Cracks Performance of Lightweight Concrete Beams

Nabaa Safaa Hussein (1) Sultan A. Daud (2)

[1]MSC Student. Civil engineering department, college of Engineering, Al-Nahrain University, Baghdad, Iraq.

[2]Assistant Professor, Civil engineering department, college of Engineering, Al-Nahrain University, Baghdad, Iraq.

Abstract

Creep, shrinkage and loss of tension stiffening are the main factors that effect the long-term behavior of reinforced concrete structures. This study aims to investigate numerically the long-term behavior of lightweight concrete beams under sustained loads. A nonlinear finite element software (Diana FEA) was used to simulate the experimental results and it was found that, Diana FEA predicts the long-term behavior of normal and lightweight concrete beam accurately. Also, the loss of tension stiffening is almost twice in LWC beams than that in NWC beams.

Keywords: Lightweight concrete, Long-term deflection, Loss of tension stiffening Diana FEA.

Introduction

Lightweight Concrete (LWC) is a versatile material that can be used for various application such as panel and block construction, wall and full house casting, sound barrier walls and many other applications. LWC is typically required to reduce construction costs, improve efficiency, or to reduce the dead wight of the structure. The structural LWC density is lower than that on normal concrete (15-40%). Whereas the LWC compressive strength could be equal to that achieved by Normal Weight Concrete (NWC) (Clarke, 2002, Alallaf 2016).

The splitting tensile strength of LWC gradually decreases as the lightweight aggregate content rises from 30% to 60%, according to Gesoglu, et al**.** Also the tensile strength of LWC is lower than that for NWC as its cohesion between aggregate particles and the paste is less compared to CC with the same compressive power**.** Al-Khaiat & Haque, founds that, the tensile strength elastic modulus and rupture modulus of LWC to be 80% less than that obtained from NWC for a period of 9 months. In 2011, Alengaram found that, the workability of LWC was higher compared to NWC if the LWC have the same strength but 20% less density than NWC. By replacing 60% of the volume of aggregates with Expanded Polystyrene EPS beads, sandwich panels of lightweight concrete could be made and that suggested only for non-load bearing walls which can provides a good thermal insulation and reducing the self-weight ,also mixing 40% of coarse aggregate with 60% of EPS beads gives a compressive strength and flexural strength of 13.73 N/mm2 and 0.57 N/mm2 respectively ,also they can reduces the self-weight and thermal conductivity in a percent of 25.7% and 25.3%,respectively. (Sivakumar.C. G. & Naga Priya.S, 2021)

The behavior of reinforced concrete members is influenced by creep and shrinkage over time, mainly in cracked members. tension stiffening relationships is linked with creep and shrinkage effects (Eigelaar, 2010).

Liu at al., (2007), Haranki (2009) and Gambhir (2013) found that, creep affected by many factors such as the concrete age, the applied load amplitude, raw material characteristics. Gilbert & Ranzi, in 2010, reported that when the aggregate content or the maximum size of aggregate increase and\or water\cement ratio decreases, the concrete resistance to creep will be decreases.When the creep coefficient and shrinkage increasing or decreasing in a percent of 20%, only 6% of final LWC deflection will be decreased or increased (Birjandi & clarke,1993). In 1999, Kayali et al., studied the drying shrinkage of fiber-reinforced lightweight aggregate concrete containing fly ash as 23% of the total cement paste content, they showed that when the LWC has the same compressive strength of NWC, the drying shrinkage for LWC will be doubled its value for NWC, but the early shrinkage is similar to that of NWC the same. The LWC shrinkage cracking is less than that for CC. Also, higher shrinkage was obtained during the first 50 days when the mixture comprises higher aggregates volume. according to w\c ratio effect, shrinkage increases as w\c ratio increases. (Gesoglu et al., 2004). Tension stiffening is anther factore that effecting the long-term behaviour of concrete structure. Tension stiffening is the concrete ability to withstand stresses even after cracking. It was previously showed that, 50% of the loss of tension stiffening of the normal concrete beams take place in the first 20 to 30 days (Scott and Beeby 2005). Moreover, Higgins et al. (2013) and Daud et al., (2018) mensioned that, for the case of repeated laod, the extra defection take place in the first 10days. Daud et al., (2021-a) found expermently that, 9% to10% of the overall deflection of the noramal concrete beams is due to the loas of tension stiffening. Although the loss of tension stiffening of normal concrete has been investegated (Daud et.al 2021-a)**,** further areas of research have not been conducted yet. In this paper, the long-term behaviour of lightweight concrete beams under long-term loads was investigated numerically using Diana FEA. Followed up by a parametric study to get a general understanding on the environmental conditions that effect the overall behaviour.

Experimental Overview

A previous work was done by Wang, et al., in 2020 which studied the long-term performance of lightweight aggregate reinforced concrete beams (16 large scale LWC beams and 1 control NWC beam) was selected in this paper to be simulated. All 17 beams

with different geometries were tested after 30 years to study the long-term behavior of them. Beams 1 to 13 were rectangular beams having length of 3200mm, width of 120mm and depth of 240mm, while beams 14 and 15 were inverted T-beams having 60mm deep bottom (tension flange) and width of 480, 240mm respectively. and beam 17, 18 were T beams with 60 mm deep flange and 480, 240 mm wide respectively. All beams have two primary bars in tension zone and two bars in compression zone (to support the shear reinforcement of 6mm bars spaced at 150mm, ($\rho = 0.003$) with the same diameter as tension bars. only beams (10-11-12-13) have two continuous compression bars which made them doubly reinforced beams as shown in Figure 1.
Beam 5 have (plain smooth) primary bars with a measured tensile strength of 265 MPa, all other beams have a deformed reinforcing bars with a nominal yield capacity of 345 MPa. The average measured tensile strength was 386 MPa.

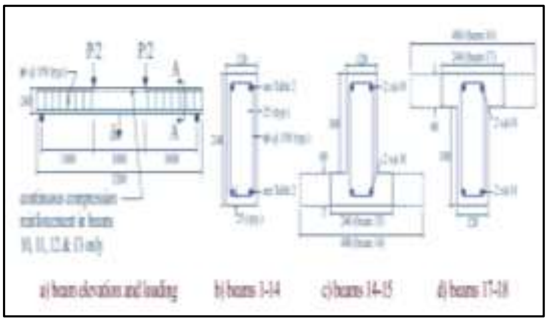

Figure 1: Specimen Geometry and Reinforcing Details

Finite Element Modelling

A nonlinear finite element (Diana FEA) was employed to reflect the long-term behavior of reinforced lightweight aggregate concrete beams. The validation of the current numerical model was achieved by using data published by Wang, et al. (2020). Total Strain Crack was the constitutive model used to represent the concrete in this work. Where concrete after cracks in this model will be treated as a new material. Whereas, for nonlinear calculation, Von Mises plasticity with plastic-yielding properties is chosen as steel material constitutive model (Daud et. al 2021-B). Also, for steel plates, Linear elastic isotropic model is chosen. concret is model according two design codes i.e. Eurocode 2 and Fib Model Code, each of them have a specific compressive and tensile behaviours. Solid elements and interface elements are the selected element types for concrete and the interface between concrete and steel plates, respectively. While for the reinforcement and the stirrups, embedded reinforcement type is automatically selected by Diana FEA. The number of elements and mesh size was chosen according to a sensitivity studying. the Hexa/Quad mesh type is used, as it is suggested by the manual to use this type of elements to mesh large scale concrete structures. Related to number of elements, the lower element size gives better and closer behavior to the experimental one. Also for time consuming 50mm element size found to be the appropriate one (see Figure 2).

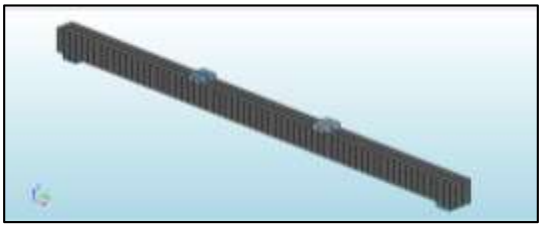
Figure 2: Diana FEA Model Concrete Mesh

Numerical Validation

As the modern codes cannot consider the influence of all variables with their provided analytical models, the use of finite element method is proceeds, to examine the deterministic nonlinear response of reinforced concrete structures. (Daud et. al 2021-C)
In this study , a numerical solutions was developed for the experimentally tested beams to estimate carefully the long-term deflection of the chosen LWC beam and the NWC one with the use of finite element analysis (FEA) software. The obtained numerical results are compared with the experimental results for the same beams. The FEA was carried out using the Diana FEA program. By specifying a solution approach and material characteristics, the software creates complicated material models that may be incorporated into non-linear finite element models.
Only two beams (1 and 3) were analyzed with Diana FEA using two design codes i.e., Eurocode 2 and Fib Model Code. Results shows that, for NWC (beam 1) in general, It can be also seen that, both Eurocode 2 and Fib Model Code 2010 overestimates the results over the 20 years. However, Fib Model Code 2010 overestimated the developed deflection within only 5% error. Whereas 13.5% was the error that Eurocode 2 overestimated the developed deflection. This could be explained by the tensile behavior of the concrete that the Eurocode 2 adopted (concert is brittle). While in Fib Model Code 2010 tensile behavior consider the effect of tension stiffening. As shown in Figure 3. Also, there is a surface strain development with time although the applied load was kept constant. This strain development is due to the creep and shrinkage. Where shrinkage induces stresses in the concrete. As shown in Figure 4.

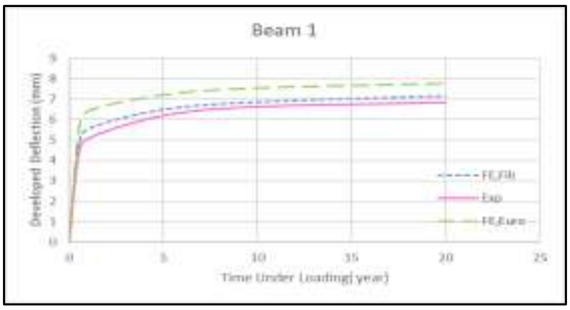

Figure 3: Developed Mid-Span Deflection of Beam 1 with Time (FE Fib Model Code, FE Eurocode 2, Experimental Results)

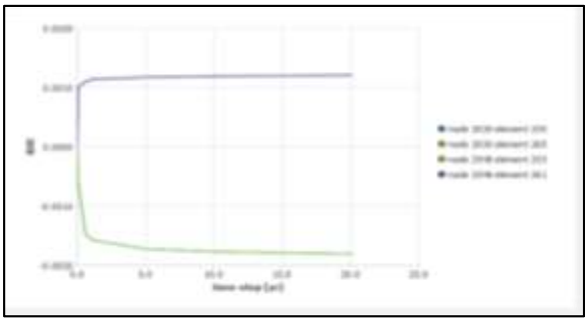

Figure 4: Surface Strain Development of Beam 1 in The Compression and Tension Zone

For LWC beam, Figure 5 compares the time dependent behavior of LWC (beam 3) simulated by Diana FEA with the experimental results. Results showed that, both Eurocode 2 and Fib Model Code 2010 overestimates the results over the 4 years. After that Fib Model Code 2010 gives closer underestimation to the experimental results with an error percent of 0.02%, while Eurocode 2 gives underestimated results with an error percent of 8.7% over the 20 year. Similar to beam 1the surface strain development with time of beam 3 in compression and tension zone is presented in Figure 6. Which shows that the surface strain development of LWC beam 3 is more than that for NWC beam1 due to its larger deflection. Also, the surface strain is higher in tension zone that on compression zone.

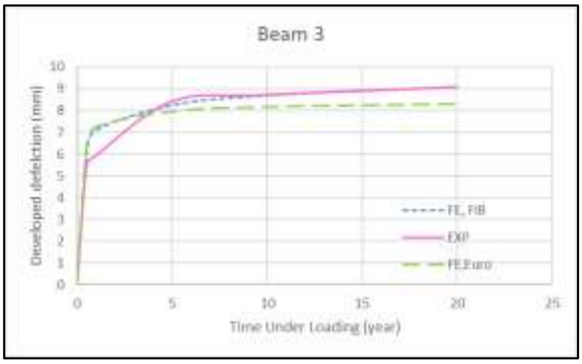

Figure 5 : Developed Mid-Span Deflection of Beam 3 with Time (FE FIB Model Code, FE Eurocode 2, Experimental Results)

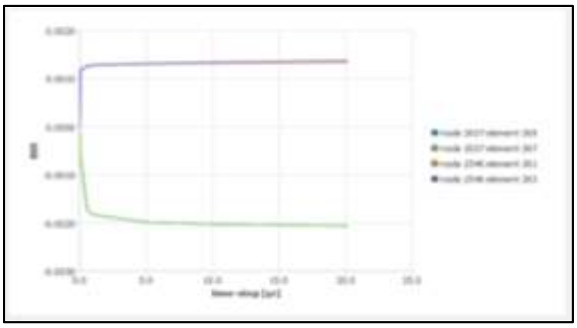

Figure 6: Surface Strain Development of Beam 3 in The Compression and Tension Zone

Loss of Tension Stiffening in LWC

Loss of tension stiffening is one of factors that can affect the propagation of deflection with time, The loss of tension stiffening is incorporated in both the calculation of the creep and shrinkage curvature. However, to represent the percent of loss in tension stiffening effect from the total deflection, Diana FEA is used with eliminating the effect of creep and shrinkage from the overall deflection.

Form figures 7 and Figure 8 ,Its found that 13% of tension stiffening is lost over the first 6 months concerning the NWC beam ,which is agreed with **(Daud et al. 2018)(20)** finding i.e. the deflection due to loss of tension stiffening alone is approximately 10% of the total deflection through the first 3 months. Whereas up to 22% loss of tension stiffening were found related LWC beam. So, it can be concluded that the loss of tension stiffening is almost twice in LWC beams than that in NWC beams. According to this inference , it can be said that the tension stiffening factor that was suggested by the Eurocode 2 (2010) equation is not suitable to be used for LWC beams deflection calculation.

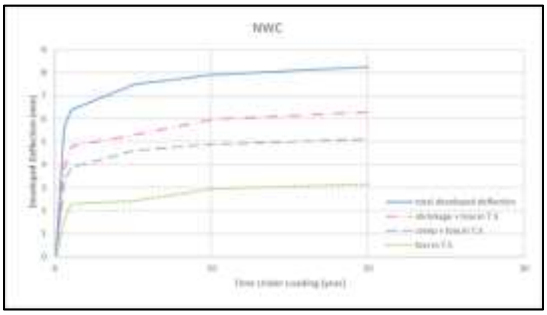

Figure 7: Loss of Tension Stiffening in NWC Beam

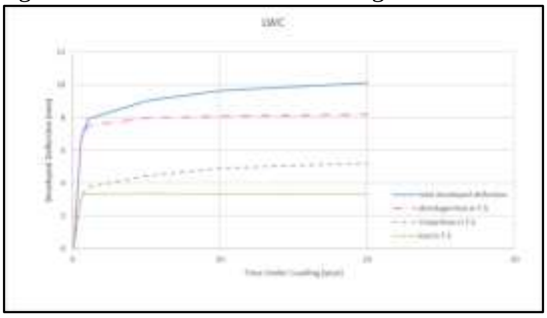

Figure 8-: Loss of Tension Stiffening in LWC Beam

Also, With the use of Dina FEA , cracks widths could be computed numerically, these numerical results are agreed with the experimental results which shows that the crack width is approximately similar for both LWC and NWC in the first 28 days. After 6 months their cracks widths start to diverge ,its found that after 20 years the increasing percents are (3.6 and 0.56) for LWC and NWC Cracks widths, respectively. Thus the LWC crack width is more than that for NWC a percent of 5.4 % from that for NWC beam .as shown in Figure 9. This is further confirm the finding that, the loss of tension stiffening is higher in LWC beams than that of NWC beams.

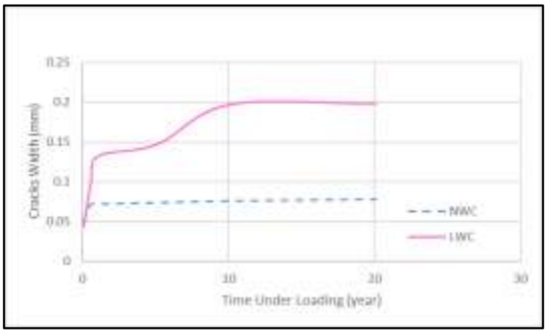

Figure 9: Cracks Width Propagation with Time for NWC and LWC beams.

Conclusions

1. The finite element models in Diana FEA verify the proposed models of mechanical properties of LWC and NWC, In Diana FEA, 3D- analysis showed a good agreement with the experimental data
2. Diana FEA giver better results when Fib Model design Code is used for all concrete types, as it gives approximately near results to the experimental deflection or an acceptable overestimated result, while Eurocode 2 gives good results for NWC beams while its underestimate the LWC beams deflections. This could be explained by the tensile behaviour of the concrete that the Eurocode 2 adopted (concert is brittle). While in Fib Model Code 2010 tensile behaviour consider the effect of tension stiffening.
3. The loss of tension stiffening is almost twice in LWC beams than that in NWC beams.
4. The increasing in crack width of LWC beams through 20 years is almost 5.4 % more than that of NWC beams

Acknowledgment
Authors would like to thank Prof. John. P. Forth and Dr. Muhammed Kashif Shezad from the University of Leeds, UK for the software facilities.

References

1. Akinwumi, I. I. (2014). *"Effect of curing condition and curng period on the compressive strength developement of plain concrete".* International journal of civil and enviromental research.
2. Al-Khaiat, H., & Haque, N. (1999). "Strength and durability of lightweight and normal weight concrete". *J. Mater. Civ. Eng.*, Vol.11 ,No. 3 , p.(231-235).
3. Alengaram, U. H. (2011). Enhancement and prediction of modulus of elasticity of palm kernel shell concrete. *Material & Design*, Vol. 2, Issue 4, pp(2143-2148).
4. Birjandi, F., & clarke, J. (1993). "Deflection of lightweight aggregate concrete beams". *Magazine of Concrete*, 45 (162) , p.(43*49).
5. Bomhard, H. (1980). " Lightweight Concrete Structural Potentialities, Limits and Realities". *Internaational Journal of Cement Composites and Lightweight Concrete*, Volume 2 , Issue 4 , pp.(193-209).
6. C. O. Orangun. (1974). "A comparative study of sustained loading effects on lightweight aggregate and gravel concrete beams". *Build. Sci.*, Vol. 9 ,No. 2 , p.(115-118).
7. Chandra, S., & Berntsson , L. (2002). *Lightweigh Aggregate concrete.* Norwich ,New York , U.S..A: Noyes Publications / William Andrew Publishing.
8. Chen, H., Huang, C., & ZY, K. (2004). "Experimental investigation on steel–concrete bond in lightweight and normal weight concrete ". *Structural Engineering and Mechanics*, p. 141-152.
9. Daud, R. A., Daud, S. A., & AL-Azzawi, Adel A., (2021). *" Tension stiffening evaluation of steel fibre concrete beams with smooth and deformed reinforcement".* Journal of King Saud University-Engineering Sciences 33 (3), 147-152
10. Daud, Harbi A., Daud, S. A., AL-Azzawi, Adel A., Thermal Behaviour of Hollow and Solid Steel Beams with Different Boundary Conditions. *Computer Assisted Methods in Engineering and Science*, [S.l.], oct. 2021.
11. Daud, S. A., Daud, R. A., & AL-Azzawi, Adel A., (2021). *" Behavior of reinforced concrete solid and hollow beams that have additional reinforcement in the constant moment zone".* Ain Shams Engineering Journal 12 (1), 31-36
12. Daud, S. A., Forth, J. P., & Nikitas, N. (2018). *"Time-dependent behaviour of cracked, partially bonded reinforced concrete beams under repeated and sustained loads"*: Engineering Structures 163, 267-280
13. Eigelaar, E. (2010). *"Deflections of reinforced concrete flat slabs".* Stellenbosch: University of Stellenbosch.
14. Evangeliou, P. (2016). *MSC thesis"Probabilistic nonlinear finite elemnt analysis of reinforced concrete beams without shear reinforcement".* the netherlands: Delft University of Technology.
15. Gesoglu, M., T., O., & E., G. (2004). "shrinkage cracking of lightweight concrete made with cold-bonded fly ash aggregates". *Cement and Concrete Research*, Vol. 34 , No. 7 , pp. (1121-1130).
16. Gilbert, R. (2001). "Shrinkage Cracking and Deflection The Serviceability of Concrete Structures". *Electromic Journal of Structural Engineering*, Vol.1 ,p.(2-14).
17. GILBERT, R. 2002. Creep and shrinkage models for high strength concrete–proposals for inclusion in AS3600. Australian Journal of Structural Engineering, 4, 95-106.
18. H. Sun, L. P. Ye, & Y. S. Guo. (2006). "Long-term deflection of high-strength lightweight aggregate concrete beams". *Indust. Constr.*, Vol. 36 ,No. 6 , P(88-91).
19. Hossain, K., ASCE, M., & Lachemi, M. (2008). "Bond Behavior of Self-Consolidating Concrete with Mineral and Chemical Admixtures". *Journal of Materials in Civil Engineering*, Voume 20 , issue 9 .
20. Kayali, O., M. N. Haque, & B. Zhu. (1999). "Drying shrinkage of fibre-reinforced lightweight aggregate concrete containing fly ash". *Cement and Concrete Research*, Vol.29 , No. 11 , p.(1835-1840).
21. Kim, Y.-J., Hu , J., Lee, S.-J., & You, B.-H. (2012). "Mechanical properties of aerated lightweight aggregate concrete". *Magazine of Concrete Research*, Volume 64 , Issue 3, pp.(189-199).
22. Lachemi, M., Bae, S., & Sahmaran, M. (2009). "Experimental investigation on steel–concrete bond in lightweight and normal weight concrete. Structural Engineering and Mechanics ". *Materials and Structures*, 42, p.1015-1023.
23. Luka, D., Guri, M., & Cullufi, H. (2015). *"Effect of Relative Humidity on Creep and Shrinkage of Concrete According to the European Code for Calculation of Slender Columns"s.* : International Journal of Engineering Research and Technology .
24. MIAS, C., TORRES, L., TURON, A. & SHARAKY, I. 2013. Effect of Material Properties on Long-Term Deflections of GFRP Reinforced Concrete Beams. Construction and Building Materials, 41, 99-108.
25. Reichard, T. (1964). *"Creep and drying shrinkage of lightweight and normal weight concretes".* Washington, D.C.: National Bureau of Standards.
26. Sim, J., Yang, K., Lee, E., & Yi, S. (2014). "Effects of Aggregate and Specimen Sizes on Lightweight Concrete Fracture Energy". *Material in Civil Engineering*, Volume 26, Issue 5 , p.(845-854).
27. Sivakumar.C. G. , & Naga Priya.S. (2021). *"Experimental Investigation of the Properties of Light Weight Concrete Wall Panels".* India: Vol. 6 No. 3 "International Journal of Mechanical Engineering".
28. Tamisia, B., & Beaudoin, J. (2000). "Basic Creep of Hardened Cement Paste a Re-Examination of The Role of Water". *Cement and Conceret Research*, Vol. 30 , p.(1465-1475).
29. Tasdemir, M., Akyuz, S., & Uzunhasanoglu, N. (1988). "Creep of lightweight aggregate concrete under variable stresses". *Cement, Concrete and Aggregates*, 10(2) , P.61-67.

30. Troxell, G., Raphel, J., & Davis, R. (1958). "Long-time creep and shrinkage tests of plain and reinforced concrete.". *American Society for Testing Materials (ASTM)*, Vol.91.
31. Wang, Z., Li, X., Jiang, L., Wang, M., Xu, Q., & Harries, K. (2020). "Long-term performance of lightweight aggregate reinforced concrete beams ". *Construction and Building Materials*, Volumr 264.
32. Wenzhong, Z., & Can, T. (2015). *"study on the effect of the strength grade on the creep behaviour of concrete".* China: The Open Civil Engineering Journal ,9,881-887.
33. Yang, H., Xu, X., Cui, H., & Lin, Z. (2016). *"Effect of Cured Time on Creep of Lightweight Aggregate Concrete".* China: 5th International Conference on Durability of Concrete Structures.
34. Zhang, Q., Le roy, R., Vandamme, M., & Zuber, B. (2014). "Long-Term Creep Properties of Cementitious Materials: Comparing Microindentation Testing With Macroscopic Uniaxial Compressive Testing". *Cement and Concrete Research*, Vol. 58 , p.(89-98).