Engineering Structures 163 (2018) 267–280

Contents lists available at ScienceDirect

Engineering Structures

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

Time-dependent behaviour of cracked, partially bonded reinforced concrete beams under repeated and sustained loads

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ARTICLE INFO

Keywords:
Bonds
Long-term deflection
Midas FEA
Repeated
Sustained
Tension stiffening

ABSTRACT

This paper compares the flexural behaviour of cracked partially bonded (in the mid-span, maximum moment zone) reinforced concrete beams subjected to (i) static sustained load and (ii) static sustained with cyclically repeating load. Information relating to surface strains and mid-span deflections were continuously recorded for a period of 90 days. The sustained load level represented that which produced the stabilized crack pattern. The amplitude of the superimposed cyclic load was considered to be a small fraction of the sustained load. The experimental outcome shows that under sustained load alone, the long-term mid-span deflection of reinforced concrete beams with artificially debonded reinforcement is substantially higher than that of normally bonded equivalent beams. For the cyclically exerted load addition there was no substantial difference between the observed ultimate deformations of bonded and debonded beams. Nonlinear finite element software (Midas FEA) was used to simulate these results and it was found that a numerical-experimental match can be achieved after applying necessary modifications to the distribution of shrinkage down through the beams' cross-section.

1. Introduction

Two forms of guidance are provided in Eurocode 2 (BS EN 1992-1-1) to assist designers with the estimation of the long-term deflections of reinforced concrete spanning elements. The span to effective depth ratios derived by Beeby and Scott [1] estimate deflection in terms of a pass/fail check and have previously been shown to be adequate [2]. However, with the trend for longer spans/shallower depths, more accuracy is required. With this in mind, a second system of guidance is provided in the form of a prediction method which considers the estimation of the elastic, creep and shrinkage (incorporating tension stiffening and its loss) curvature. Previous work by Forth et al. [3] investigating the accuracy of this prediction method has suggested shortcomings in the theory (e.g. the fact that the approach is based on the theory of uncracked sections but uses cracked section properties and the fact that the method uses a fixed tension stiffening factor for either short or long-term loading). Further questions on the prediction method were raised by Higgins et al. [4] and Daud et al. [5] relating to the use of a single factor for loss of tension stiffening to represent both a sustained and repeated long-term load. In these latter two investigations, the definition of a repeated load is one which can cycle about the design maximum sustained load. Higgins et al. [4] and Daud et al. [5] showed that a repeated or cyclic load will produce a significantly higher deflection than the deflection of a beam subjected only to a sustained load representing the average of the overall, cyclic-inclusive, load. They attributed the extra deflection found in the cyclic load tests to the loss of tension stiffening during the early stages of the tests. In the Eurocode 2 [6] prediction method, the factor β, which represents the loss of tension stiffening correctly suggests a reduction in tension stiffening with time under a constant, sustained load – this has been adequately shown by Beeby and Scott [7]. But very rarely in practice is the load constant and sustained; Vollum [2] has shown that the applied load can frequently exceed the design load and that it is reasonable to consider a 10 to 15% exceedance. The loss of tension stiffening is incorporated in both the calculation of the creep and shrinkage curvature. Scott and Beeby [8] illustrated that under sustained load, up to 50% of the tension stiffening is lost over the first 20 to 30 days, at which point the loss stabilised. This finding was achieved when a stabilised crack pattern was present within the test samples; the losses were allegedly due to the development of internal cracking, which inevitably will reduce the composite action between the steel and the concrete [9]. In practice, it is quite common for a spanning element to be stressed well below the stress required to produce a stabilised crack pattern. In these cases, therefore, tension stiffening will be higher and its loss lower, as such the predicted deflection will likely be an overestimation of the actual deflection. However, where a beam is subjected to the maximum design

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https://doi.org/10.1016/j.engstruct.2018.02.054
Received 19 December 2016; Received in revised form 21 December 2017; Accepted 19 February 2018

serviceability load and a stabilised crack pattern does therefore exist, any additional cyclical load/repeated load in excess of the design load would likely lead to enhanced internal cracking/loss of bond between the steel and the concrete and could cause an additional loss in tension stiffening. In this case, the predicted deflection will likely be an underestimation of the actual deflection. Based on these examples, it is clear how the use of a single value β for long-term loads can mislead practising engineers. Further evidence of the variation in β due to load types is provided by Zanuy et al. [10] who presented an experimental study on a lightly reinforced concrete bridge deck subjected to repeated (fatigue) loading. As the number of load cycles increased there was a progressive loss in tension stiffening [11]. Vakhshouri and Nejadi [12] also indicated that load types (i.e. cyclic or a combination of different loading types) might affect the deflection behaviour of reinforced concrete beams.

In this study, the effect that the loss of tension stiffening has on beams subjected to long-term sustained and repeated load was investigated experimentally. For some of the tested beams, any tension stiffening was artificially removed in the region of the beams relating to the constant moment zone. Through all cases, both the mid-span deflection and surface strain development in the compression and tension zones were monitored continuously for a period of 90 days. In addition, the nonlinear finite element software Midas FEA was used to simulate the behaviour of the experimental beams. In order to use this proprietary software, modifications were proposed for correctly incorporating within the displacement estimation the effect of shrinkage on the curvature of a cracked section.

2. Bond between concrete and steel

In reinforced concrete flexural members, when the load is applied, it is resisted compositely by the concrete and the reinforcement through the mechanical bonding that exists between the concrete and the steel. At low levels of loading (i.e. $M_a \le M_{cr}$, where M_a and M_{cr} are the applied and cracking moment, respectively) both the concrete and reinforcement act compositely and elastically. As the load increases (i.e. $M_a \ge M_{cr}$), primary cracks are produced as the concrete tensile strength is exceeded by the applied tensile stresses. At $M_a >> M_{cr}$ a stabilised cracking pattern is achieved (i.e. no further primary cracks can develop), however, between these primary cracks, variable but sufficient bond between the two materials still exists, allowing the steel and concrete to still behave compositely. In 1971, there was an attempt by Goto [9] to study the mechanism of the bond between the deformed reinforcement and the surrounding concrete by injecting red ink inside tension specimens. He found that internal cracks which formed at each rib on the bar, had a great influence on the bond between the reinforcement and the concrete. Moreover, he discovered that secondary cracks were formed near the primary cracks rather than midway between the primary cracks.

There are many factors affecting the bond strength between the concrete and the steel such as the strength of the concrete, and the yield strength, diameter and surface geometry of the steel reinforcement. Confinement is another factor which effects the bond; it was found that the bond increases with an increase in the confinement [13]. The basic behaviour of reinforced concrete members depends on the bond between the concrete and the reinforcement; this composite interaction is indicated by the bond stress [14], which is thought to have some effect on crack widths, crack distribution and deflections [15]. Crack width and spacing in reinforced concrete members have also been studied by different researchers [16–18] and an extensive analysis was carried out by Forth and Beeby [19] in order to better understand the relationship between the reinforcement and the concrete in the tension zone. They found that the crack width increases almost linearly with an increase in the cover. Generally cracked beams with plain reinforcement have less surface and internal cracks than beams with ribbed reinforcement. Moreover the crack spacing in beams containing ribbed reinforcement is less than that of beams with plain reinforcement [20].

As mentioned in the Introduction, load types (i.e. static or dynamic) are another factor which influences the bond between the concrete and the reinforcement (and hence the deflection). Comprehensive studies were conducted on the behaviour of reinforced concrete beams under short-term cyclic loading, focusing on the bond between the steel and the concrete [21]. According to Neild et al. [21], under monotonic or low cyclic loading, at a certain stress level, the adhesive component of the bond between the reinforcement and the concrete deteriorates and only the frictional component eventually remains. Daud et al. [5] showed experimentally that the interaction between concrete and reinforcement depends on the type of load applied i.e. sustained or cyclic load. They found that the overall deflection is substantially higher in the case of repeated cyclic loads than in the case of equivalent sustained loads.

It is common practice to examine the concrete/reinforcement bond using pull-out tests. Rehm and Eligehausen [22] conducted pull-out tests on 308 specimens. They noticed that if fatigue failure does not occur, repeated loading only has an influence on the bond under service loading. Also statically, the bond strength was 5% higher in the case of preloaded specimens. Hawkins et al. [23] showed experimentally that the bond stress-slip envelope is similar up to the maximum capacity for both cyclic and monotonic loading. However, in the descending part of the bond stress-slip curve, the bond stress for a given slip is always less in the case of cyclic than in the case of monotonic loading.

3. Experimental arrangement

In light of the review above, both beam tests and pull-out tests were performed in order to try and better understand the loss of tension stiffening and its effect on deflection. Four normal reinforced concrete beams were cast and tested under long-term loading in the concrete laboratory at the University of Leeds. Two of the beams were cast under normal conditions, meaning that their reinforcement was fully bonded, enabling composite action, with the concrete. One of these two beams was subjected to a sustained load, while the other was subjected to a repeated load (designated as FB-SUS and FB-REP, respectively). The remaining two beams were cast such that the reinforcement in the constant moment zone was artificially debonded from the concrete. Of these latter two beams, one was subjected to a sustained load and the other to a repeated load (denoted as UB-SUS and UB-REP, respectively). The section dimensions, span length, material properties and reinforcement ratio were the same for all beams. The main variable in this study was the loading type (sustained and repeated) and the composite nature of the concrete and the reinforcement (bonded and debonded). All beams were simply supported and subjected to a four-point loading. All details are shown in Fig. 1. Table 1 provides a key for the beam designations.

All beams had the same properties; mean cube compressive strength, $f_{cm,cube}$ = 55 MPa (standard deviation, std, 5 MPa), mean flexural strength, f_{ct} = 4.8 MPa (std 0.6 MPa) and mean modulus of elasticity E_{cm} = 33.7 GPa (std 0.25 GPa). The beam dimensions were 300 mm wide, 150 mm deep and 4200 mm long (actual span between supports = 4000 mm). Three bars with nominal diameter of 16 mm, yield stress of 510 MPa and modulus of elasticity of 180GPa were used as the bottom longitudinal reinforcement. Two 10 mm diameter bars were located in the compression zone to support the links.

For the debonded beams, the ribs of the tension reinforcement in the constant moment zone (i.e. the central 1500 mm beam portion) were ground away. The area was then wrapped with thermal shrinkage wrap (the surface of the shrinkage wrap which would come into contact with the concrete was also treated with degreasing agent) to try and ensure that the concrete was debonded in the constant moment zone. Three strain gauges were placed on the underside of the tension reinforcement of each beam. Steel formwork was used and the concrete was cast in two pours. After casting, the beams were cured and covered with plastic