Kardan Journal of Engineering and Technology (KJET)

ISSN: 2706-7815 (Print and Online), Journal homepage: https://kardan.edu.af/KJET

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To cite this article: Haddad, A. and Shinwari, Z. D. (2022). The control of flexural cracks in the design of reinforced concrete beams for Kabul city's exposure condition, *Kardan Journal of Engineering and Technology, 4 (1), 1-11.*
DOI: 10.31841/KJET.2022.23

To link to this article: http://dx.doi.org/10.31841/KJET.2022.23

Article

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Kardan Journal of Engineering and Technology 4 (1) 1–11
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Kardan Publications
Kabul, Afghanistan
DOI: 10.31841/KJET.2022.23
https://kardan.edu.af/journals/CurrentIssue.aspx?j=KJET

Received: 27 July 22
Revised: 20 August 22
Accepted: 25 Oct 22
Published: 25 Dec 22

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Abstract

For a concrete structure to be serviceable crack width must be controlled and must not exceed the limited values for a specific exposure condition. Cracking in the concrete is the most challenging issue for engineers since it reduces the overall strength of the structure, damages the aesthetics of the concrete, and causes corrosion in steel bars. The current study addresses the effects of flexural cracks on the serviceability of concrete structures and the control of cracks in the design of reinforced concrete beams. The study also aims to outline the importance of the control of flexural cracks, their major consequences, and the magnitude of cracking in reinforced concrete beams. A reinforced concrete beam model is designed and described for predicting the flexural cracks through numerical analysis and remarking its parameters, such as steel bars diameters, concrete covers, and steel bars arrangements that affect the size of flexural cracks in the tensile zone of concrete members. A total of 14 specimens are used to measure the range of crack widths for various scenarios based on which the significant variables affecting crack width are identified. The study concludes that the consideration for crack control in the design of reinforced concrete beams is essential. Hence, structural engineers should take extreme measures to ensure safety and serviceability when designing the structure by taking the crack-limit state into account.

Keywords: *Reinforced Concrete Beams, Flexural Cracks, Serviceability, Steel Bars' Arrangement, Concrete Cover.*

Introduction

Concrete is an important and extensively-used building material in construction due to its high compressive strength and good durability [1]. However, concrete is very strong in resisting compression forces, but it has a significant weakness against tensile forces. The tensile strength of concrete is measured between 8 to 15 percent of its compressive strength which indicates a substantial gap between its compressive and tensile strength. Therefore, the tensile strength of concrete is negligible in the design of reinforced concrete structures. Hence, as a solution engineers propose reinforcing steel bars to be used as a combined material with concrete to strengthen the structural member against the tensile forces [2].

The performance of reinforced concrete members depends on their serviceability and strength which maintain the structure sustained over the course of time. One of the significant variables that affect the serviceability and strength of the structural elements is the cracking phenomenon [3]. Cracking phenomena such as pattern, orientation, extension, and width are dependent on the available reinforcement. The load capacity of concrete structures is affected by the cracking of concrete structural members. Cracking usually starts to develop on the tension surface of reinforced concrete beams and starts at stress levels as low as 20MPa in reinforcement [3]. All reinforced concrete members are vulnerable to cracking both in the plastic and hardened state. Concrete has a natural tendency to crack due to either internal or external factors influenced by materials, design, construction, service loads, and exposure conditions [4].

Flexural cracks or bending cracks are unavoidable in reinforced concrete beams. If these cracks are too wide, they will destroy the structure's aesthetics as well as provoke strength. They may also cause reinforcement to become exposed to the environment and result in steel corrosion. To minimize these adverse effects, the serviceability must be verified that the crack widths under normal service conditions are maintained within acceptable limits. Cracks reduce the service life of the structure by permitting more rapid penetration of carbonation and allowing chloride ions, moisture, and oxygen to reach the reinforcing steel bars [5-7].

The analysis is dedicated to typical reinforced concrete beams with longitudinal reinforcing bars intending to control the crack width at the tension surface of reinforced concrete beams. Design engineers can use the guidelines prescribed in the design standards of different recommended codes. Each code standard discussed different parameters with respect to the serviceability limit state. These guidelines are stated based on certain analytical crack width solutions.

1.1 Problem Statement

Reinforced concrete beams usually experience cracking, because it transfers the final loading to columns and takes part in balancing the structural frames. Besides, it is a flexural member that goes under deflection easily as compared to other structural members. Cracks in reinforced concrete beams cause a major problem to the structure's strength since it is the main reason for steel corrosion, surface deterioration of concrete, destruction of aesthetics, and weakness of the concrete strength. On the other hand, flexural failure occurs with the development of flexural cracks in reinforced concrete beams. In recent years, for many construction projects in Kabul City, the structural designers have not considered the effects of cracks in reinforced concrete beams. These structures have been designed without any consideration of serviceability. The inappropriate design and incorrect detailing of reinforced concrete beams generate flexural cracks that reduce the strength and serviceability of the structures, and this may consequently endanger the life of occupants.

1.2 Significance of the Study

Crack control is an important feature of the serviceability limit state. Cracking in reinforced concrete beams diminishes the age of the concrete, produces corrosion on steel bars, and weakens the structure's overall strength. This study includes an in-depth analysis of the serviceability limit state, the significance of crack control, and a mechanism for limiting the extent of cracks.

1.3 Study Purpose

The aim of this study comprises an investigation of an adequate procedure intending to limit flexural cracks and remarking on the main parameters which have a significant effect on the crack size and crack propagation. Analysis and design of reinforced concrete beams are the initial stages to comply serviceability limit state. Design engineers are responsible to consider all aspects regarding serviceability and safety aiming to prevent failures in the structure. The main objectives of this work are consideration of crack limitations in reinforced concrete beams including control of flexural cracks, prediction of crack width, and providing a design solution. In general, the following objectives fulfill the investigation throughout this research.

1. Reporting the critical factors affecting the magnitude of flexural cracks in reinforced concrete beams.
2. Minimizing/limiting the width of flexural cracks in reinforced concrete beams.
3. Demonstrating comprehensive design solutions to control flexural cracks in reinforced concrete beams.

2. Review of Literature

An extensive literature review on crack width, its parameters, factors, and causes are presented. The basic intention of the present study is to summarize and overview the development of flexural cracks and collect the most relevant formulae and data for the investigation and analysis of flexural cracks.

2.1 Serviceability-Limit State

Nowadays the structural design profession is concerned with limited state philosophy. The word "Limit State" determines a condition up to which a part of the structure safely performs its specific function. The serviceability limit state determines the performance of structures under normal service loads. Serviceability is measured by considering the limited values of deflections, cracks, and vibrations. The limited values are developed by design codes and are usually proposed by a number of equations. In addition, serviceability considers the amount of corrosion in steel bars and concrete surface deterioration. The corrosion of reinforcing steel bars can be greatly minimized by giving careful attention to concrete quality, good compaction of the concrete, using adequate cover for steel bars, and limiting crack size [8].

The design for serviceability is partially the most challenging and least well-understood aspect of the design of concrete structures. Service load behavior depends primarily on the properties of concrete and these are often not known reliably at the design stage. Moreover, concrete behaves in a non-linear and inelastic manner at service loads. The non-linear behavior that complicates serviceability calculations is due to cracking, tension stiffening, creep, and shrinkage. It results in a gradual widening of existing cracks and a significant increase in deflections in flexural members [9].

2.2 Flexural Cracks in Reinforced Concrete Beams

Flexural crack is one of the most common structural failures that can occur particularly in the tension zone of flexural members. These cracks are formed in reinforced concrete beams due to overloading, and when the tensile deformations from loads or restraining forces reach the tensile deformation capacity of concrete. Flexural cracks can be usually observed on concrete structures in service that have a significant influence on strength, durability, aesthetics, and load transfer capacity. Flexural cracks in the beginning start with deflection of the beam along the span and after some time it leads the reinforced concrete beam to extensive damage as it generates micro-cracks and gradually propagates throughout the beam's height and length. Steel reinforcement is used to resist tension, protect the concrete against brittle failure, and limit crack width and crack spacing. When the reinforcing steel bars are not properly designed, the structure will crack excessively and may fail [8-11].

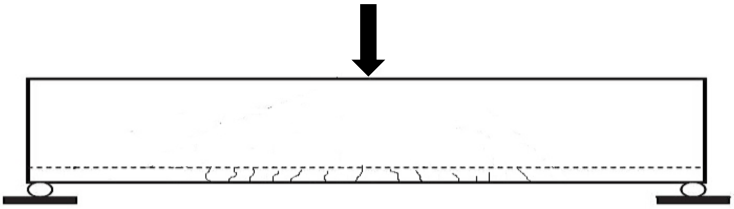

Figure 1: Flexural cracks generated in the tension zone of the beam [12].

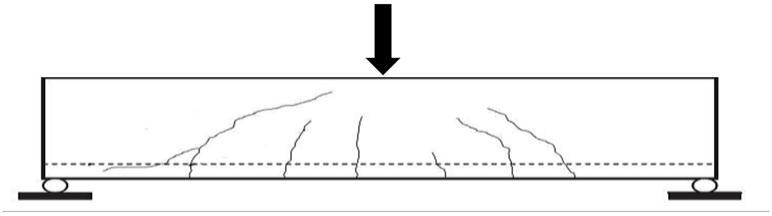

Figure 2: Flexural cracks propagated across the compression zone [12].

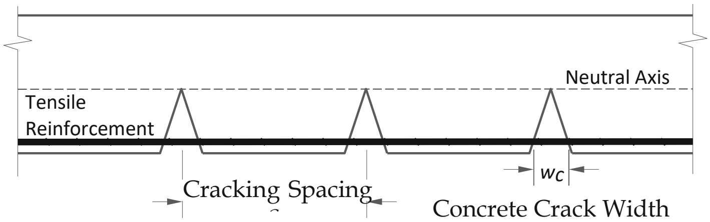

Figure 3: Steel and concrete bond separation due to flexural cracks [13].

2.3 Crack Width Limitation

ACI 224R-01 on control of cracking, presents a set of approximate permissible maximum crack widths for reinforced concrete members exposed to different conditions. The limited values are summarized in the following table.

Exposure Condition	Crack Widths	
	(in.)	**(mm)**
Dry air	0.016	0.41
Moist air, soil	0.012	0.30
Deicing chemicals	0.007	0.18
Seawater and seawater spray	0.006	0.15
Use in water-retaining structures	0.004	0.10

Table 1: Reasonable crack widths under service load (ACI 224R-01)

The above limit states of ACI are obtained through laboratory tests on reinforced concrete beams to determine crack sizes on each sample. The sizes are greatly affected by shrinkage and other time-dependent factors. The purpose of crack-control calculations is not really to limit cracks to certain rigid maximum values but rather to use reasonable steel bars details as determined by field and laboratory experience that will in effect keep cracks within a reasonable range. When the ACI 318 requirements for flexural cracks control in beam and thick one-way slab introduced serviceability requirements into the code for conventionally reinforced flexural design, the committee purposely modified the Gergely-Lutz crack width equation to emphasize reinforcement detailing [14].

2.4 Causes of Flexural Cracks

The flexural cracks in the initial stage develop slowly and change fast at the final stage of collapsing beam due to the reduction of the flexural resistance of the beam. The mode of failure in the beams varies according to a longitudinal reinforcement ratio. Longitudinal reinforcing bars can effectively protect from the unstable growth of flexural cracks when it is designed correctly. Control of cracking is important for obtaining long-term durability for concrete structures especially, for those that are subjected to aggressive environments. It can be concluded that the effective clear cover, reinforcing bars diameter, the surface geometry of the reinforcing bars, rebar distribution, depth variation, increasing the number of steel bars and externally applied loads affect crack widths [15-18].

3. Methodology

The research work is performed analytically on a G+9 story building which is located in Kabul city. The building was analyzed and designed through the Finite Element Software Etabs V.17. In order to investigate the flexural cracks, a critical member (Beam) is selected and modified to get 14 specimens with different steel bars arrangement and details. The crack widths from each specimen are estimated through ACI Crack Control Equation. The ACI 224R-01 states that requirements for flexural crack control in reinforced concrete beams are based on statistical analysis (Gergely and Lutz) of maximum crack width. The following equation is considered the best to predict the probable maximum bottom and side crack width.

$$w_b = 0.0113 \times \beta h \times f_s \sqrt[3]{dc \times A} \times 10^{-3}$$

Eq. 1: Crack control equation SI version [1]

Where:

- w_b = The most probable maximum crack width at the bottom of the beam;
- βh = The ratio of the distance between the neutral axis and extreme tensile fiber of concrete to the distance between the neutral axis and centroid of tensile steel;
- f_s = Reinforcing steel stress under normal service load;
- A = The effective tension area of concrete around tensile steel (having the same centroid as reinforcing) divided by the number of steel bars;
- dc = The distance from the extreme tensile fiber of the beam to the center of the closest steel bars

3.1 Specimens Detailing

The length, height and width of the selected beam model are measured as 7550mm, 550 mm and 450 mm respectively. All specimens are equal in dimensions and reinforcement ratio however, specimens differ in arrangement of reinforcing bars, concrete cover, and steel bars diameter. Each specimen shows different detailing hence, the analysis is performed for different scenarios intending to verify the main variables that have significant effects on the width of flexural cracks. Specimens are categorized into two main groups based on the reinforcing arrangement, concrete cover, steel bars diameter, and spacing between steel bars. Group-1 specimens have an effective cover of 50 mm, while it is 60 mm for Group-2 specimens.

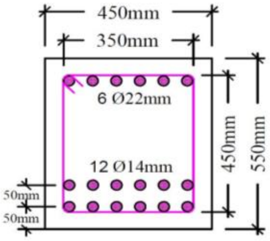

Figure 4: Specimen-1

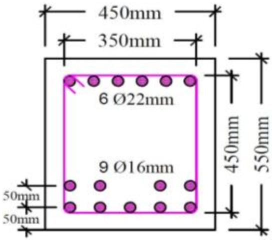

Figure 5: Specimen-2

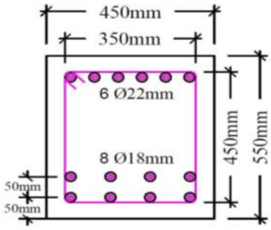

Figure 6: Specimen-3

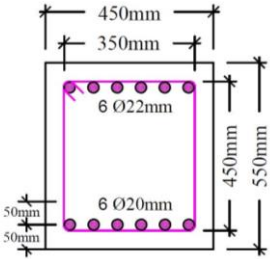

Figure 7: Specimen-4

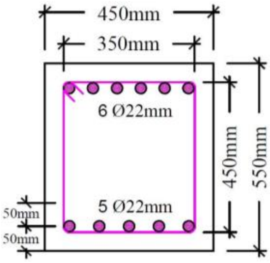

Figure 8: Specimen-5

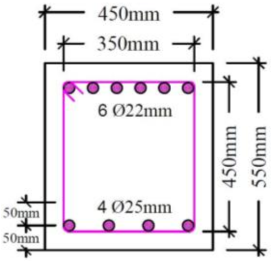

Figure 9: Specimen-6

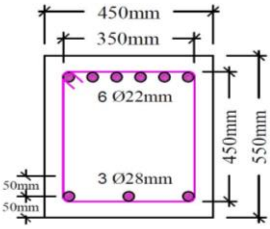

Figure 10: Specimen-7

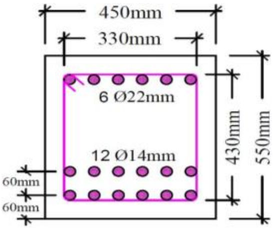

Figure 11: Specimen-8

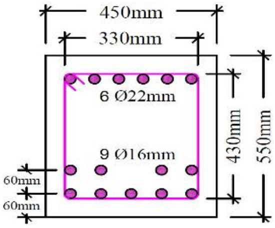

Figure 12: Specimen-9

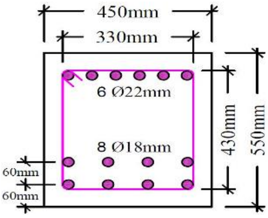

Figure 13: Specimen-10

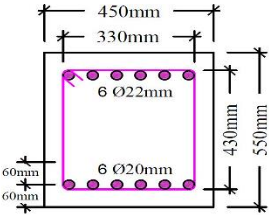

Figure 14: Specimen-11

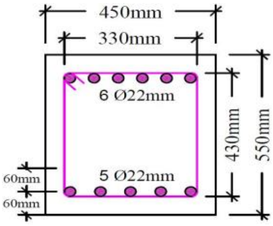

Figure 15: Specimen-12

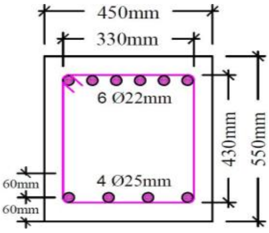

Figure 16: Specimen-13

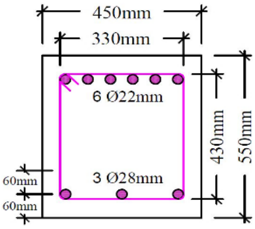

Figure 17: Specimen-14

Specimens	Cross Section (mm)	Effective-cover (dc) (mm)	Clear-cover (cc) (mm)	Diameter of bottom Reinforcing bars (mm)	Steel Bars Spacing (mm)
Specimen-1	550x450	50	43	14	53.2
Specimen-2	550x450	50	42	16	67.5
Specimen-3	550x450	50	41	18	92.66
Specimen-4	550x450	50	40	20	46
Specimen-5	550x450	50	39	22	60
Specimen-6	550x450	50	37.5	25	83.33
Specimen-7	550x450	50	36	28	133

Table 2: Specifications of Specimens in Group-1

Specimens	Cross Section (mm)	Effective-cover (dc) (mm)	Clear-cover (cc) (mm)	Diameter of bottom Reinforcing bars (mm)	Steel Bars Spacing (mm)
Specimen-8	550x450	60	53	14	41
Specimen-9	550x450	60	52	16	62.5
Specimen-10	550x450	60	51	18	86
Specimen-11	550x450	60	50	20	42
Specimen-12	550x450	60	49	22	55
Specimen-13	550x450	60	47.5	25	76.66
Specimen-14	550x450	60	46	28	123

Table 3: Specifications of Specimens in Group-2

4. Analysis and Results

The crack widths from 14 specimens are estimated through numerical analysis and listed in Tables 4 and 5.

Specimens	f_y (MPa)	f_s (MPa)	$\acute{f}_C$ (MPa)	dc (mm)	Cross Section (mm)	w_b (mm)
Specimen-1	420	252	28	50	550x450	0.223
Specimen-2	420	252	28	50	550x450	0.246
Specimen-3	420	252	28	50	550x450	0.256
Specimen-4	420	252	28	50	550x450	0.246
Specimen-5	420	252	28	50	550x450	0.261
Specimen-6	420	252	28	50	550x450	0.282
Specimen-7	420	252	28	50	550x450	0.31

Table 4: Crack widths in Group-1 specimens

Specimens	f_y (MPa)	f_s (MPa)	$\acute{f}_C$ (MPa)	dc (mm)	Cross Section (mm)	w_b (mm)
Specimen-8	420	252	28	60	550x450	0.252
Specimen-9	420	252	28	60	550x450	0.278
Specimen-10	420	252	28	60	550x450	0.289
Specimen-11	420	252	28	60	550x450	0.278
Specimen-12	420	252	28	60	550x450	0.295
Specimen-13	420	252	28	60	550x450	0.318
Specimen-14	420	252	28	60	550x450	0.35

Table 5: Crack widths in Group-2 specimens

4.1. Comparison of Crack Widths for Different Steel Bars Diameters, Steel Bars Arrangements and Concrete Covers

The results of both groups are compared in terms of their detailing and variables that affected crack widths such as the arrangement of reinforcing bars, concrete cover, and diameter of steel bars.

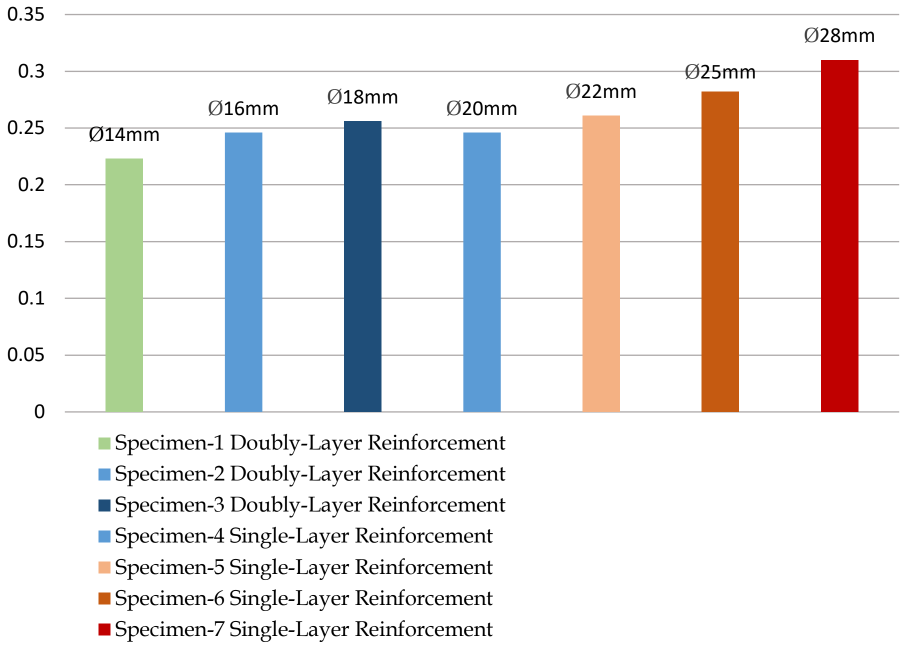

Figure 18: Crack widths in Group-1 specimens

According to Figure 18, the crack widths in Specimen-1, Specimen-2, and Specimen-3 increased gradually as the diameter of the reinforcing bars increased. On the other hand, Specimen-4 has a narrower crack regardless that the diameter of the steel bars is bigger than in the prior specimen. Because Specimen-4 is arranged with single-layer reinforcement and the steel bar spacing was reduced by 37.27 percent when compared to Specimen-3. Since crack size constantly developed in each situation, the results in Specimen-5, Specimen-6, and Specimen-7 illustrate alternative crack widths. As a result, it clearly proves that increasing the diameter of steel bars increases crack widths. Based on the Group-1 results, Specimen-1 and Specimen-4 are in better condition than the other specimens. The magnitude of the crack in Specimen-1 is 10 percent lower than in Specimen-4. This is because the spacing between steel bars in Specimen-1 is 53.2 mm while it's measured at 67.5 mm in Specimen-4. It was early discovered that the steel bars spacing has a direct relation with the increment of crack width. According to the previous literature, it was found that doubly-layer reinforcing beams have a negative effect on crack size. However, in this study, it is investigated that Specimen-1 a doubly-layer reinforcing beam model has the best condition among the other beam models. Based on the detailing of Specimen-1, the number of steel bars is doubled when compared with Specimen-4 thus, the value of "A" (effective tension area of concrete divided by the number of steel bars) in the crack control equation affects the width of cracks. In general, the results of Group-1 illustrate that beams with doubly-layer reinforcing have superior conditions than single-layer reinforcements.

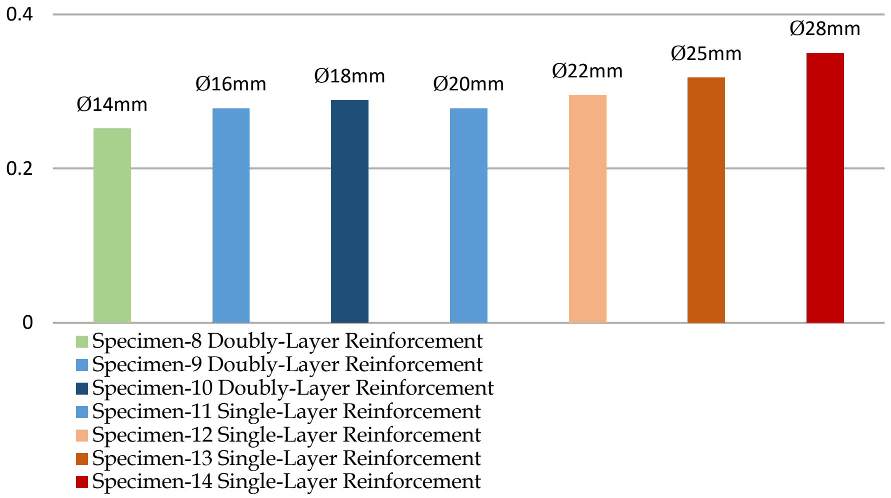

Figure 19: Crack widths in Group-2 specimens

As per Figure-19, in Group-2 specimens, the concrete cover (dc) increased by 20 percent compared to Group-1 however, the arrangement of steel bars, dimensions of beam models, and steel ratio remained constant. The overall results in Group-2 demonstrate that the concrete cover has a direct relation with the increment of the crack width since the crack widths increased in each specimen. When comparing the average crack size of specimens in Group-1 and Group-2, the increment of average crack widths in Group-1 is 0.26 mm while in Group-2 it is measured at 0.294 mm which shows a 13 percent variation. Group-1 specimens have better conditions than Group-2 since the maximum crack size in Group-1 is estimated as 0.31 mm on Specimen-7 while the maximum crack width in Group-2 is calculated as 0.35 mm on Specimen-14. Hence, it is quite obvious that the alternative concrete cover affects the size of cracks.

4.2. Comparison of Crack Widths for Alternative Exposure Conditions

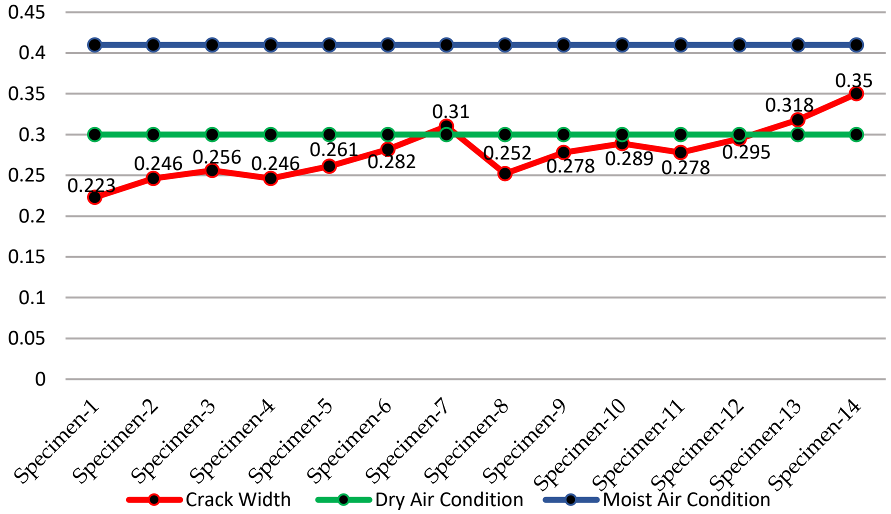

Figure 20: Comparison of crack widths with permissible values

As per Figure-20, the comparison shows that Specimen-7, Specimen-13, and Specimen-14 have exceeded the limited crack widths. It indicates that these beam models have critical situations compared to other specimens. ACI 318 through ACI Report 224R-01 recommends a minimum crack width of 0.3 mm that should be considered for all exposure conditions although, the report provides different crack limitations for different conditions. However, due to variations in air temperature ACI code suggests a minimum average crack width that should be limited for serviceability satisfaction.

5. Conclusions

The major remarks intending to limit crack width in reinforced concrete beams are concluded. The study reports several significant factors that influence crack widths such as concrete cover, steel stress, steel ratio, and reinforcing arrangement. The following conclusions have been drawn based on the results and analysis of all specimens.

- The doubly-layer reinforcing bars in the beam are better than single-layers. However, the analysis shows alternative results. Based on the results of multiple specimens, Specimen-1 had a superior condition compared to other cases. Hence, it indicates that the number of steel bars has a major effect on crack control.

- The adequate concrete cover, the diameter of steel bars, and steel distribution in the tensile zone, are also important factors that affect crack widths.
- In terms of verifying the serviceability limit state for flexural cracks, the ACI 318 (ACI 224R-01) Crack Control Equation is the best to be used for predicting and limiting crack widths.
- It is very effective to provide minimum spacing between steel bars while designing reinforced concrete beams with the consideration of the Maximum Size of Aggregate.
- The concrete cover is best to be used at around 50 mm for beams. If the condition is more humid, then a 60 mm concrete cover can be used to protect steel bars against corrosion. In spite of this, the crack width must be carefully checked such that it does not exceed 0.3 mm.

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