Engineering Structures 79 (2014) 365–374

Contents lists available at ScienceDirect

Engineering Structures

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

Novel shear capacity testing of ASR damaged full scale concrete bridge

Jacob Wittrup Schmidt [a,b,*], Søren Gustenhoff Hansen [c], Ricardo Antonio Barbosa [a], Arne Henriksen [d]

[a] *Technical University of Denmark, Department of Civil Engineering, Brovej, Bygning 118, 2800 Kgs. Lyngby, Denmark*
[b] *COWI A/S, 2800 Kgs. Lyngby, Denmark*
[c] *COWI A/S, 5000 Odense, Denmark*
[d] *The Danish Road Directorate, Thomas Helsteds vej 11, Postboks 529, 8660 Skanderborg, Denmark*

ARTICLE INFO

Article history:
Received 6 December 2013
Revised 13 August 2014
Accepted 14 August 2014
Available online 7 September 2014

Keywords:
ASR
Testing
Fluorescence
Impregnation
DIC

ABSTRACT

A large number of concrete bridges in Denmark have to undergo wide-ranging maintenance work to prevent deterioration due to aggressive Alkali Silica Reaction (ASR). This destructive mechanism results in extensive cracking which is believed to affect the load carrying capacity of the structure. However, sufficient knowledge concerning how it influences the structures load carrying capacity and stiffness is still lacking. In particular, more knowledge concerning the shear capacity of concrete slabs without reinforcement is needed. Often ASR deterioration result in demolition of the affected concrete bridges with considerable economical expenses as a consequence. A novel ASR test and measurement method, which can be used to perform shear testing locally on concrete bridges, is presented in this paper. Shear capacity testing is performed on a three span concrete bridge and several material test samples were taken from the test areas on the bridge deck. In addition, the test method is used to directly predict the shear capacity without disturbing the traffic significantly. Verification of the load carrying capacity of the bridge was the ultimate goal of the tests. A test rig, which could easily be moved between the slab test specimens, was constructed and the test areas were made in a way which enabled simple repair of the damaged areas after testing. In general, the novel test method worked very well since it provided an on site test method, which efficiently provides an evaluation of the load carrying capacity of the tested bridge. In addition, testing and monitoring provided important information concerning the shear behaviour of ASR deteriorated concrete. The results provided sufficient information to conclude that demolition of the bridge was not necessary and consequently significant savings related to the rehabilitation costs were obtained.

1. Introduction

In Denmark 600 concrete road and railway bridges may have to undergo wide-ranging maintenance work in order to prevent deterioration due to aggressive Alkali Silica Reaction (ASR). At present, a relatively large number of these bridges are subjected to ongoing deterioration. No exact knowledge concerning the effect on mechanical properties and thus the load carrying capacity of these bridges is available. Lack of sufficient knowledge in this field has resulted in the demolition of several bridges with large (economical) expenses therefore. The Danish Road Directorate estimates that the Danish society challenge related to maintaining these ASR deteriorated bridges from 2020 could result in increased expenses compared to today's budget – an expense corresponding to 200–250 million DDK (27–34 Million Euro) [23].

Deleterious Alkali Silica Reaction is a chemical process which occurs in concrete if following three conditions are present at the same time in an alkaline environment (the concrete): (1) reactive particles in the aggregates, amorphous, disordered or poorly crystallised silica, (2) alkalis in the concrete pore fluid either from the cement and/or added from the surrounding environment, (3) water or high humidity [15]. ASR occurs when reactive silica (e.g. as a mineral found in porous opaline flint) reacts with alkali ions in the concrete pore fluid in an alkaline humid environment. The reaction forms a hygroscopic reaction product, Alkali Silica gel, which imbibes water and swells. If a sufficient amount of reactive aggregates is present in the concrete, deleterious expansion may occur exceeding the concrete tensile strength. Consequently, cracking occurs together with Alkali Silica gel, which flows into the cracks and porosities.

The Danish researcher, Poul Nerenst, became aware of the ASR mechanism during a journey to the United States in 1950. After this journey, it was clear that similar deterioration mechanisms due to ASR were ongoing in Denmark [11]. In 1961, this led to a

* Corresponding author at: Technical University of Denmark, Department of Civil Engineering, Brovej, Bygning 118, 2800 Kgs. Lyngby, Denmark.
E-mail address: jws@byg.dtu.dk (J.W. Schmidt).

http://dx.doi.org/10.1016/j.engstruct.2014.08.027
0141-0296/

preliminary recommendation to avoid damaging ASR in new concrete structures [16]. However, inspection of older Danish bridges shows that this knowledge was not used until the late 70s. The influence of ASR on the load carrying capacity of the affected bridges has been discussed since the first observations of ASR. A number of papers conclude that ASR cracks do not lead to a reduction of the shear capacity [1]. A small number of papers concluded that the shear capacity is slightly reduced [2–4]. There is a general view among researchers that if the ASR expansion is restraint by the reinforcement a prestress will be induced in the concrete. The prestress will depend on the ASR expansion and deemed to vary depending on the structures reinforcement ratio. The possible prestress may contribute to the explanation of the contradicting results in the literature [1,15]. However, despite great efforts by researchers it has not resulted in an internationally accepted model or procedure, which can predict the prestress due ASR expansion and the shear capacity of concrete structures subject to ASR.

A common way to assess an ASR deteriorated structure has therefore been through component, substructure and full-scale testing in combination with a conservative use of applied theory for structures without deteriorations. Tests with ASR damaged concrete have been conducted in order to measure the effect on the load carrying capacity. The tests were also conducted in order to determine the influence on the structure in the service limit state (deflection, i.e. stiffness, etc.). Especially bridges with no shear reinforcement are a major concern because it is believed, that shear and punching shear could be greatly affected by the deterioration [1–3,5,6].

In Japan, early developed large crack widths were found in the Hanshin Expressway, constructed between 1969 and 1979, which were ascribed to ASR deterioration. Proof test loading using trucks was applied at the bridge edge line to measure the response of the deteriorated bridge. The displacement was monitored until eighty percent of the design load was reached. Consequently, it was concluded that the ASR damages did not significantly affect the load carrying capacity and stiffness of the damaged bridge piers. However, a small increase in displacement was reported [20].

Also in Johannesburg, South Africa, a test program was conducted in 1977 on a portal, which forms a major double deck road structure, where cracking was found due to ASR. Long-term monitoring was conducted on the bridge and two full-scale tests were performed in 1982 and 1988, respectively. During testing the bridge frame was subjected to almost eighty-five percent of the design load during a five-hour period using loaded trucks on the upper deck. The testing resulted in the conclusion that the portal frame was structurally adequate [17].

In Austin, Texas, six large-scale bent cap specimens, representing examples of severe deterioration in the field, were tested. Expansion monitoring, shear testing and forensic analysis were performed in this research program. The shear capacities were compared to a reference concrete beam (non-deteriorated beam). It was found, that the capacity of the ASR deteriorated beams exceeded that of the non-deteriorated beam. Additionally, it was reported that the shear capacity exceeded ACI 318-08 [21] and 2088 AASHTO LRFD [22] estimations [7].

In Denmark, a full-scale test was conducted on an ASR damaged bridge. The scope of this test was to: (1) investigate whether full-scale testing can be used to verify the bridge actual capacity (not the ultimate capacity) and (2) develop a method to predict the capacity in relation to the degree of damage. The programe involved shear testing, compression and tension testing, crack initiation measurements, deflection measurements as well as strain measurements at the middle supports of the bridge's longitudinal beam. However, this test setup did not give information concerning the shear forces. Before the experiment, surface cracks were observed through the full thickness of the bridge with an inclination of 10–15°. By cylinder testing it was seen that the compressive and splitting tensile strength were reduced significantly compared to the design strengths while no reduction of the shear capacity was reported [12].

Also in Denmark a second full-scale ASR bridge test was performed. The purpose of these non-destructive tests was to verify the remaining capacity before eventually demolishing the bridge. By using loaded trucks at five different load magnitudes 44 load cases were studied. Deflection and strain measurements where conducted too. These experiments were repeated every 4–5 years and the results were used to conclude whether demolishing of the bridge could be postponed [13].

Since ASR occurs in existing structures, which are in use, it can be difficult and expensive to perform component capacity testing. Several attempts to introduce accelerated ASR deterioration on concrete beams have therefore been initiated to simulate a real-life ASR case.

In Denmark, the Danish Road Directorate initiated a research programe [6] in 1984 where beams without shear reinforcement were stored for different periods of time in a sodium chloride solution at 50 °C. The test results showed an increase of about 78 percent of the shear strength compared to corresponding non-deteriorated reference beams. The loss of material strength (compressive strength and elastic modulus) was suggested to be compensated by the compressive stress induced by expansion restrained by the reinforcement [6].

Results from other tests with accelerated ASR deterioration have been reported. The shear strength of non-shear reinforced beams increased by 7.4–9.8 percent compared to corresponding reference beams. This increase in shear strength was deemed to be caused by the compressive stress induced by ASR expansion, but also the fact that the alkali–silica gel could acts as strong filler, which increases the shear capacity of the cracks [14]. However, in another paper a loss of shear strength for beams without shear reinforcement of 11.7–25 percent was reported [16].

The lack of sufficient theoretical models results in approaches, which are a rough estimation, based on cylinder tests and visual inspection. Decision-making based on this lack of models could lead to demolishing of bridges, which actually have sufficient capacity.

A theoretical model that converts information from such testing into a method that can predict the structural capacity and deformation of a structure exposed to ASR, is still non-existing. The researchers and consulting engineers therefore seek a common test procedure and a common theoretical model to determine the load carrying capacity of structures subjected to ASR deterioration. Several models for predicting the shear capacity are based on the tensile strength of the concrete [18]. Therefore, it is a common view that serious cracks will reduce the shear capacity.

In the Netherlands a recommendation for structural evaluation of ASR is introduced CUR Recommendation 102 [18]. The recommendation includes an evaluation procedure and model for predicting the shear capacity. The model includes the tensile strength from concrete cylinders but the results underestimate the shear capacity for structures with serious ASR-deterioration. Thereby, new evaluation methods have been developed – e.g. the EKSTRA-method. The EKSTRA-method consists of a load test where an external load is applied. Besides load testing, the method includes monitoring of deformation and internal cracking by Acoustic Emission. Monitoring is used in order to an irreversible state. The scope of the test method is to verify the required load carrying capacity, not the ultimate load carrying capacity [5].

Inconsistencies in the conclusions regarding the load carrying capacity of ASR deteriorated concrete structures are reported. Some results show a reduction of the shear capacity, other evaluations