Construction and Building Materials 124 (2016) 776–785

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effects of sustained loading and pre-existing cracks on corrosion behavior of reinforced concrete slabs

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HIGHLIGHTS

- Pre-cracking and sustained loads severely affect corrosion behavior of RC slabs.
- Ductile failure mode of RC slabs changes to brittle mode after corrosion of steel.
- Corrosion level of RC slabs cannot be assessed purely based on surface inspection.

ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 28 July 2016
Accepted 3 August 2016

Keywords:
Corrosion
Sustained loading
Pre-existing cracks
Reinforced concrete

ABSTRACT

An experimental study was conducted to characterize the structural behavior of reinforced concrete (RC) slabs subjected to accelerated corrosion. Eighteen steel reinforced concrete slab specimens were cast for testing. Transverse cracks were formed in some of the test specimens by applying controlled amount of static loading. Sustained loading was maintained during the entire time of the corrosion process. Three different test conditions were induced: (i) specimens without pre-existing cracks and sustained loading, (ii) specimens with pre-existing cracks but no sustained loading, and (iii) specimens with pre-existing cracks and sustained loading. The crack patterns and crack widths were recorded for each specimen. The final mass loss and the ultimate load carrying capacity after achieving the desired corrosion level were also determined. The results highlight that un-corroded steel reinforced concrete slabs exhibit several bending-induced cracks transverse to the steel reinforcement with a ductile failure mode. Corroded specimens exhibit fewer but wider transverse cracks under bending loads and the failure mode is a brittle failure mode. Pre-cracked initial condition and sustained loading during the corrosion process have noticeable influence on the corrosion behavior of RC slabs. These conditions cause a larger reduction in ultimate load carrying capacity of such slabs compared to slabs subjected to corrosion when there are no cracks and the loading is not sustained in nature during the corrosion process. Ignoring this deleterious performance can lead to unsafe condition assessment.

1. Introduction

Corrosion of steel reinforcement embedded in concrete is a worldwide problem that affects numerous reinforced concrete (RC) structures. While corrosion has always been problematic since the beginning of mining and refinery of metals, corrosion in RC structures only gained research attention during the 1960s and 1970s, following widespread use of de-icing salts on highways within the United States and a construction boom in the Arabian Gulf. Since then, research has been undertaken worldwide to address corrosion issues. Theoretical models have also been developed and calibrated with experimental results to predict the behavior and service life of concrete structures with corroding steel bars [1–10]. Malumbela et al. [11–13] performed a critical review and experimental work with beam specimens and found that while in-service, RC structures normally corrode under sustained loading [14]. The majority of articles on corrosion have focused on structures that corroded in the absence of sustained loading [1–3,5–8,15–36]. Since 1999, some researchers have examined sustained loading effects [6,17,18,22,25,30,32,37]; however, none of these studies focused on corrosion during the service life of the structural components of RC structures having pre-existing surface cracks.

Cracks in reinforced concrete elements are a common occurrence due to the low tensile strength of concrete. Cracking that occurs in reinforced concrete structures at service load

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http://dx.doi.org/10.1016/j.conbuildmat.2016.08.010

(i.e., during the normal use of the structures) cannot generally be avoided. Among the studies published after 1999, only a study by Yoon (2000) [32] considered preloaded test specimens where cracks existed prior to accelerated corrosion testing, but the test program in this study did not use a sustained loading condition. Sustained service loads on structures, surface cracks, or a combination of both conditions can affect the rate of corrosion, the residual moment strength of corroded RC members, and the effectiveness of repairs. Experiments conducted and theoretical models developed without the consideration of pre-existing cracks and sustained loading conditions do not capture the true behavior of in-service RC structural elements that are subjected to corrosion and can lead to unsafe and non-conservative condition assessment.

The primary objective of this study is to highlight that two important factors (i) pre-existing cracks and (ii) sustained loading need to be considered in corrosion performance evaluation and to determine the influence of these two factors on the mass loss of the reinforcement as well as the crack expansion ratio and the patterns of cracks on the surface of the concrete specimens. To address these factors, concrete slab specimens having steel reinforcing bars were prepared. These specimens were carefully loaded in static loading to introduce the first visible transverse crack and then unloaded. Each specimen with this prior transverse cracking was set up in a corrosion cell, and sustained loading was applied along with an external induced current over the entire duration to accelerate the corrosion process. The electrical current applied in the accelerated corrosion test was based on a desired theoretical mass loss design levels (10%) calculated from Faraday's law. The experimental results were used to compare the theoretical calculations of metal loss and the actual measured mass loss. The ultimate load carrying capacity of the corroded specimens with various experimental conditions (different wetting and drying cycles and sustained loading levels) were measured and compared. After bending test, the different failure modes of corroded and un-corroded specimens are also compared. The mechanisms regarding the effect of the transverse cracks were developed based on the observations of this experimental program to explain the different characteristics of the longitudinal crack expansion ratio of specimens corroded under different test conditions (i.e., with or without pre-cracking and sustained loading).

2. Motivation of experiment work related to corrosion of slab specimens

Few corrosion-related experimental studies [32,33] on slab specimens are reported in the literature. The motivations for conducting accelerated corrosion experiments on slab specimens with and without pre-existing cracks and sustained loading is as follows:

(1) Pre-cracked condition has not been considered by researchers in earlier studies for RC slab elements. Consequently, there is a need to study the effects of this condition.
(2) Sustained loading (primarily from dead loads and permanent parts of live loads) exists during the service of continuous span structural slab bridge decks exposed to de-icing salts. Exposure of the deck slabs to these salts can be simulated in an accelerated corrosion test.
(3) The wetting–drying cycle is an important experimental condition for accelerated corrosion tests employed to simulate bridges subjected to a corrosive environment due to the use of de-icing salt, since de-icing salt is not applied continuously during the winter season.
(4) Structural slabs do not have shear reinforcement (stirrups) around the main tensile reinforcing bars and therefore behave differently from beams. The failure modes of corroded RC slabs need to be assessed and compared with those for un-corroded RC slabs.

3. Test setup

All specimens were cast using concrete (ASTM Type I Portland cement) with a cement content of 335 kg/m^3(564 lb/yd^3), a coarse aggregate to fine aggregate ratio of 1.3, and a water-to-cement ratio (w/c) of 0.44. A total of 18 slab specimens with dimensions of 305 × 76 × 711 mm (12 × 3 × 28 in) were cast in four batches. For each batch of concrete, several cylinders that were 102 mm (4 in) in diameter and 204 mm (8 in) in length were also cast to determine the compressive strength of each batch of concrete. The reinforcement configuration of the test specimens is shown in Fig. 1. Each test specimen was loaded from the bottom upward at the mid-span and supported at the ends from the top. This loading configuration was designed to cause tension on the top surface of the test specimens and compression at the bottom. The test specimens were placed in a curing room for 28 days approximately 24 h after casting. The curing room maintained the required humidity and temperature during the entire curing period.

After curing, three un-corroded specimens were subjected to a three-point bending test to determine the ultimate load carrying capacity. The flexural strength is expressed in terms of the critical load when the specimen reached the failure point. The failure loads recorded from the structural load tests for three un-corroded specimens were 42 kN, 36 kN and 42 kN (9.45 kips, 8.19 kips and 9.43 kips) with the average of 40 kN (9.02 kips). Fig. 2 shows the test setup and the failure mode of an un-corroded specimen, with typical flexural cracks.

4. Specimen groups and their designation

Concrete cylinders were used to determine the compressive strength of the concrete used for making the test specimens. Test results for eighteen test slab specimens are reported in this paper. These specimens were cast in four batches on different days but with same mix proportions and target 28-day strength. The average compressive strength for each set of specimens was determined on the first day of the start of the corrosion test for the set. Therefore, the average compressive strength for different sets of

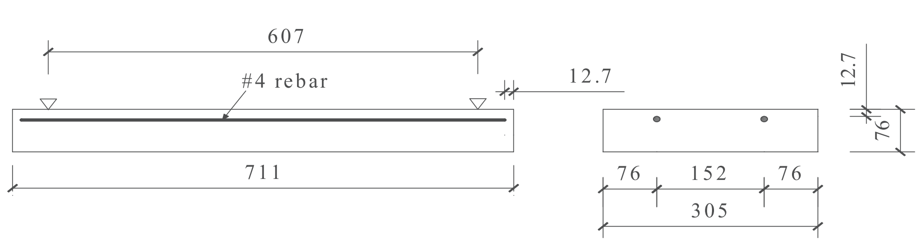

Fig. 1. Reinforcement configuration within test slabs (mm).