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Behaviour of cracked reinforced concrete beams under repeated and sustained load types

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ABSTRACT

This paper compares the behaviour of reinforced concrete beams subjected to sustained and repeated load types in bending. Mid-span deflections and surface strain profiles were monitored over an 80 day period so that comparisons could be made between the structural response of RC (reinforced concrete) beams to the different load types tested. The load level at which beams under a sustained load were held represented the mean value of the upper and lower load of the repeated load types. The two different repeated load amplitudes investigated corresponded to 24% and 12% with respect to the mean load. In addition, beams were subjected to two different loading frequencies throughout testing (0.2 Hz and 1 Hz).

Measured surface strains were considerably higher in both the tension and compression zones of beams subjected to repeated load types. This was thought to be primarily due to the effects of cyclic creep in the compression zone and a higher degree of cracking within the tension zone. The progressive long-term increase in deflection is shown to be a result of strain development primarily in the compression zone. In contrast, the strain increase at tensile reinforcement level after 10 days under load is limited, regardless of the applied load type.

The repeated load types are shown to affect the section stiffness most significantly within the initial period of loading (0–10 days). Results also show that the beam's response is sensitive to increases in both the loading frequency and load amplitude. This study aims to highlight the importance of considering not only the current loading conditions, but also the load history of a reinforced concrete section (particularly any temporary load peaks, which would lead to a permanent deterioration of section stiffness) when attempting to determine the current state of an RC section.

Using experimental results, the validity of Expressions 7.19 and 7.9 of Eurocode 2 (EC2) are examined. The additional damage within the tension zone caused by the repeated load types is not accounted for in either expression, meaning that the tension stiffening effect is overestimated. Consequences of this are that design code SLS (serviceability limit state) checks for beams with complex load histories may be inaccurate, and that the average steel stress within the reinforced concrete sections may be underestimated.

1. Introduction

1.1. Research outline

This study investigates the effects of subjecting reinforced concrete (RC) beams to different load types in bending. Comparisons are made between beams subjected to repeated load types and identical beams held under a sustained load. The degree of damage within the tension zone, hence the loss of section stiffness due to repeated loading, is commented on and the relevance of the findings are discussed in terms of the current design code, Eurocode 2 (EC2).

All beams were loaded for a total duration of 80 days. By assessing the development of concrete surface strain in the tension and compression zones, it was possible to identify the long-term drivers of progressive curvature increase for beams under each load type. The test duration also allowed an insight into whether the additional deformations caused by the repeated load types occurred only during the initial loading period (0–10 days), or had a continual effect on the reinforced concrete beam's behaviour.

To assess the significance of the repeated loading frequency, beams were cycled at either 0.2 Hz or 1 Hz. The loading frequencies tested within the current study were chosen as they apply to numerous loading scenarios in practice including offshore loading,

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pedestrian loads, traffic loads, machine loads and seismic loading. In addition to this, the repeated load amplitude was also varied between individual beam tests. This was done to investigate whether altering the load amplitude resulted in a proportionate increase/decrease in beam deformation. The repeated load amplitudes investigated within the current study were seen as acceptable and realistic overload values.

1.2. State of the art review

The concrete in the oceans (CiO) research programme, which was conducted throughout the 1970s and 1980s, identified and addressed a number of key long-term structural degradation mechanisms associated with offshore concrete gravity structures (CGS). Many of the studies carried out under the umbrella of the CiO programme focussed specifically on the fatigue performance and the response of RC sections to repeated load types [1–4]. The CiO studies, however, were primarily focussed on determining the endurance capabilities of RC sections, rather than studying how repeated load types altered the properties and serviceability behaviour of an RC section.

More recently, extensive research has been carried out into the behaviour of RC sections subjected to repeated load types. Zanuy et al. [5] observed that under a repeated load, the tension stiffening of lightly reinforced concrete members is progressively reduced with an increasing number of load cycles, with the member's response eventually approximating the fully cracked state (State II). Other work by Zanuy et al. [6,7] identified that on the unloading branch of a load cycle, negative tension stiffening (due to the development of negative bond stresses at the steel–concrete interface) can occur, resulting in deformations which are larger than those given by the fully cracked state (State II). In addition, Oh and Kim [8] reported that under repeated load types, crack width increases with an increased cycle number. Much of the increased deformation under repeated load cycles is thought to be due to the deterioration of the bond–slip relationship, as first identified by Balazs [9].

Many of these state-of-the-art studies do not specifically investigate the structural deterioration of offshore concrete platforms. However, they are still of relevance and interest to the offshore industry. The current study aims to build on the existing knowledge of reinforced concrete's response to repeated load types, while also acting to promote further research specific to the offshore concrete industry.

1.3. Industry relevance

The behaviour of reinforced concrete beams in bending under a sustained load at serviceability levels is complicated. However, formulae exist within current design codes which approximate the serviceability behaviour (crack characteristics, deflection, etc.) of a reinforced concrete member subjected to an applied load. Often, an *intermediate* cracked state is calculated which lies somewhere between an uncracked and theoretically fully cracked reinforced concrete section. The intermediate cracked state assumes some degree of stiffness contribution from the concrete in the tension zone between cracks. This concrete contribution is commonly referred to as the *tension stiffening effect*.

Within EC2, both load-dependent and load-independent approaches are used to estimate the contribution of concrete within the tension zone. Expression 7.19 of EC2 can be used to calculate a distribution coefficient (ξ), which is a measure of the cracked state of a reinforced concrete member. Expression 7.19 is a load-dependent approach; meaning that at low loads (below the cracking load), the distribution coefficient is equal to 0; it will approach 1as the applied load is increased and a stabilised crack pattern is achieved. Expression 7.19 also includes a parameter, β, which takes into account the influence of the duration of loading or of repeated loading. Expression 7.9 of EC2 attempts to quantify the concrete contribution in the tension zone, giving load-independent expressions for the tension stiffening effect and for the mean strain in the concrete between cracks (ε_{sm}) Within the current study, reinforced concrete beams have been tested under different load types in order to investigate the validity and accuracy of Expressions 7.19 and 7.9 of EC2.

2. Theory

2.1. Tension zone

When an RC section is subjected to bending, at low loads strain compatibility exists between the steel and the concrete. However, as the applied load increases, the inherent low tensile strength of concrete is exceeded and cracking occurs. Cracking within a reinforced concrete section causes a disruption to the bond between the steel and concrete and, as a result, the section experiences a loss of stiffness.

At a cracked section, tensile stresses within the reinforcement cannot be transferred to the surrounding concrete. Therefore, a stress concentration exists within the steel. The amount of stress that can be transferred to the surrounding concrete is a function of distance from the crack. With increasing distance from the cracked section, concrete stress increases until at some distance, S_0, a uniform concrete stress distribution is again achieved (although if the strain remains constant, the uniform stress achieved away from the crack will be below the level of stress achieved just prior to crack formation, i.e. below the tensile strength of the concrete, as the stiffness of the section has been reduced by the formation of the crack). Eventually, with increasing strain a stabilised crack pattern will emerge consisting of cracks having some distribution of spacing within the range $S_0 \leqslant S \leqslant 2S_0$, where S is the observed crack spacing [10].

2.1.1. Internal cracking

Goto [11] revealed that shortly after the formation of a primary crack, internal cracks are formed at the steel–concrete interface. These internal cracks first form along portions of the reinforcement which are immediately adjacent to the primary crack. As adhesion along the bar is lost and stress is transferred to the bar's ribs, internal cracks begin to develop and extend from the ribs. Further loading causes continued stress transferral and additional internal cracks form at ribs progressively more distant from the main crack. Internal cracking effectively deteriorates the bond, separating the reinforcement and the concrete. This means that along portions of the reinforcement where internal cracking has occurred, the two materials cannot behave in a composite manner and the tensile force is not effectively transferred from the steel to the surrounding concrete. Because of this, internal cracks lead to additional loss of section stiffness and also higher average stresses in the debonded steel. It should be noted that Goto's research was carried out on axially loaded RC specimens. However, it is generally acknowledged that in an RC member subjected to a bending moment, the tension steel and surrounding concrete behave similarly to the axially loaded case. Therefore, internal cracking would also be expected to occur at the steel–concrete interface within the tension zone of an RC beam subjected to a bending moment.

2.1.2. Tension stiffening

Between cracks, a reinforced concrete section will exhibit some composite behaviour. Portions of the reinforcement will remain partially, if not fully bonded to the surrounding concrete. The