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NUMERICAL VALIDATION OF LONG-TERM BEHAVIOUR OF REINFORCED RECYCLED AGGREGATE CONCRETE BEAM

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Abstract

This research presents an advanced computational framework for predicting long-term deflection, crack width, and creep recovery in reinforced concrete beams incorporating recycled aggregate. The study employs a sophisticated nonlinear finite element analysis using Diana FEA software to construct three distinct models based on widely adopted design codes, i.e., Eurocode 2 EN 1992-1-1, fib Model Code (2010), and ACI 209R-92. The numerical models were rigorously validated through comparative analysis with extant experimental data, with a specific focus on examining the effects of creep, shrinkage, and loss of tension stiffening on long-term deflection, crack width, and creep recovery. This investigation specifically addresses the calculation of long-term deflection, crack width, and creep recovery in recycled aggregate concrete beams subjected to sustained loading over a 3000-day period. The study findings indicate that the fib Model Code (2010) is the most reliable for predicting long-term deflection, crack width, and recovery phenomena, consistently aligning closely with experimental results. In contrast, Eurocode 2 EN 1992-1-1 tends to overestimate deflections during early loading. While ACI 209R-92 shows lower error percentages initially, it significantly underestimates deflections by the end of the loading period.

Keywords:

Long-Term Deflection;
Recycled Aggregate Concrete;
Non-linear Analysis;
Diana FEA. Creep Recovery

1. Introduction

Concrete is the most widely used structural material in all types of construction projects. Each year, around 10 billion tons of concrete are utilized globally [1]. The increasing demand for concrete presents two significant concerns: the depletion of natural resources required for its production and the extensive landfill space needed for disposing of construction and demolition waste. Consequently, concrete is not considered an environmentally friendly construction material. Concrete structures generally endure for many decades, yet their demolition can occur unexpectedly due to structural decay, material deterioration, natural disasters, urban development, or wartime destruction. The Environmental Protection Agency (EPA) has recently approximated that construction and demolition activities, along with building renovation, yield approximately 170 million tons of debris annually in the United States [2]. According to the European Environment Agency (EEA), construction and demolition activities, including building renovation, generate approximately 850 million tons of debris annually in the European Union (EU) [3]. A large number of research studies were conducted to assess the use of CDW as recycled aggregate (RA) in producing concrete made with recycled aggregate concrete (RAC) for structural purposes [1,4,5]. There is limited research on the prolonged performance of RAC; the long-term behaviour is determined by three major phenomena: shrinkage, creep, and loss of tension stiffening [6,7,8]. Non-linear finite element analysis (FEA) is a key method for evaluating the performance of reinforced concrete structures under different loads and periods [6]. One of the significant advantages of FEA is its versatility. It can model complex geometries, account for varying material properties, and simulate diverse loading conditions [9,11].

Extant literature examining the comparative behaviour of RAC and conventional normal concrete has yielded significant insights into their respective structural performances. A corpus of investigations [12, 13] has consistently demonstrated that the incorporation of RA into concrete mixtures engenders notable alterations in beam behaviour. Specifically, these studies have elucidated a pronounced tendency for RAC beams to exhibit augmented deflection characteristics relative to their normal concrete counterparts. Understanding how different factors affect RAC structure's flexure behavior is crucial for predicting long-term deformation and crack propagation. While experimental studies are important, they can be time-consuming and may not fully capture structure behavior. The finite element model provides a more efficient way to study structure by breaking down large, complex structures into smaller ones, allowing for accurate predictions of structural behavior, considering factors like temperature, humidity, and sustained stress conditions, and serves as an indispensable tool for simulating and analysis structure response, offering an alternative method to empirical testing [14]. many studies employed FEA to model reinforced concrete and predict the long-term behavior by focusing on capturing the effects of non-uniform shrinkage, and creep [15,17].

This study aims to develop a comprehensive computational framework for accurately predicting long-term deflection and crack width in RAC beams. Utilizing the nonlinear finite element method and the commercial software Diana FEA, the research constructs two models based on three widely used codes: Eurocode 2 EN 1992-1-1, fib Model Code (2010), and ACI 209R-92. These models are validated by comparing their results with experimental data from previous studies [12,13], highlighting inherent drawbacks and limitations.

2. Experimental Overview

A numerical model was developed to simulate two prior experimental works. The first experimental study, conducted by Sryh et al. [12], involved casting three reinforced beams with varying RA content (0%, 50%, and 100%). All beams were identical in size: 300 mm in width, 150 mm in depth, and 4200 mm in length. The beams were reinforced with the same longitudinal and shear reinforcement: 2Ø12 at the top and 3Ø16 at the bottom, with Ø8 stirrups spaced at 150 mm intervals, as detailed in Figure 1. A constant load of 23 kN was applied for 90 days. One beam with 100% RA was selected for the numerical modeling. Table 1 presents the mechanical properties of the concrete and steel reinforcement obtained from the experimental study.

The second experimental study, was carried out by Zhu et al. [13]. Their test included casting of three reinforced concrete beams with different RA replacement levels (0%, 50%, and 100%). These beams measured 130 mm in width, 260 mm in depth, and 2000 mm in length. The reinforcement details and material properties are provided in Table 2 and illustrated in Figure 2. A constant load of 57.5 kN was applied for 3045 days. A beam with 100% RA was chosen to validated the numerical model.

Table 1A: Mechanical characteristics of concrete [12]

Specimen	f_{CU} [MPa]	f'_c [MPa]	f_{ft} [MPa]	E_c [MPa]	f_{spt} [MPa]
NC	51.6	41.5	5.3	30,600	4.2
RAC-50% (selected)	49.2	39.0	4.8	25,200	3.7
RAC-100% (selected)	47.3	37.4	4.3	22,500	3.2

Compressive strength for cubic (f_{CU}); Compressive strength for cylinder(f_c'); Flexure tensile strength (f_{ft}); Modulus of Elasticity (E_c); Splitting strength (f_{spt}).

Table 1B: Mechanical characteristics of steel [12]

Reinforcement Diameter(mm)	Young's Modules	Yield Strength	Units
8, 12, 16	200,000	500	N/mm^2

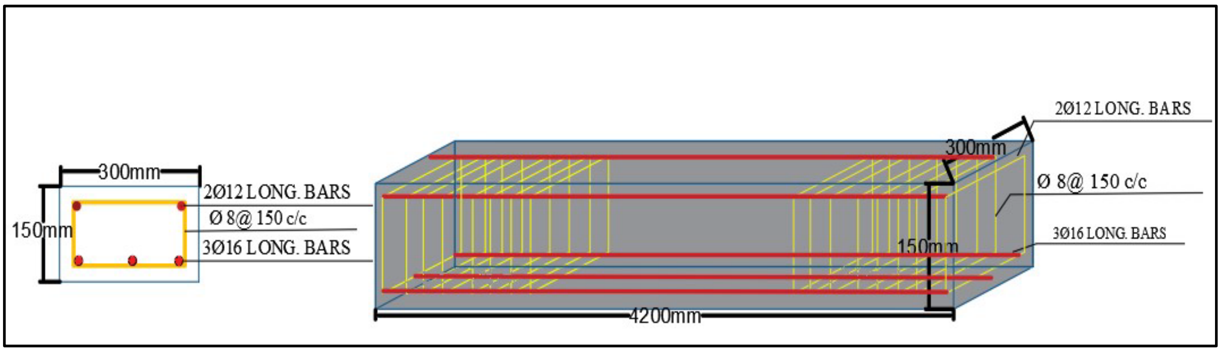


Figure 1: Details of the RAC beam (50 and100%) RA ratio from the first experimental study [12]

Table 2A: Mechanical characteristics of concrete [13]

Specimen	Slump	f_{CU} (Mpa)	E_c (Mpa)
RBF-L-0	67	34.0	32,000
RBF-L-50	48	31.7	30,000
RBF-L-100 (selected)	39	31.7	28,000

Compressive strength for cubic (**f_{CU}**); Modulus of Elasticity (**E_c**).

Table 2B: Mechanical characteristics of steel [13]

Reinforcement Diameter(mm)	Young's Modules	Yield Strength	Units
8	210,000	321	N/mm^2
14	200,000	408	N/mm^2

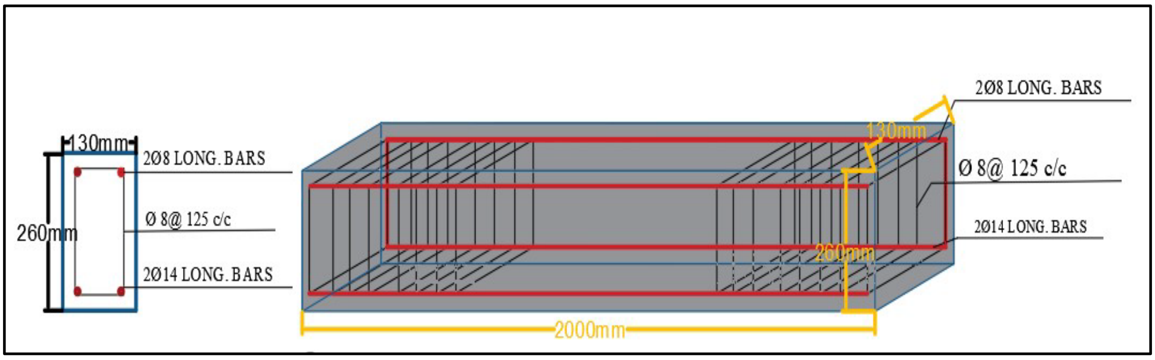


Figure 2: Details of RAC beam (100%) RA ratio from second experimental study [13]

3. Finite Element Analysis (FEA)

FEA is a potent numerical technique for predicting how structures respond to various loading. By dividing complex structures into smaller elements, FEA enables detailed calculations of stress, strain, and deformation [18]. When analysing the nonlinear responses of structures under long-term loading, factors such as creep, shrinkage, and loss of tension stiffening cause significant stress redistribution within the concrete, leading to crack propagation and deflection [19].

Diana FEA software is well-known for its ability to conduct a nonlinear FEA, offering a wide range of complex element models. These models can be used in non-linear analysis by selecting the right solution technique and material characteristics [20].

One of Diana‘s most notable attributes is its comprehensive suite of material models, which facilitate the accurate simulation of complex mechanical behaviour [20]. This software package offers a diverse array of constitutive relationships, enabling researchers and engineers to effectively capture the nuanced responses of various materials under diverse loading conditions.

3.1 Geometry Modelling

The nonlinear finite element modelling process requires several steps to ensure the integrity of the structure as represented in Figure 3. A three-dimensional model was created, and only one-half of the beam was represented due to its symmetrical shape. A rectangular shape with a length of 2100 mm in the X-direction, 300 mm in the Y-direction, and 150 mm in the Z-direction, which represented the first expermintal study conducted by Sryh et al. [12]. The same methodology was used for the second expermintal study conducted by Zhu et al. [13]. For identifying the boundary conditions, two types of support were used to restrict the model. The first support was drawn as a line and projected on the bottom surface of the beam at 100mm from the edge, restricting in the (Y and Z direction), and the second support was identified as fixed support on the other side of the beam (due to symmetrical shape) and restricted from X-direction. The load was placed as a concentrated force on the top surface of the beam.

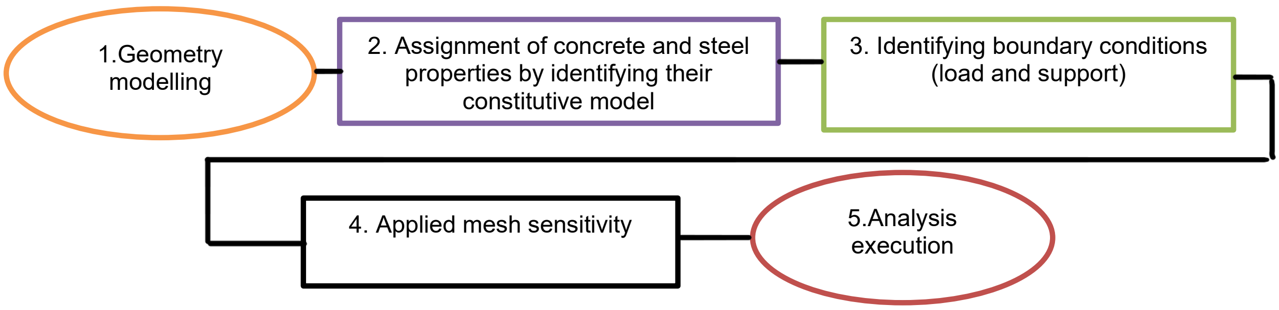


Figure 3: The flowchart summarizes the operation of the numerical model

3.2 Concrete Constitutive Model

This study utilized the fib Model Code 2010, Eurocode 2 EN 1992-1-1, and American ACI 209R-92 in Diana FEA software, to accurately represent the concrete ability characteristics including the effect of creep, shrinkage, and loss of tension stiffening.

3.2.1 Fib Model Code (2010)

In accordance with the fib Model Code (2010), the analysis of tensile behaviour was conducted by incorporating a tension-softening function. These constitutive relationships were implemented to simulate the post-cracking response of reinforced concrete members subjected to tensile stresses. The adopted tension softening model, as depicted in Figure 4A [21], characterises the progressive degradation of tensile capacity following crack initiation. This model incorporates fracture energy-based functions to simulate the tensile behaviour of reinforced concrete members within the total strain crack model. For compression behaviour, the fib Model Code (2010) specifies a predetermined compressive behaviour curve as illustrated in Figure 4B [21]. When the concrete strength reaches the point where it intersects with the inflection and convergence, and the value is sufficiently small, it decreases to zero, along with the horizontal coordinate values of strain (εcu). After that, there is a horizontal straight line on the coordinate axis. In representing creep and shrinkage, the fib Model Code (2010) accounts for the impact of these phenomena on long-term performance by incorporating automatic modeling of creep and shrinkage. The behaviour depends on input factors such as ambient temperature, member size, relative humidity, and element age. The model's approach to creep and shrinkage is characterized by Diana FEA using Maxwell chains for non-aging curves and Kelvin chains for aging creep curves [21].

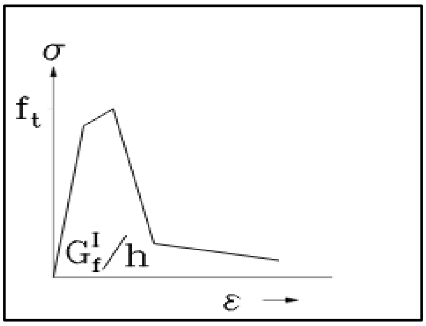


Figure 4A: Concrete tensile behaviour according to fib Model Code (2010)

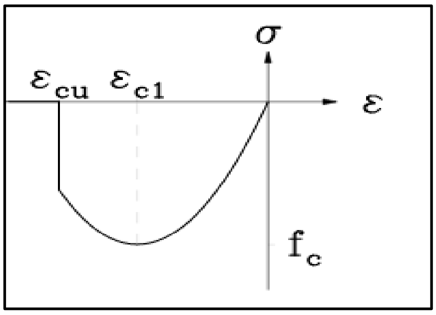


Figure 4A: Concrete compression behaviour according to fib Model Code (2010)

3.2.2 Eurocode 2 EN 1992-1-1

The analysis of the tensile behaviour according to Eurocode 2 EN 1992-1-1 is modeled by a total strain rotating cracked model which is cosidered as brittle concrete. While defining the compressive behaviour of concrete considering a parabolic-rectangular stress-strain curve, as the Eurocode 2 EN 1992-1-1 predefined compression curve. This curve captures the non-linear behaviour of concrete in compression, which is characterized by an initial linear portion followed by a nonlinear increase until it reaches the peak compressive strength, and then a descending branch that represents the post-peak softening behaviour. Both tensile and compressive behaviour are depicted in Figure 5. Regarding creep and shrinkage, models are similar to those in fib Model Code (2010).

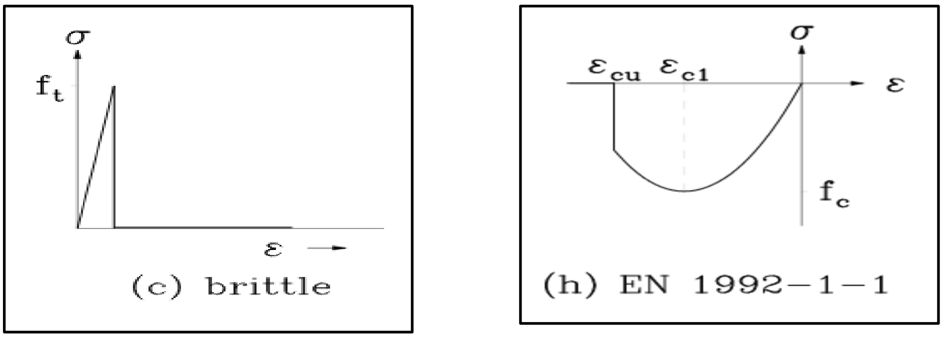


Figure 5: Concrete stress-strain diagram according to Eurocode2 EN 1992-1-1

3.2.3 American ACI 209R-92

For the tensile behaviour, the ACI 209R-92 code adopted a total strain fixed crack Model, which is used to simulate how concrete cracks under tension. In this model when the tensile stress in a concrete element reaches the tensile strength of the material, a crack is formed and stress reduction, in ACI 209R-92 considers tensile behaviour as brittle. while compressive behaviour employs the predefined ideal behaviour. This model represents concrete's compressive strength increasing gradually until it reaches its peak stress after cracking. Subsequently, the strength curve shows a continuous and linear trend. Both tensile and compressive behaviour are depicted in Figure 6.

The creep and shrinkage modeling approach in ACI 209R-92 shares similarities with the fib Model Code (2010) and Eurocode 2 EN 1992-1-1, using both the creep function and the generalized Kelvin model.

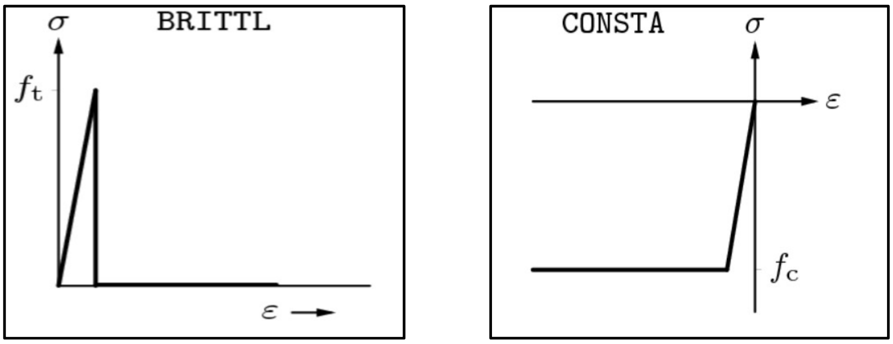


Figure 6: Concrete stress-strain diagram according to ACI 209R-92

3.3 Reinforcement Constitutive Model

The method chosen for steel components in this study involved Diana's embedded reinforcement feature, which eliminates the need for manual bonding interface elements between reinforcement and concrete by specifying reinforcement details, including young modulus, cross-sectional area, spacing, and diameter. For nonlinear calculations, von Mises plasticity is selected as the constitutive model for steel reinforcement, incorporating plastic-yielding characteristics. Longitudinal reinforcement, and stirrups, were simulated in Diana FEA with automatically embedded reinforcement types using reinforcement bars. Reinforcement elements could simply couple with any type of surrounding mother concrete elements, according to the known embedding concept, indicating that only mother concrete elements as well as embedded reinforcement may improve rigidity. This prevents a need for users to manually determine bond interface elements among reinforcement and concrete.

3.4 Mesh Modeling

Two types of mesh options in Diana FEA and based on the degree of convergence of nonlinear computation, the preference is given to selecting quadratic/hexagonal elements (20 nodes for 3 dimensions).

3.5 Analysis Method

Diana FEA contains wide options for analysis, but in this study, non-linear analysis is chosen as it includes the effect of cracking behaviour and long-term behaviour. A maximum number of 50 iterations was set for achieving equilibrium. The force was selected as the Convergence norm, while convergence tolerance and Abort criterion were 0.01 and 10,000 respectively.

3.6 Recovery Phenomena

Recovery refers to the process where material gradually returns to its original state (strain decreases) after removing the sustained load [22]. In Diana FEA, recovery phenomena are typically modelled as part of the viscoelastic material behaviour.

Diana FEA uses combinations of Maxwell and Kelvin chains to model viscoelastic behaviour, including both creep (deformation over time under constant stress) and recovery (reduction in deformation after the removal of stress).

In a Maxwell chain, when the stress is removed, the spring returns to its original length, leading to some immediate recovery. However, the dashpot (which represents viscous flow) can prevent complete recovery, especially if significant plastic deformation has occurred. while in Kelvin Model both the spring and dashpot work together to gradually reduce strain over time when the load is removed. This model tends to better capture time-dependent recovery.

Diana FEA numerically integrates the constitutive equations governing the behaviour over time.

- During load application, the software calculates how the strain evolves under the applied stress.
- When the load is removed, the same numerical methods are used to calculate how the strain reduces over time as the material recovers. And the material's stress-strain state is continuously updated as the load changes, when transitioning from a loaded state to an unloaded state [21].

3.7 Validation of First Expermintal Study

3.7.1Validation of Developed Deflection According to Various Codes

The numerical validation process simulating beams with 100% RAC was based on the initial experimental study conducted by Sryh et al. [12]. To evaluate the efficacy of the analysis model in predicting long-term behaviour, Three codes are used: fib Model Code (2010), Eurocode 2 EN 1992-1-1, and ACI 209R-92 code, the experimental deflection curves were compared with the corresponding predictions obtained from the numerical model results under 90 days. As shown in Figure 7, according to fib Model Code (2010), the developed deflection increases over time almost consistently, indicating that the FEA model can effectively simulate long-term behaviour. More specifically, the developed deflection beam under sustained load shows an error of 6.5%, While it accurately predicates the deflection over time, it tends to have a small overestimation at an early age, this is due to the Diana FEA overestimating the effect of creep and shrinkage deflection at an early age which led to overestimating the impact of total deflection [23].

While Eurocode 2 EN 1992-1-1 tends to overestimate deflection by 15% over 90 days due to considering the concrete's tensile behaviour as brittle, leading to increased deflection. Conversely, the fib Model Code considers tension stiffening, resulting in a more acceptable error, and takes into account the effect of creep, shrinkage, and loss of tension stiffening separately, as well as identifying the type of aggregate, distinguished from recycled from natural aggregate concrete. While ACI 209R-92 code underestimates the developed deflection by up to 30% during 90 days due to its reliance on a simplistic equation that overlooks crucial factors like concrete creep, shrinkage, and environmental conditions[22,24]. Additionally, the multiplier factor in the ACI 209R-92 code does not account for the loss of tension stiffening over time caused by shrinkage or crack propagation. Utilizing a single-parameter formula to calculate the long-term deflection of reinforced concrete members may not yield precise results [25]. By comparing Eurocode2 EN 1992-1-1 with the ACI0209R-92 code, it becomes evident that Eurocode 2 EN 1992-1-1 is often deemed more acceptable behaviour. This is because Eurocode 2 EN 1992-1-1 accounts for the creep and shrinkage effect separately.

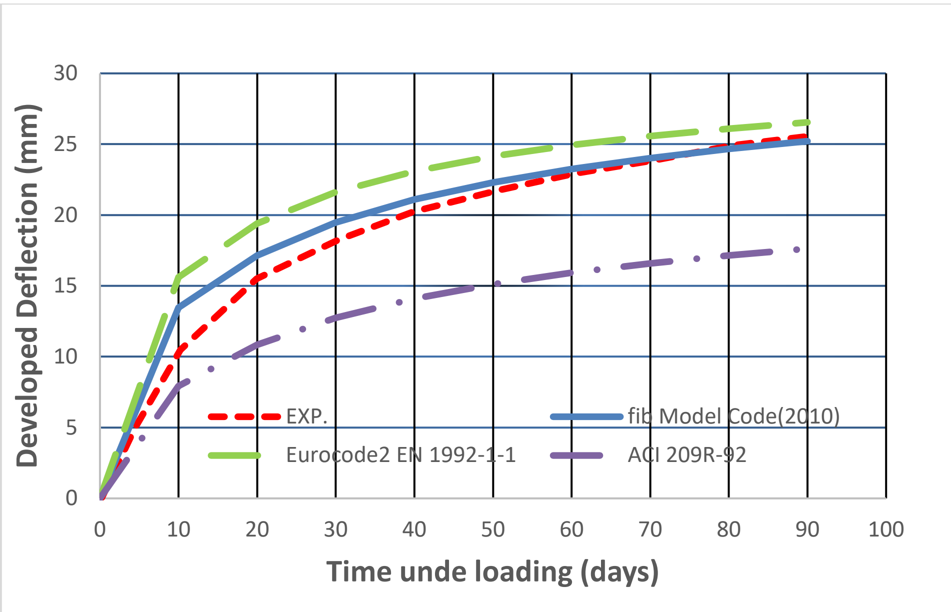


Figure 7: Developed mid-span deflection of RAC beam with time using (fib Model Code (2010), Eurocode2 EN 1992-1-1, ACI 209R-92, VS experimental results)

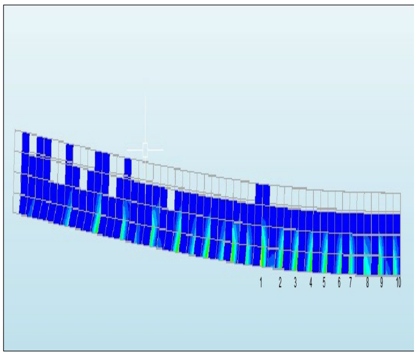
3.5.1 Validation of Crack Width

According to the validated model, the analysis included validating the crack width values of the same specimen with various codes. As detailed in table 3 the experimental finding showed a crack width of 0.20 mm at the first day of loading, increased to 0.30 mm after 90 days. The comparison between codes showed that the fib Model Code (2010) provides the most accurate predictions for both initial and long-term crack patterns. The predicted cracks width are closely aligned with the experimental results, where, an initial crack width of 0.17 mm and 0.29mm at 90 days suggests that the fib Model Code (2010) can capture the initial and long-term behaviour of crack width accuracy.

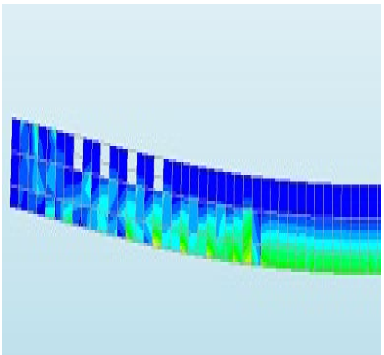
Eurocode2 EN 1992-1-1 predicts significantly lower crack widths of 0.09 mm and 0.15 mm, which is less than half of the experimental measurements. Similarly, the ACI 209R-92 predicts even lower initial crack widths of 0.08 mm and 0.11 mm. In situations where controlling crack width is particularly important, the fib Model Code (2010) may offer a more accurate assessment. Unlike Eurocode 2 EN 1992-1-1, and ACI 209R-92. Additionally, the Fib Model Code (2010) shown to accurately predict the number of cracks at midspan, as evidenced by experimental results presented in figure 8. The inability of Eurocode 2 EN 1992-1-1 and the ACI 209R-92 Code to accurately predict the number of cracks could lead to an incomplete or less precise understanding of crack behaviour in concrete beams, potentially affecting the overall structural performance assessment.

Table 3: Validation of crack width

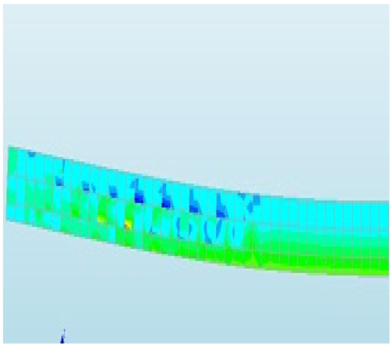
Duration	Exp. Crack width (mm)	Fib. crack width (mm)	EC2 crack width (mm)	ACI crack width (mm)
At first days	0.20	0.17	0.09	0.08
At 90 days	0.30	0.29	0.15	0.11



Fiure 8 A: Cracks according to fib Model Code(2010)



Fiure 8 B: Cracks according to Eurocode2 EN 1992-1-1



Fiure 8 C: Cracks according to ACI 209R-92

3.6 Validation of Second Experimintal Study

3.6.1 Validation of Total Deflection

The second case study, conducted experimentally by Zhu et al. [13], followed a methodology similar to the first study by employing Diana FEA to analysis the long-term deflection of RAC beams. Three codes were utilized for comparison: the fib Model Code 2010, Eurocode 2 EN 1992-1-1, and ACI 209R-92. The experimental total deflection curves were compared with predictions from the numerical model results over 3045 days. As illustrated in Figure 9, the total deflection predictions according to the fib Model Code 2010 increase steadily over time, demonstrating the FEA model's capability to effectively simulate long-term behaviour. Specifically, the beam under sustained load shows a deviation of only 5%, ensuring the accuracy of the fib Model Code 2010 in predicting both initial and long-term deflection. In contrast, Eurocode 2 EN 1992-1-1 overestimates the total deflection at an early age with an error of

15%, though this error decreases to 8% at 3045 days. The ACI 209R-92, on the other hand, underestimates the total deflection by 12%. These results highlight the fib Model Code 2010 superior ability to predict initial and long-term deflection more accurately compared to Eurocode 2 EN 1992-1-1 and ACI 209R-92.

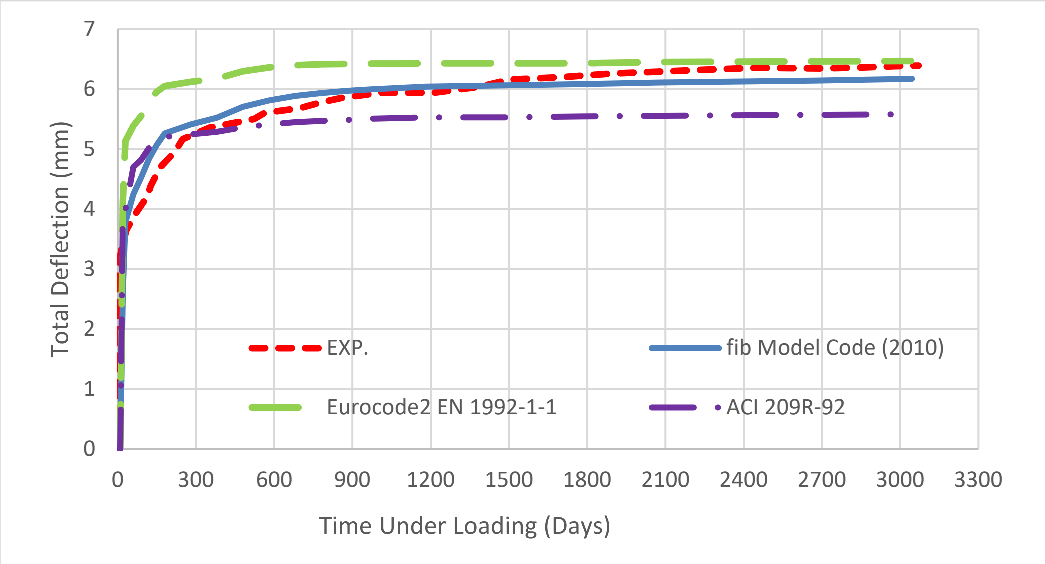


Figure 9: Comparing the total deflection between FEA results with experimental data

3.6.2 Validation of Recovery Phenomena

The prediction of creep recovery in concrete structures is essential for accurate long-term performance. Creep recovery is the reduction in deformation when a sustained load is removed[24], and is influenced by various factors such as material property, environmental condition, and loading history. Three structural design codes were used to compare the predictions of creep recovery which is fib Model Code (2010), Eurocode2 EN 1992-1-1, and ACI 209R-92. From the second experimintal study, after removing the sustained load, the recovery phenomena (both initial and creep) were observed and calculated from the two days and compared with the results obtained from FEA software. As shown in table 4, the fib Model Code (2010) is the most accurate in predicting the creep recovery phenomena. It provides predictions that are closest to the experimental result, with minor overestimation ranging (5.2-9.5%) that are acceptable. The consistent performance of the fib Model Code (2010) across both days demonstrates its reliability and effectiveness in capturing the creep recovery behaviour of concrete structures. In contrast, the Eurocode2 EN 1992-1-1 consistent underestimation and the ACI 209R-92 significant initial underestimation highlight the limitations of these codes in accurately predicting creep recovery.

Table 4: Total deflection recovery

Total Deflection	Δ1 mm	Δ2 mm	Δ1- Δ2 mm	Δ3 mm	Δ1- Δ3mm
Experimental	6.39	2.93	3.45	2.85	3.53
Eurocode2 EN 1992-1-1	6.55	3.70	2.85	4.12	2.43
fib Model Code (2010)	6.24	2.60	3.64	2.36	3.87
ACI 209R-92	5.60	5.22	0.38	1.69	3.91

Δ1: represents the long-term deflection of the final result. Δ2; represents the immediate value after the removal of the load. Δ3: value after two days of unloading.

3.7 Conclusion

In this numerical validation study, the focus was on examining two RAC beams, each with different reinforcement levels and applied loads. The main aim was to compare experimental results with predictions from the FEA model designed to forecast deflection. The analysis was carried out using Diana FEA software and incorporated three different structural design codes: fib Model Code 2010, Eurocode 2 EN 1992-1-1, and the American Concrete Institute (ACI) 209R-92 code. The goal was to evaluate and compare the precision of these codes in predicting long-term deflection behaviour. The following conclusions can be drawn from the study.

1) The nonlinear finite element models demonstrate the ability to accurately predict the long-term deflection of RAC beams.

2) Eurocode 2 EN 1992-1-1 overestimated deflections by 15% after 90 days of sustained loading in the first experimental study and initially overestimated deflection by 15%, reducing to 8% by 3045 days in the second study. Conversely, the ACI 209R-92 underestimates deflection by 30% and 12% in the first and second experimental studies, respectively. The overestimation in Eurocode 2 EN 1992-1-1 and the underestimation in ACI 209R-92 are attributed to their use of Diana's recommended total strain cracked model, which is considered too brittle for simulating concrete tensile behaviour. Additionally, Eurocode 2 EN 1992-1-1 considers a higher safety margin, while ACI 209R-92 code calculating long-term deflection, which relies on a simple multiplier, lacks precision and fail to consider all relevant factors, including the effect of tension stiffening.

3) The fib Model Code (2010) proves to be more reliable than other codes in predicting long-term deflection, consistently showing superior alignment with experimental results within an acceptable error range of 5% to 6.5%. This accuracy is due to the fib Model Code (2010) advanced concrete tension models and its comprehensive methodologies for calculating long-term deflections, which account for factors such as creep, shrinkage, and tension stiffening effects.

4) The fib Model Code (2010) delivers the most accurate predictions of crack width, both initially and over the long-term loading, closely matching the experimental results. It also accurately predicts the number of cracks. In contrast, Eurocode 2 EN 1992-1-1 and the ACI 209R-92 Code do not accurately predict the number of cracks, which can affect the overall assessment of crack behaviour in concrete beams.

5) The fib Model Code (2010) consistently performs well in capturing the creep recovery behaviour of concrete structures with minor overestimation ranging (5.2-9.5%), demonstrating its reliability and effectiveness over time. In contrast, Eurocode 2 EN 1992-1-1 and ACI 209R-92 consistently underestimate creep recovery highlighting the limitations of these codes.

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