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Shear capacity assessment of reinforced concrete beams with corroded stirrups

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HIGHLIGHTS

- Procedures are proposed for assessing residual shear of stirrup-corroded RC beams.
- Measured width of corrosion crack is used for assessing corrosion damages.
- The proposed procedures are validated using test data available in the literature.

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ABSTRACT

This paper presents proposed design procedures for quantifying the residual shear strength of reinforced concrete (RC) beams with corrosion-damaged stirrups. Most of the building codes worldwide prescribe different approaches for shear design of RC beams in their provisions based on the type of beams: slender or deep. Conventional sectional method is widely recommended for slender beams while strut and tie model which is based on member analysis is recommended for deep beams. To account for the corrosion effects on shear, modifications to the current design methods were proposed. For sectional design method of slender beams, the reduction in cross-sectional area of steel stirrups due to corrosion was considered along with the reduction in geometry of concrete cross section due to spalling. For strut and tie modeling for deep beams, the reduction in effective concrete compressive strength because of corrosion cracks was considered along with the reduction in geometry of concrete cross section. One important feature of the proposed procedures is that the corrosion effects can be determined based on the width of corrosion cracks which can be easily determined in real situations. The proposed design procedures were validated using the experimental test data available in the literature.

1. Introduction

Corrosion of embedded reinforcing steel is one of the main causes of deterioration of reinforced concrete (RC) structures. The main problem associate with corrosion is not only the reduction in the area of the reinforcing steel bars, but also the corrosion products which cause volume expansion. That expansion generates stresses that may lead to cracking and spalling of the concrete cover affecting the transfer of stresses between the reinforcement and concrete.

A large number of experimental tests have been conducted to investigate the influence of corrosion on the mechanical characteristics of reinforcing steel bars [1–3]. The effect of reinforcement corrosion on the bond between reinforcing steel and the surrounding concrete has attracted the interest of several researchers [4–8]. A considerable amount of research has been directed to investigate the corrosion effects on the flexural behavior of RC beams [9–17]. Analytical studies have been also conducted to model the corrosion effects on the flexural and bond behavior of RC beams with longitudinal corroded steel bars [18–20]. On the other hand, there are few studies that have been directed to investigate the corrosion effects of stirrups on the shear resistance of RC beams [21–28]. Stirrups play important roles as shear reinforcement in RC beams. In addition to direct contribution to the shear resistance of the beams, stirrups also restrict the opening of diagonal cracks preserving the aggregate interlock and integrity of the beam. They improve the dowel action and prevent the breakdown of bond when splitting cracks develop in anchorage zones. The location of stirrups in the cross section of the beams as an outer reinforcement makes them more vulnerable to environmental conditions and

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corrosion. Moreover, the diameter of steel stirrups is generally small compared to that of longitudinal reinforcing bars so that relative loss of the cross-sectional area due to corrosion in the stirrups is expected to be much more significant than that in the longitudinal bars.

Shear failure in RC members is sudden and catastrophic in nature. This is why RC beams are designed to have shear capacity higher than the load carrying capacity corresponding to the flexural capacity to avoid such a brittle failure. Corrosion of steel stirrups may affect the shear capacity of RC beams and result in undesirable shear failure. The extent of the stirrups damage due to corrosion and its consequences on the behavior of the structures must be established as part of the preliminary analysis required to determine the reliability of the existing structure prior to repair [26]. This paper presents analytical procedures accounting for the effects of stirrup corrosion on the shear resistance of RC beams. It is well known that the shear strength and behavior of RC beams are affected by the shear span to depth ratio, a/d. Based on this ratio, RC beams are divided into two categories: slender beams ($a/d \geqslant 2.5$) or deep beams ($a/d < 2.5$) [29], as shown in Fig. 1. Most of the building codes provide separate design procedures for each category. Conventional sectional method is recommended by the design codes for determining the shear capacity of RC slender beams where the predominant mechanism is the beam action. The contribution of the arch action to the strength and behavior of such beams is insignificant. On the other hand, strut and tie model (STM) is recommended by the design codes for evaluating the shear capacity of RC deep beams. The arch action significantly contributes to the shear strength and behavior of deep concrete beams. The analytical procedures described in this paper for assessing the residual shear strength of stirrup-corroded beams are based on modifications to the current shear provisions for both conventional sectional method and STM. The procedures were verified against experimental data available in the literature.

2. Background

There has been limited experimental research on the corrosion effects on the shear behavior of RC beams. Rodriguez et al. [21] studied the effects of corrosion on the strength of reinforced concrete beams. It was concluded that corrosion changed the failure mode from flexure to shear and pitting corrosion of the stirrups influenced the load carrying capacity of the beams. Higgins and Farrow [22] conducted a study designed to investigate the shear capacity of RC deep beams where the stirrups were damaged due to the effects of corrosion. The results indicated a reduction in the shear capacity of the corroded beams as well as a loss in ductility. Shear-compression failures for the non-corroded beams and lowest corrosion level beams were observed. In the higher corrosion level, beams failure by stirrup fracture was observed. The stirrup fracture was due to significant localized corrosion and the associated section loss. The maximum strength loss occurred when the locations of pitting corrosion matched the location of the diagonal shear crack. It was concluded that structural performance in shear can be decreased significantly when sequential stirrups have a reduction in cross sectional area.

Suffern et al. [23] examined the structural performance of disturbed regions with corroded stirrups in RC deep beams. The test results indicated that the corroded beams exhibited reduced shear strength in comparison to the uncorroded control specimens. The shear strength reduction was up to 53%. Furthermore, the reduction in shear strength due to stirrups corrosion was found to be increased with the decrease of the shear span-to-depth ratio of the tested beams. Xia et al. [24] have investigated the shear performance of RC beams with corroded stirrups. The outcomes of the study showed that the crack width of the concrete cover induced by the reinforcing steel corrosion can be used as an indicator of the corrosion level of the corroded reinforcing steel bars. It was also concluded that the shear capacity of the beams decreased with the increase of the corrosion level of the corroded reinforcing steel stirrups. In addition, the shear failure mode of the beams changed from concrete crushing to stirrup rupture as the corrosion level became severer.

Alaskr [25] examined the influence of corrosion of stirrups on the shear behavior of RC slender beams. The corrosion cracks formed were parallel to the locations of stirrups as evidence of the corrosion damage in the corroded beams. The loss in the ultimate shear strength of the beams was up to 14.4% for beams with relatively higher corrosion level. El-Sayed et al. [26] investigated experimentally the shear performance of RC slender beams with corrosion-damaged stirrups. The test results indicated that the corroded beams exhibited reduced shear strength in comparison to the uncorroded control specimens. The reduction in shear strength was found to increase with the decrease of stirrup spacing. Khan et al. [27] presented the test results of two highly corroded shear-critical deep beams. The beams were 26 year old and were subjected to long term chloride environment. The corrosion of stirrups was the cause of the reduction in both ductility and shear strength of the beams. Wang et al. [28] investigated the effects of stirrup and inclined bar corrosion on the shear behavior of RC beams. The results indicated that severe corrosion of stirrup and inclined bar decreased significantly the shear strength and stiffness of the beams.

There are limited analytical studies that have been conducted addressing the shear capacity of RC beams with corrosion-damaged stirrups. Val [30] conducted an analytical study on the reliability of beams where the shear reinforcement was subjected to corrosion. The analysis was carried out for beams subjected to corrosion at different levels of intensity. The results showed that corrosion (both general and pitting) with low and moderate rates had insignificant influence on the reliability of the considered beams. For higher rates, the effect of corrosion became significant. At higher rates, pitting corrosion is more dangerous than general corrosion. Moreover, at these rates the reduction of shear resistance due to corrosion of stirrups, especially pitting corrosion, has a major effect on the beam reliability. The results demonstrate that assessment of the performance of reinforced concrete beams in corrosive environment should include consideration of the effect of corrosion of stirrups on

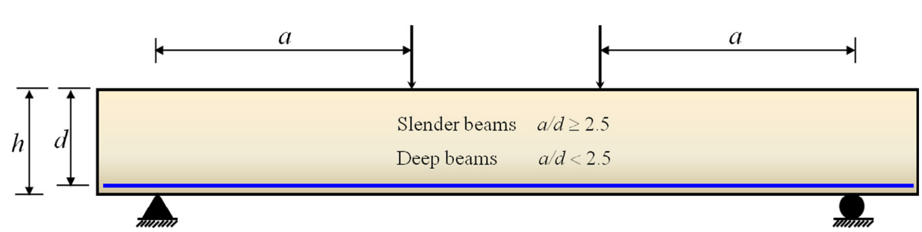

Fig. 1. Categories of reinforced concrete beams based on a/d ratio.