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

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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

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

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 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. $M_a \leq M_{cr}$, 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. $M_a \geq M_{cr}$), primary cracks are produced as the concrete tensile strength is exceeded by the applied tensile stresses. At $M_a >> M_{cr}$ a stabilized 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 Figure 1. Table 1 provides a key for the beam designations.

All beams had the same properties; mean cube compressive strength, $f_{\mathrm{cm,cube}}$ = 55MPa (standard deviation, std, 5MPa), mean flexural strength, f_{ct} = 4.8MPa (std 0.6MPa) and mean modulus of elasticity E_{cm} = 33.7GPa (std 0.25GPa). The beam dimensions were 300mm wide, 150mm deep and 4200mm long (actual span between supports = 4000mm). Three bars with nominal diameter of 16mm, yield stress of 510MPa and modulus of elasticity of 180GPa were used as the bottom longitudinal reinforcement. Two 10mm 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 1500mm 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 sheets for one week, at which point the beams were demoulded and placed in a fog room (99% relative humidity). Three days before the test, the beams were placed in the test rig and prepared. Both sides of the beams were painted in white to allow for easier monitoring of the cracks. Longitudinally, four sets/rows of DEMECs (150 mm horizontal spacing) were placed on both sides of the beams to monitor the curvature and surface strain. The bottom and top rows of the DEMECs were positioned at the level of the top and bottom reinforcement. As well as the DEMECs, two LVDTs (Linear Variable Differential Transformers) were placed under each beam to monitor the mid-span deflection of the beam. Surface strain and developed deflection were monitored for a period of 90 days; this duration was chosen based on the following:- it was in accordance with previous research carried out by Troxell et al [24] and Mias et al [25]; it was shown that up to 80 % of the final creep and shrinkage occurs in the first 90 days [24]; up to 50 % of the tension stiffening is lost over the first 30 days, after which the loss stabilised [8]; Higgins et al [4] showed experimentally that, the extra deflection due to repeated loading occurred in the first 10 days; previous tests of this type resulted in sufficient convergence of the long-term deflection such that an accurate assessment of the ultimate deflection could be made using the approximate extrapolation methods; and finally, Mias et al [25] showed experimentally that, up to 90 % of the final long term deflection in reinforced concrete members occurs at 90 days of loading. Figures 2 and 3 show the casting preparations and test set up.

3.1 Beam test protocol

All beams were initially preloaded to 19kN (this is the magnitude of the sustained load) to produce a stabilised crack pattern. Adhering to the conjecture that the average crack spacing of a fully cracked reinforced concrete beam is 2/3 of the theoretical crack spacing, 2 S_0 [1], where S_0 = 2.1C for flexural member [26] with C being the cover depth, and C for the tested beams being 36 mm, the average crack spacing is estimated as 101mm. Thus, the typical/expected crack number in the constant maximum moment mid zone (see Figure 1) should be 15. However, in these tests the number of cracks for the bonded beams was 15 whereas it was 8 for the debonded ones.

The tensile steel stresses were checked at this load and were found to be 198MPa (it is estimated that a steel stress of 200MPa is sufficient to produce stabilised cracking for this type of beam). For the beams subjected to a repeated load, the load was then cycled between an upper and lower limit about the constant sustained load of 19kN. This cyclic amplitude was selected to be 2.5kN which is about 10% of the sustained load [2, 4]. A cyclic frequency of 0.2Hz was chosen; this is considerably lower than the beam natural frequency which is about 4Hz and close to a typical low frequency input in offshore structures i.e. 0.15-0.2Hz [27]. For the cyclic/repeated tests, when a reading was recorded (for displacements this was at 15 min intervals), this was always taken when the instantaneous amplitude of the cyclic load was zero (i.e. at 19kN; crossing the mean value). The deflection on initial application of the sustained load (19kN) was recorded and represented the elastic deflection at time t_0. Surface strains where recorded every 10 days and

3.2 Pull-out tests

In order to assess the efficiency of the artificial debonding method adopted in this investigation, a series of pull-out tests were performed. A total of 8 concrete cubes of (200 x 200 x 200) mm^3 were cast, each with a single 16 mm rebar. The concrete cubes had the same material properties as the beams. The variable in these pull-out tests was the bonding of the reinforcement; for four of the samples the steel was composite and bonded with the concrete; the other four samples contained bars which were artificially debonded. The embedment length-to-bar diameter (*L/d*) ratio was 5. All the specimens were demoulded after 1 day and cured in the fog room until testing. The cube dimensions and the embedded length were similar to that adopted by previous studies[28, 29].

Figure 4 illustrates the preparation of the specimens. A slow loading rate of 2kN/min was utilised. Three LVDTs were attached to the specimen (as shown in Figure 5). The first two samples were tested at an age of 14 days to study the compressive strength development with time; this allows a later correlation with the bond strength loss for both bonded and debonded samples. The rest of the samples were tested at 28 days. None of the reinforcement bars reached their yield stress during the tests.

The average bond strength τ over the embedded length was calculated using the maximum load sustained during the test, assuming a uniform stress distribution along the embedded length of the reinforcement [30]:

$$\tau = \frac{P}{\pi d_b l_b} \tag{1}$$

Where P is the ultimate load (kN), l_b is the embedded length (mm) and d_b is the diameter of the reinforcement (mm).

This equation is used widely to determine the bond strength, although it is based on a uniform stress distribution along the embedded length of the reinforcement, which is not accurate. The stress distribution actually varies greatly as the slip develops [31, 32]. The bond strength values are presented in Tables 2 and 3 where it can be seen that the artificial method of debonding did not achieve a 100% loss of bond as envisaged; there still appears to be some adhesive bond between the reinforcement and the surrounding concrete. At 14 days, the loss of bond was approximately 94%. At 28 days, it was approximately 93% which agreed with the outcome of Weathersby [33], i.e. bond-slip of smooth reinforcement is not significantly affected by the compressive strength of the concrete.

A previous study showed that, under normal loading scenarios up to 50% of the bond could be lost in case of plain reinforcement [34] – this is reflected in the factor k_1 in Eq 7.11 of EC2. In this study (i.e. debonded specimens) the bond lost is higher than that of plain reinforcement. This is because the concrete was effectively trying to bond with the thermal shrinkage wrap which had been treated with degreasing agent rather than with smooth steel. In addition the concrete cover adopted in this research was nearly three times that which Edwards and Yannopoulos [34] used for their specimens.

Unsurprisingly, the debonded reinforcement pulled out with very little effort and its slip was very high when compared to the slip of the bonded specimens (nearly 10 times higher). This was clear evidence that the artificial debonding was effective; once the bond (adhesion) was lost, the reinforcement pulled out of the concrete without disturbing the concrete.

The load-slip behaviour of the bonded and debonded specimens are shown in Figures 6 and 7. It can be seen that the ultimate load in the case of the bonded reinforcement was much higher than the debonded case. The average ultimate load was 110.5kN for the bonded specimens whereas it was only 8.1kN for the debonded specimens. The slip at ultimate load in the case of the debonded samples was about ten times more than that of the bonded ones. Therefore, it can be assumed that debonding the reinforcement increases the failure slip and decreases the plastic energy absorption capacity (as debonded samples have much less ultimate load than the bonded ones).

Figure 7 indicates that although the same technique was used for the artificial debonding of the reinforcement, the degree of debonding was not quite the same in all samples. This agreed with previous work carried out by Feldman and Bartlett [35], who found that the bond stress magnitude may not be uniform along the embedded length of the plain reinforcement.

Two types of failure mode were recognised during the test for the bonded samples; the first one was a pull-out failure i.e. shear failure between the reinforcement and the concrete interface. The second one was by crushing of the concrete (see Figure 8a) i.e. the concrete around the reinforcement undergoes radial stresses which lead to splitting failure [28]. Whereas in debonded samples, only bond failure was recognised and that because there is approximately

8 % bond strength left, and the bond transfer by adhesion between the reinforcement and the surrounding concrete [35] (see Figure 8b).

4 Results and Discussion

4.1 Deflection

The effect of the reinforcement condition (bonded, debonded) on the tension stiffening and deflection of reinforced concrete beams was investigated experimentally. Figure 9 compares the long term mid span developed deflection of the debonded and bonded reinforced beams under sustained loading.

It can be seen that during the early ages of sustained loading, the debonded beam developed more deflection than the bonded beam. After 90 days, the debonded beam had approximately 36% extra deflection than the bonded beam. This extra deflection is thought to be due to the greater loss of tension stiffening promoted in the debonded beam.

Figure 10 compares the time-dependent mid-span deflection of the debonded beams under sustained and repeated load types. It can be seen that the deflection of both beams was similar during the first 20 days, however, at the end of the test, the beam subjected to the repeated load exhibited more deflection (+7%) than the beam subjected to the sustained load. The 7% extra deflection after 90 days seen in this investigation (note that this may be considered close to the setup accuracy) theoretically may be due to 1) the effect of cyclic creep, since the cyclic creep enhances static creep [36] or 2) the fact that the artificial debonding method had not worked in its entirety. Also relate to the fact that any residual bond may have been removed during the loading stage.

In Figure 11 the behaviour of the debonded beam under sustained load was compared with that of the fully bonded beam under repeated load. After 20 days, there was only a minimal difference in the deflection (0.5 mm, i.e. 2% of the total) (the debonded beam had a slightly greater deflection than the bonded beam). After 20 days of loading, the deflection rate in both beams was almost identical, suggesting that the bond between the concrete and reinforcement in both beams must be equivalent (i.e. removed).

This implication is important as it suggests that the bond between concrete and steel in reinforced concrete beams when subjected to a repeated load can be significantly damaged due to the loading nature, even though the frequency is relatively low (i.e. 0.2Hz; far from any possibility of dynamic resonance effects). On similar grounds [22, 37], researchers previously attributed this damage effect to the inherent asymmetry within the cyclic loading and unloading process selected here; this results in residual slip and subsequently bond damage.

4.2 Tension and Compression Zone Surface Strain

The average surface strain (averaged along a DEMEC row) development with respect to time in the compression and tension zone was monitored for a period of 90 days, at 10-day intervals, throughout the constant moment area. In all cases, it can be seen that, the surface strain development is higher in the compression zone than in the tension zone. This is thought to be due to the effects of creep and shrinkage and how they act on the two stress zones, i.e. creep and shrinkage are in the same direction in the compression zone – they are effectively a contraction; whilst shrinkage (a contraction) is in the opposite direction to creep (an extension) in the tension zone. In addition, there is less reinforcement in the compression zone so less restraint to movement. Finally, the concrete stress in the compression zone is higher than that in the tension zone.

Figure 12 compares the surface strain development for the fully bonded beams, under repeated and sustained loading. It can be seen that in the compression zone there is an additional deformation developed with time in the repeated load case to that seen in the sustained loading case, whereas in the tension zone the increase only occurs during the first 25 days.

Both beams had the same number of cracks after loading (15 cracks). After 90 days no more cracks developed in the beam subjected to sustained loading but three more cracks (thought to be internal cracks which developed sufficiently to reach the surface [4]) developed in the beam subjected to repeated loading (all were developed during the first 15 days).

Figure 13 illustrates the surface strain development with time for beams where the reinforcement has been artificially debonded. From the figure it can be seen that, both beams had almost the same development of strain in the compression zone, although there is still more strain in the beam subjected to the repeated load. This suggests that probably cyclic creep is not present in this case (i.e. at a low frequency of 0.2Hz). In the tension zone, the surface strain in the beam subjected to repeated loading is more than that in the beam subjected to the sustained load. No more cracks were produced in either beam after loading (eight cracks were observed); the additional deformation of the repeated load beam may have been the result of greater crack widths. Unsurprisingly, beams with debonded (smooth) reinforcement had fewer cracks in the constant moment zone than the beams with bonded (ribbed) reinforcement. Previously, it has been shown that beams with smooth reinforcement have less surface cracks than beams with ribbed reinforcement [20].

Figure 14 shows the effect of debonding the reinforcement on the development of surface strain for the beams under sustained loading only. Within this figure clearly the debonded beam had more strain development in both the compression and tension zones than the bonded beam. In the compression zone the higher surface strain development might be because the debonded beams had higher developed deflection due to the artificial loss of the tension stiffening. Whereas the higher surface strain development in the tension zone indicates that the crack widths are higher in the debonded beams than in the bonded beam, although the debonded beam had a lower number of cracks (average crack widths after 90 days were 0.35mm and 0.12mm for debonded and bonded beams, respectively).

For the bonded beam subjected to repeated loading, the surface strain development in the compression and tension zones was compared with the debonded beam subjected to sustained loading, as shown in Figure 15. It can be seen that both beams behave almost identically; this again confirms that, all the bond between the concrete and reinforcement was eliminated in the bonded beam by the repeated load case giving further substance to the argument that tension stiffening cannot always be relied upon.

One final comment on the success of the debonding method adopted in this investigation; from the pull-out tests there appeared to be some residual bond in the debonded samples. This may have been down to the fact that the concrete surrounding the bars in the test was in compression and hence would have 'gripped' the bar more efficiently. In the beam tests, the concrete surrounding the debonded steel is in tension and so this residual bond may not be present. On the other hand, in the beams the steel is only debonded in the constant moment zone. Either side of the constant moment zone, the steel is bonded and will therefore anchor the bars; this composite action outside of the constant moment zone may explain the number of cracks in the debonded beams (8) which were higher than expected.

4.3 Extrapolated Beam Deflection from 90 days

In this section, the experimentally developed mid span deflection of the beams under sustained and repeated load were extrapolated to estimate the ultimate deflection. The aim here is again to investigate the use in Eurocode 2 [6] of a single identical parameter to represent both sustained and repeated long term loading (i.e. β=0.5). Adopting the theory of Eurocode 2 [6], it is expected that the ultimate long-term deflection, regardless of load case will be the same. Although the 90 days data gained during this investigation suggests that this will not be the case, the extrapolation below will allow this to be scrutinised. The average deflection curve was extrapolated using the Ross [38] and Lorman [39] hyperbolic creep model as shown below [40]:

$$d(t, t_0) = \frac{(t - t_0)}{A + B * (t - t_0)} \tag{2}$$

Where, $d(t, t_0)$ is the deflection at anytime, *A* and *B* are constants, and $t - t_0$ is the time duration under loading (days)

When $(t - t_0)$ tends to infinity the ultimate long-term deflection will tend to $1/B$. Hence, the ultimate long-term deflection can be found from the experimental results by plotting $[(t - t_0)/d(t, t_0)]$ against $(t - t_0)$. The slope of the straight line will be *B* and the intercept of the ordinate will be *A*. Figure 16 shows the extrapolated developed deflection for the fully bonded beams under sustained and repeated load. The constants *A* and *B* for the beams under sustained loading are 1.0966 and 0.042, respectively, and 0.7901 and 0.0336, respectively, for the beam under repeated load. Thus, the ultimate long-term deflection for the beam under sustained load will be 23.8mm and for the beam under repeated load will be 29.7mm. This finding disagrees with the message presented in Eurocode 2 [6] and suggests that, beams under sustained load are unlikely to have the same deflection as beams subjected to a repeated load.

For the case of the debonded beams of this investigation (Figure 17), the ultimate long-term deflection will be 29.7mm and 31.8mm for the beam under sustained and repeated load, respectively. It can be noted also that the ultimate deflections are the same for FB-REP and UB-SUS (i.e. 29.7mm), which further illustrates that the small amount of frequency applied in this investigation could possibly destroy the bond between the reinforcement and the surrounding concrete, negating any tension stiffening effect. Such an observation is in accordance with the notes of Zanuy [37], where for cyclic load an equivalent negative tension stiffening contribution was conjectured to add to the rest tension stiffening influencing factors.

5 Finite Element Modelling

The nonlinear finite element software Midas FEA, was used to simulate the behaviour of the tested beams. The beam was modelled as a 3D solid model with 20-node quadratic elements. For the long term behavior, "construction stages" were defined in the analysis to allow for the contribution of time-evolving material properties (creep and shrinkage) to be sequentially updated. The concrete was considered as piece-wise elastic in order to activate the relevant (creep/shrinkage) long term embedded function provisions. For the elastic analysis the modulus of elasticity was reduced to 85% based on CEB-FIP 1990 [30], to account for any initial plastic strain. For steel reinforcement, Midas FEA provides a linear/bar reinforcement element, in which specific steel properties need to be defined (perfectly plastic in this case). Beyond geometric and material properties (as per the experiments) it is necessary to define also whether the reinforcement and its "mother" concrete solid elements are perfectly or partially bonded; in all cases a perfect bond was assumed and debonding was modelled through an effective modulus of elasticity reduction (for the specific figures see below).

Daud et al [5] previously proposed that Midas FEA could not predict the shrinkage curvature accurately, as it applies the shrinkage uniformly over each cross section, whether cracked or uncracked and regardless of the reinforcement layout. For this study, and in order to address this limitation, the beam cross-section was divided into two sections (i.e., compression and tension section) as indicated in Figure 18. Beyond information provided herein details on the modelling approach/input can be complemented by these in [5]. Another problem with the software is that it does not allow for the simulation of repeated/cyclic loading effects on the concrete-steel bond. This was solved by reducing the modulus of elasticity in the tension zone to 10% [3]. Such a figure is also in agreement with the work of Castel et al [41], who experienced considerable stiffness degradation.

In the compression zone, all the shrinkage was applied as ordinarily expected, whereas in the tension zone, the amount of shrinkage applied was optimised until the output matched the experimentally measured deflection and the equivalent surface strain. The tension section depth was selected to be twice the cover depth.

Figure 19 shows this resulting numerically modified developed mid-span deflection with time for the case of the bonded beams against the equivalent experimental (FB-SUS) output. Three different values of shrinkage percentages were applied to the tension zone (i.e. 10%, 20% and 30% of the theoretical maximum shrinkage).

Similarly, for the surface strain development within the constant moment zone, Figure 20 shows that this particular modification of the modelling approach now accurately allows the model to better predict the surface strain in both the compression and tension zones.

In order to identify the most appropriate percentage of shrinkage to apply to the tension zone in the software Figure 19 and Figure 20 and Table 4 were produced. From these figures and the comparison shown in Table 4 it can be seen that the application of 20% of the maximum shrinkage should be applied to the tension zone in the software.

A similar approach was adopted for the case of debonded beams. On this occasion, shrinkages of 40%, 50% and 60% were chosen. The higher percentages reflect the lower number of cracks present in the tension zone of the debonded beams and hence the greater amount of concrete that can contribute to the shrinkage curvature. A further modification was also included due to the debonded bar in the constant moment zone. Previously [3], it has been shown that to reflect the internal cracking around the reinforcement in normal bonded reinforced concrete beams, a reduced modulus has to be incorporated in the software for the concrete elements of the model surrounding the steel. Due to the extent of the debonding in these beams, the modulus of elasticity of the concrete surrounding the steel in the tension zone has been reduced to 10% of the normal concrete's actual value.

From Figure 21 and Figure 22 and Table 5 it can be seen that 50% of the true shrinkage needs to be applied to the concrete in the tension zone.

6 Numerical Elimination of Shrinkage Curvature

The change of material behaviour due to time (creep, shrinkage and tension stiffening) was considered inside the analysis above to find the holistic long term behaviour of the reinforced concrete beams. However to eliminate the shrinkage effect out of the analysis, the shrinkage contribution was artificially nullified so that the long term mid-span deflection predictions will be solely due to creep and tension stiffening. Relevant to this, Figure 23 illustrates the mid-span deflection due to creep and tension stiffening for the distinct cases of sustained and repeated loads on identical bonded beams. It can be noted that, there is a much more rapid initial increase in the mid-span deflection in the case of repeated loading. Namely, after 10 days the beam under repeated load had 4.2mm mid-span deflection more than the one with the sustained load. In this sense, the results are in good agreement with Higgins et al [4] where the additional deformations in both tension and compression zones caused by repeated loading mostly occurred within the first 10 days. After this period both beams presented approximately the same deflection development rate.

As the shrinkage was eliminated and both beams had same amount of loading, owing to the previously quoted similarity between fully debonded beams and cyclically loaded beams the 4.2mm deflection could well be envisaged as the tension stiffening contribution on the overall deflection which is about 10% of the overall deflection, as the overall deflection for the fully bonded reinforcement beam under sustained loading was 43.8mm at the end of the test.

7 Conclusions

Four different reinforced concrete beams were used to investigate the effect of load type (sustained/repeated) on the loss of tension stiffening and subsequent deflection behaviour. Using the experimental data as input/comparison to a nonlinear finite element software package the long term behaviour of the tested beams was simulated. The study highlighted that an experimental-numerical match, in terms of deflections and strains, is only possible after introducing modifications related to the concrete shrinkage and modulus of elasticity modelling data. From the combined analysis of numerical modelling and physical testing the following conclusions can be drawn:

1. The bond between concrete and steel in reinforced concrete beams subjected to repeated loads can be significantly damaged by the cyclic nature of the loading. This happens irrespective of the fact that the frequency is relatively low to substantiate any dynamic effects (i.e. 0.2Hz).
2. The additional deformations caused by repeated loading occur 10 to 20 days after the load application (the exact time is likely to depend on the material properties and reinforcement arrangement of the structural element).
3. The long term deformation behaviour of fully bonded reinforced concrete beams under low amplitude and low frequency repeated loading is almost the same as that of reinforced concrete beams with debonded reinforcement. This suggests that, depending on the load type and the steel design service stress, it is possible to remove all tension stiffening from a concrete member.

4. Beams subjected to repeated loads are unlikely to have the same deflection as beams under sustained loads; relevant provisions should be introduced within Eurocode 2 in order to accurately estimate long term deflections under repeated loading.
5. For beams under sustained loading, finite element simulations need to adopt only a fraction of the true shrinkage in the tension zone (20% for bonded and 50% for the debonded scenarios) in order to accurately predict experimental behaviour. For the case of repeated loading, (i.e. similar to the debonded and sustained loading scenario) additionally the concrete modulus of elasticity needs to be reduced to 10%.
6. For the studied cases of this investigation the deflection due to loss of tension stiffening alone is approximately 10% of the overall deflection.
7. The method adopted in this investigation to achieve 100% debonding of the steel from the concrete in the constant moment zone was reasonably successfully; on average, 94% of the bond was lost

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