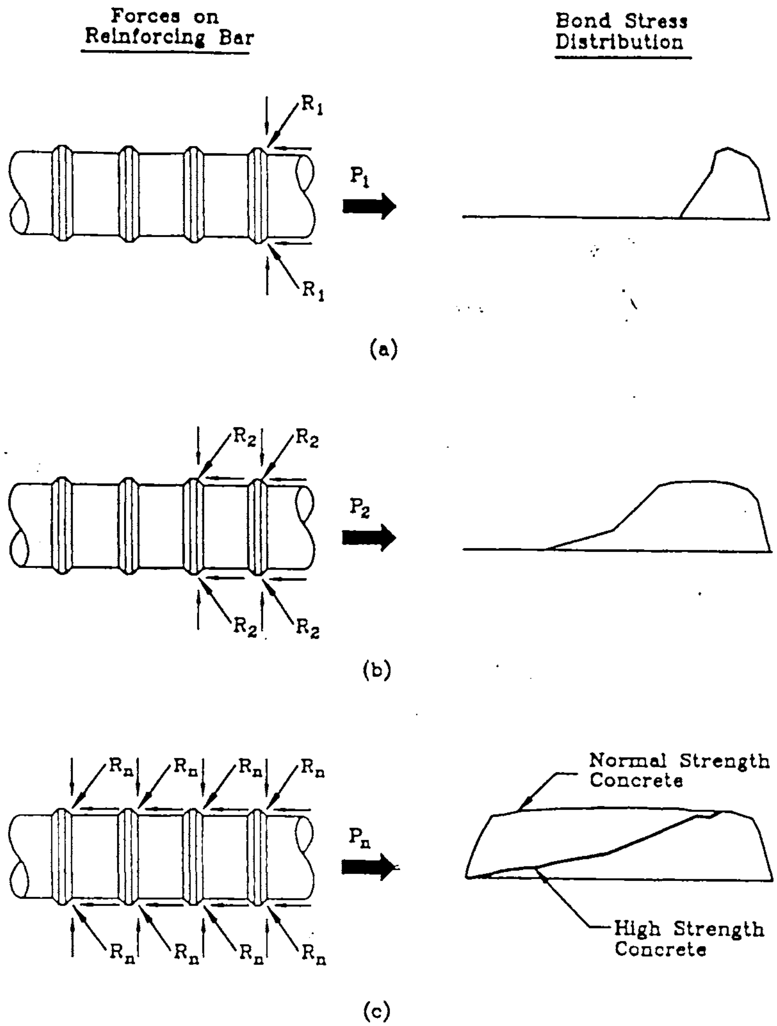
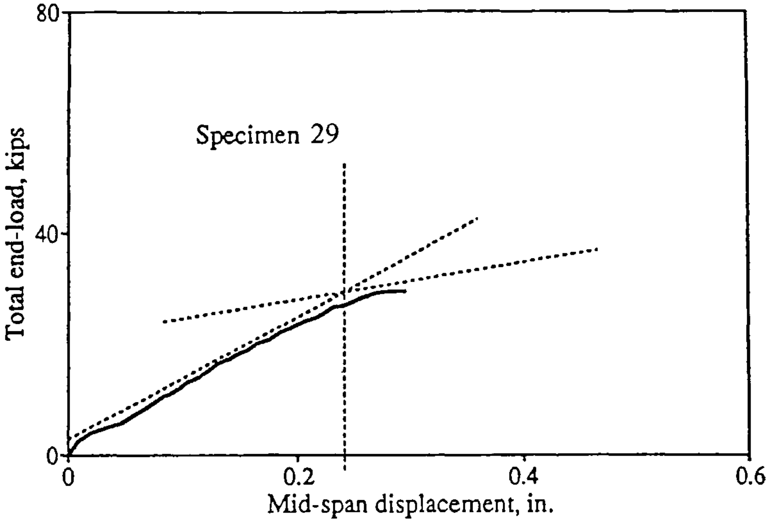
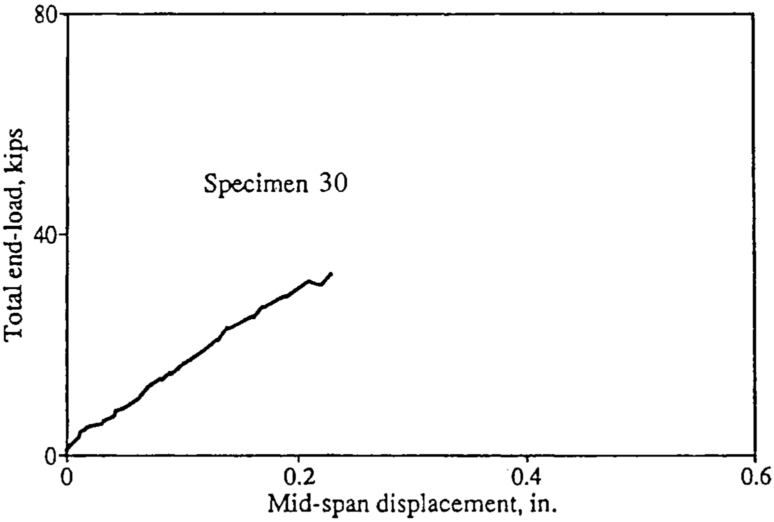


Fig. 4—Freebody diagram of a reinforcing bar embedded in concrete and subjected to tension



(a)



(b)

Fig. 5—Load displacement response of Specimens 29 and 30

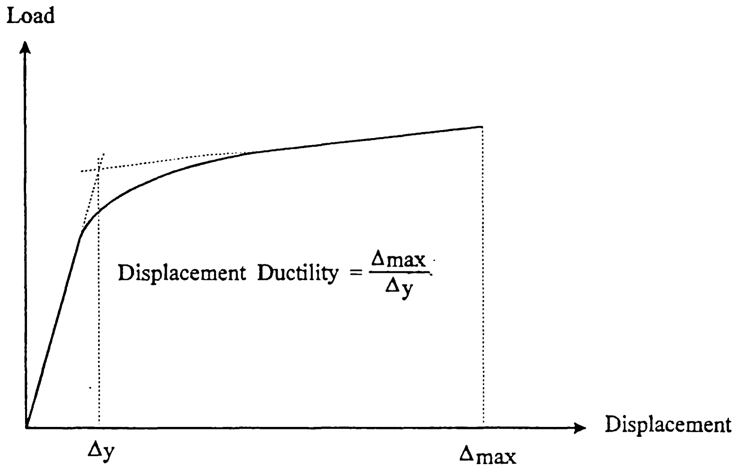


Fig. 6—Definition of displacement ductility ratio

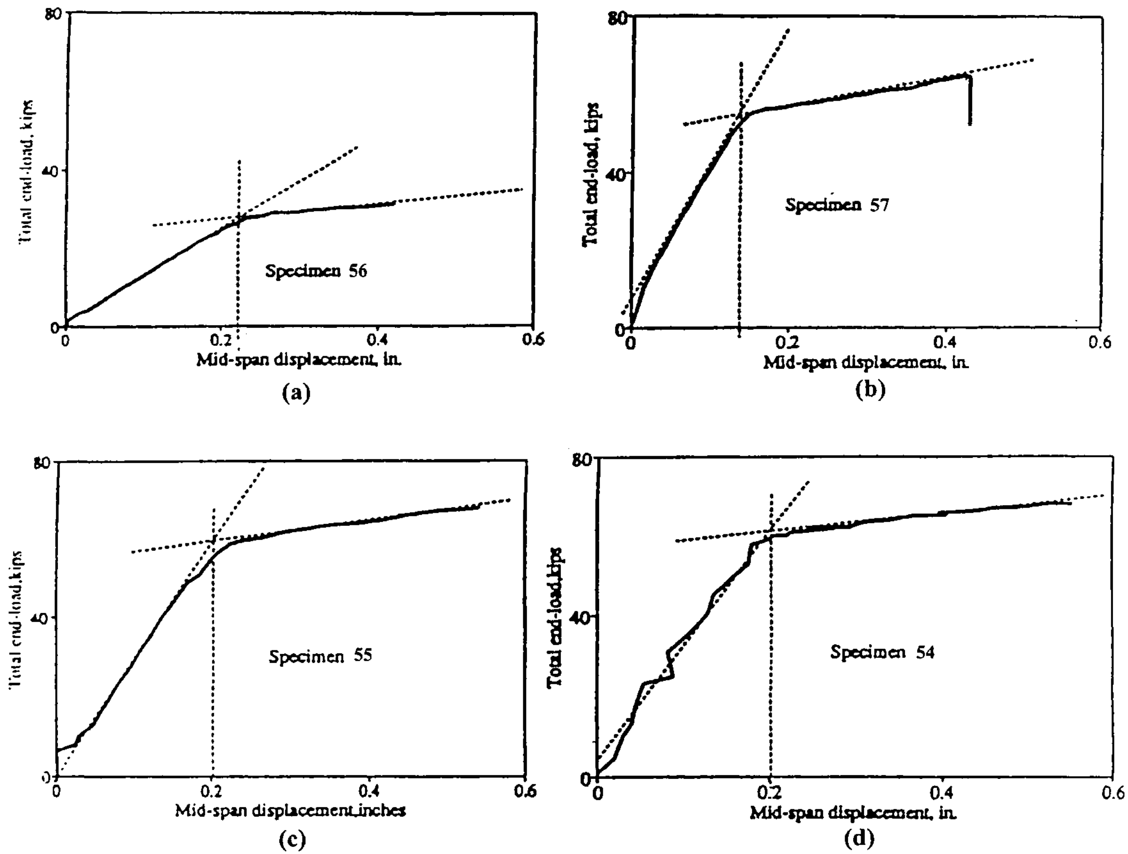


Fig. 7— Load displacement response of specimens with stirrups

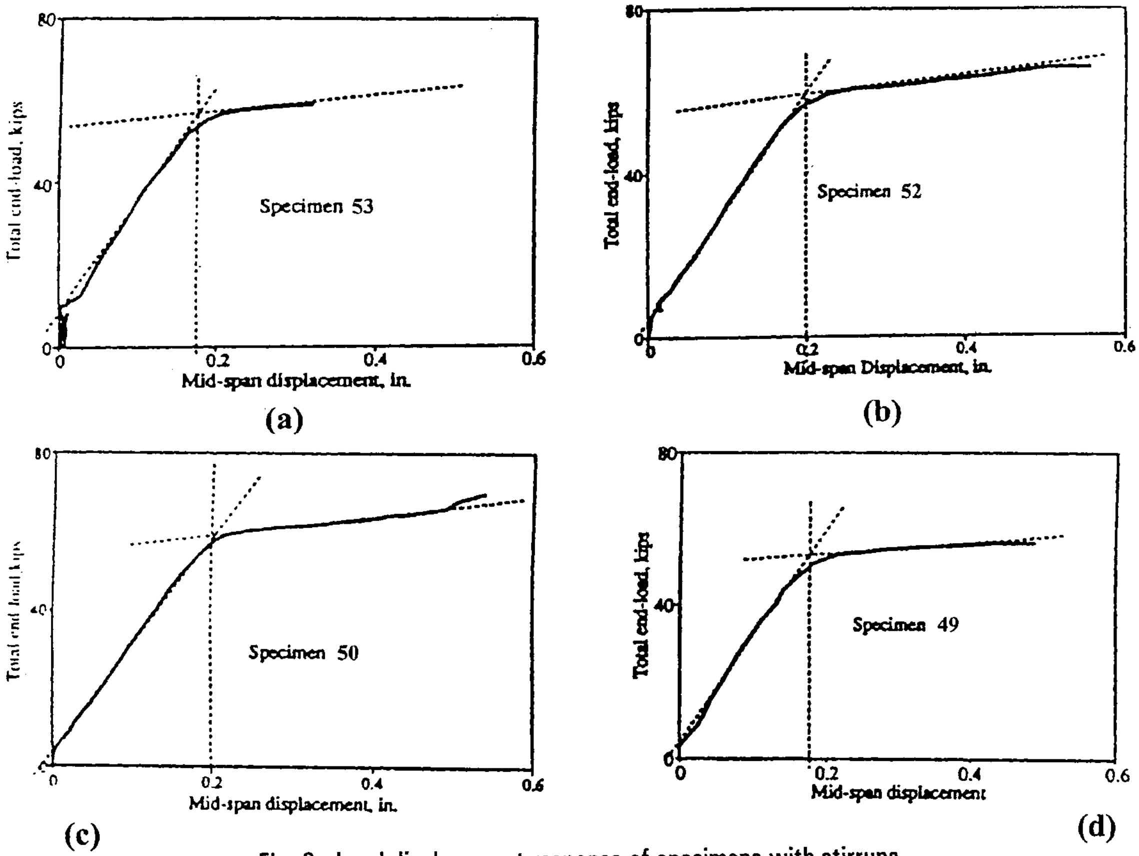


Fig. 8—Load displacement response of specimens with stirrups

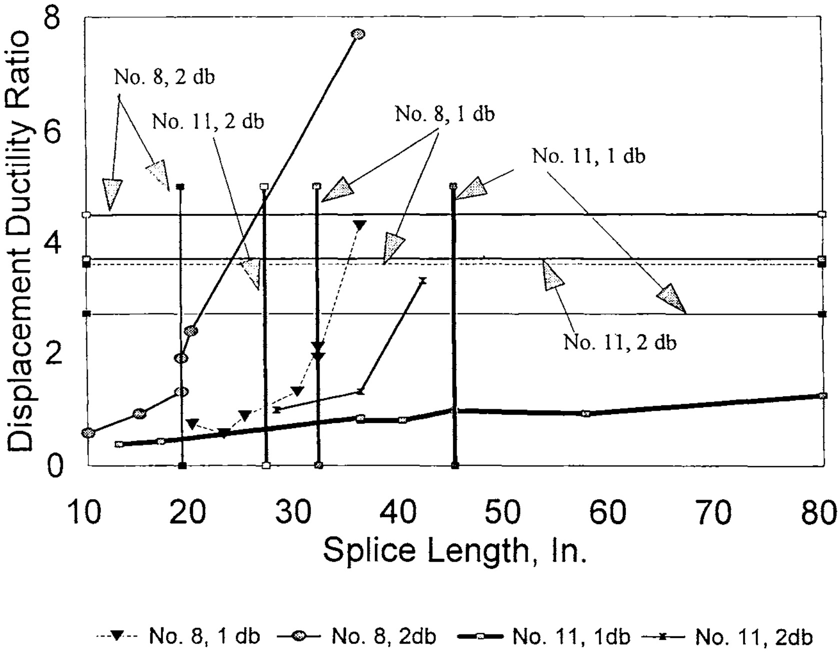


Fig. 9—Behavior of specimens without stirrups

SP 180-12

Bond of Epoxy-Coated Reinforcement in Normal and High-Strength Concrete

by T. Grundhoffer, P. A. Mendis, C. W. French and R. Leon

Synopsis: Epoxy-coated reinforcement and high-performance concrete are commonly used materials in exposed structures located in cold regions and marine environments of the United States. Their popularity is due to their resistance to corrosion in areas where chlorides are used as deicers in roads and bridges. This paper summarizes an experimental investigation regarding the difference in bond behavior of epoxy-coated and uncoated reinforcement in normal and high-strength concrete. The objectives were to investigate the effect of bar surface (epoxy, uncoated), bar size (No. 6, No. 8, No. 11), concrete strength (6, 10, 12, 14 ksi) and the addition of micro-silica to concrete. Ninety-four inverted half-beam specimens were tested. All of the specimens were designed to fail in bond by splitting of the concrete. The reinforcement in four of the specimens (two uncoated and two epoxy-coated reinforcement) was instrumented with internally embedded strain gages to measure the distribution of strain along the embedment length. The tests showed clear differences in the strain distribution at service level between coated and uncoated reinforcement. A comprehensive review of the effect of epoxy-coating on bond strength was conducted using the results of this study and 151 test results from seven other research studies in the USA. The experimental results were compared to values of design bond strength calculated using ACI 318-89 (1) and ACI 318-95 (2) equations.

Keywords: Bond (concrete to reinforcement); bridge specifications; building codes; deformed reinforcement; development; lap connections; reinforcing steels; relative rib area; reliability; splicing; structural engineering; variability

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INTRODUCTION

In cold regions of the United States, extensive use of deicing salts on roadways causes severe durability concerns for bridge decks and parking garage structures. To increase the life of these structures, epoxy-coated reinforcement has been commonly used to inhibit reinforcement corrosion in these severe environments. It has recently become commonplace to use high-performance concrete in combination with epoxy-coated rebar to further inhibit the corrosion process by increasing the impermeability of the concrete. The increased concrete impermeability inhibits the ingress of chlorides into the concrete. This two-pronged approach is an effective way to at least delay the corrosion problems associated with aggressive environments.

A disadvantage of epoxy-coated reinforcement is that longer anchorage lengths are required to fully develop the reinforcement. Current ACI and AASHTO codes (2,3) recognize the decreased ultimate bond strength of epoxy-coated reinforcement by specifying amplified development lengths for epoxy-coated reinforcement. The amplified development lengths are 20 to 50 percent greater than those of uncoated reinforcement (4,5). These requirements, based on limited sets of data, were included in design codes as an effort to prevent problems while more research clarified the mechanistic basis for this increase (6-9). It is generally assumed that the decreased bond capacity of epoxy-coated reinforcement is due to the different friction characteristics and the lack of initial chemical adhesion between the bars and the concrete. This paper reviews this assumption and provides quantitative results that expand the understanding of decreased bond capacity of epoxy-coated reinforcement.

The main objective of the study reported in this paper was to investigate the bond strength of epoxy-coated reinforcing bars cast in concrete with compressive strengths ranging from 6 to 14 ksi. Specimens were also cast using concrete of the same strength with and without micro-silica to investigate the effect of micro-silica on bond behavior. Additionally, the effect of epoxy coating on the rebar strain distribution along the development length was investigated. The results of seven other research studies conducted in the USA were used to support the findings of this study. The bond length equation given in ACI 318-89 has been modified to a more "user-friendly" format in ACI 318-95. It is shown from the results of this study and other studies that in some cases, the ACI 318-95 predicts unconservative values for bond strength of epoxy-coated bars.

BOND MECHANISM AND FAILURE MODES

Bond stresses modify the steel stresses along the length of the bar by transferring load between the bar and the surrounding concrete. The following expression may be derived from equilibrium of the concrete and bar forces:

$$l_d = \frac{A_b f_s}{u \pi d_b} \quad (1)$$

where A_b and d_b are the area and diameter of the reinforcing bar, l_d is the bond length of bar, f_s is the stress developed in the bar, and u is the average bond stress. The average bond stress can be related to the bar diameter, bar stress, and bond length:

$$u = \frac{f_s d_b}{4 l_d} \quad (2)$$

This formula is used to determine the average bond stress developed between the reinforcing bar and concrete.

The bond of deformed reinforcement in concrete is a complicated mechanism which is mostly understood in a qualitative nature. It is essential that the bar force is transferred to the concrete to maintain structural integrity. The bar force is transferred to the concrete by adhesion, friction and mechanical bearing between the deformation and concrete. Figure 1 illustrates schematically the three mechanisms of bond. Upon initial loading the forces are transferred by adhesion created through chemical bonding between the steel bar surface and concrete. The adhesion is not a sustained resistance. At low bar stresses the adhesion is lost. After adhesion is lost the bar slips relative to the concrete which enables development of the friction and mechanical bearing mechanisms. Due to the rib face angle (Figure 1) the forces are transferred to the concrete by bearing perpendicular to the rib face and friction between the rib face and the adjacent concrete. The resultant force of the bearing and friction forces produces radial tension in the concrete surrounding the bar.

Two types of bond failures exist: pullout failure and splitting failure. If adequate confinement exists in the form of transverse steel, large cover, or a combination thereof, a pullout failure occurs. A pullout failure is a direct shear failure of the concrete key at the level of the outer edge of the deformation. The confinement allows the tensile stresses in the concrete to be resisted. This allows the bearing pressures between the rib face and the concrete to increase with increasing bar load and the frictional component becomes less significant. The high bearing pressures result in failure of the concrete keys in shear.

If sufficient concrete cover and/or transverse confinement are not provided to resist the radial tension stress in the concrete, a splitting failure occurs. Once the concrete cracks, the deformations push the concrete away from the bar by wedge action. As the concrete starts to ride up the rib face the component of friction between the rib face and the concrete becomes more significant.

Splitting bond failures are more likely to occur in slabs and other structural members without transverse reinforcement or large concrete cover. The study, conducted at the University of Minnesota, focussed on splitting bond failures.

Treece and Jirsa (5) stated that the primary reason for the reduction in bond strength appears to be the loss of adhesion between the concrete and epoxy-coated bars which destroys most or all of the friction capacity. Their hypothesis is supported by the results of this investigation. Uncoated bars have good adhesion to concrete. The reduced friction of epoxy-coated bars increases the radial pressure component which sets up radial tension in the concrete cover (Figure 2). Therefore the bond strength at initial cracking is controlled by the magnitude of the radial pressure that the concrete cover can resist. In addition, the researchers in this study believe that the epoxy coating reduces the effective bearing area of the reinforcement by reducing the rib height of the deformations (Figure 3), which has been shown to reduce bond stiffness and capacity. As seen from Figure 3, the rib height is reduced by twice the coating thickness.