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IDENTIFICATION OF CRACK WIDTH BEHAVIOR OF ONE-WAY REINFORCED CONCRETE SLAB STRUCTURE AT DIFFERENT STEEL REINFORCEMENT AREA

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An evaluation study of crack limit states based on design codes and prior research is presented in this publication. Its main goal is to connect research findings to common design codes. Researchers continue to face a difficult dilemma when it comes to reinforced concrete structure fractures, particularly in one-way slab constructions where there is still significant damage and corrosion in the reinforcement because of cracks. Practitioners will find it easier to construct these structures and solve the slab durability issue if the proper formula is discovered. One can overcome reinforced concrete. A method for estimating the maximum fracture width formula in one-way reinforced concrete slabs with varying steel areas is suggested based on this research. Slabs use a variety of steel areas, including 1000 mm^2, 1200 mm^2, and 1400 mm^2. The test specimens are the same length of 2 meters and have a slab width of 0.6 meters with steel reinforcement. Findings from a literature review of research codes and prediction formulas from earlier studies, namely $w_{max(prop)}=1.5\cdot10^{-2}f^{s}A_s^{-0.4}$, indicate that the maximum crack width is not significantly influenced by steel area (As). Overall, the findings from the two methods used in this analysis match the suggested formula and the observed experimental testing. This data indicates that the maximum fracture width has been greatly lowered by increasing the steel Area (As) of the reinforced concrete slab, leading to the determination of the experimental formula, $w_{max(exp)}=0.11\cdot f^{s}A_s^{-0.630}$. As a result, a unique approximation formula has been developed to assess the impact of steel area parameters for pure slabs on the maximum crack width formula for one-way reinforced concrete slabs. This crack width formula is only applicable to one-way slabs in practice

Keywords: flexural member, crack width, one-way slab, reinforced concrete, steel area

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1. Introduction

Structural safety evaluation for service limit conditions (SLS) is becoming increasingly important, and structural optimization technology is indispensable in reinforced concrete (RC) design. Removal of structural defects such as cracks that affect the appearance or function of the structure is an important component of this inspection. Because there are still many incidents of cracks appearing in buildings and bridge decks, it is very important to increase accuracy in predicting reinforced concrete crack behavior. The problem with reinforced concrete structures is that cracks can significantly shorten the life and beauty of a building, even though their impact is minimal on the internal strength of reinforced concrete. So, in the process of planning and producing reinforced concrete, it is necessary to pay attention to cracks that occur, especially in structures with high prestige. While the level of prestige a structure has determines its aesthetic rating, the allowable cracks must also be limited.

Moreover, corrosion is widely acknowledged as one of the primary problems that reinforced concrete structures may encounter during their service life. One frequent prescriptive solution to this problem is to limit the width of cracks that are allowed to emerge over the structure's service life [1]. As a result, using a more accurate fracture width calculation can lengthen the structure's lifespan. Civil engineering science on crack clusters in reinforced concrete has currently published many design codes and guidebooks and their evaluations are still ongoing, but it is limited to one-dimensional structures, namely in the form of beams, and for 2-dimensional structures there is still limited knowledge found. Currently, the problem of cracking in reinforced concrete is especially in two-dimensional structures such as slab structures which use the dimensional parameters of height and width of the concrete cross-section. This presents a different behavior to one-dimensional beam structures, so for slab structures, cracks are still a problem that requires in-depth and ongoing research [2]. So, it is necessary to evaluate the structural width dimensional parameters regarding their interactions with all parameters that influence the width of reinforced concrete cracks. Thus, structural design optimization technology has scientific importance to the investigation and prevention of fractures in one-way reinforced concrete slabs.

2. Literature Review and Problem Statement

In terms of the effects of stress distribution in flexural and tension structures, the effects of casting position, and the effects on curvature to beam crack width, the research [3] makes corrections to the fibMC-2010 and EC2:1992-1-1:2004 regulations. It then goes on to describe in greater detail the effective concrete area by taking the effective height of reinforced concrete beams into account. Nevertheless, this study primarily discusses the curvature effect-whose value is mostly determined on the beam structure needs further research if using slab structure. from this research consider that $w_{\max}=0.0013\, f_s$ and $w_{\max}=5.189A_s^{-0.4}$.

The paper [4] present a detailed explanation of the new idea presented in pre-Eeurocode 2. A comparison with the idea now used in Germany and Austria, together with a thorough study of 2D FEM simulations with discrete fractures and appropriate consideration of the bond stress-slip relationship at the reinforcement-concrete interface, are used to analyze the concept's primary shortcomings and inconsistencies. When the reinforcing pattern varies, the experimental findings on cracking in [5] do not clearly show a relationship between the crack widths and the crack spacing. The beams with three layers of bars had longer stable crack lengths during the cracking stage, but their maximum fracture apertures were less than those of conventionally reinforced specimens with the same reinforcement ratio.

The results of the experiment [6] show that the crack width in plain reinforcement is much greater than that in deformed reinforcement. The present study has established the impact of beam height and concrete cover thickness on reinforced concrete cracking; however, the investigation has been restricted to tension structures, but there were unresolved issues related to the implications for flexural RC beams or slabs. From [7] it is possible to discover that the reinforcement ratio (ρ) has an impact on the crack width (w) on rigid pavement. For a given weight, the rigid pavement's crack width (w) decreases with increasing reinforcement number (ρ). The width of the crack at the same steel stress decreases with increasing reinforcement ratio. It is known that the ratio of reinforcement is equal to steel area, this research clearly proves that the crack width obtained from calculations in the code's formula.

For reinforcement that permits cracks to traverse the reinforcement, the embedded frame model from [8] is combined with the crack model. Structures made of reinforced concrete that are subjected to bending and tensile loads undergo crack examination. Comparing the suggested model with existing experimental and numerical data has demonstrated how useful it is for examining fracture behavior in reinforced concrete structures. This method can only be applied to reinforced concrete structures that have a thickness of more than 250 mm. This model is less applicable to slabs structures.

According to research [9], there are several crack width formulas that produce average crack width values that are in accordance with experimental data. However, predictions are never certain as there is a minimum coefficient variation of 30 % in the ratio of theoretical and experimental values. It is known from the [10] study that the mean spacing for primary and secondary cracks in bending members is determined independently. In the present work, constitutive parameters are quantified and validated against independent test results. A comparative study has shown that the suggested model's mean crack distance predictions and the RC element testing accord quite well.

EC2:1992-1-1:2004, fibMC-2010, Japanese Code, and the Beeby crack distance model were chosen for research [11] because they represent most theoretical formulations. The prediction model is compared with the experimental results of this study as well as with several selected literature sources. For axial tensile tests, the JSCE 2010 provides better predictions. All calculation models-apart from Eurocode 2 with the German Annex-are in good agreement with the findings of the four-point bending test. The generally recognized theory that links crack widths to crack spacing and predicts the formation of the largest crack near the uncracked block with the maximum length is not supported by the cracking results from [12]. In sixty percent of the prisms under consideration, the maximum crack in the examined specimens was found adjacent to the uncracked block of maximum length; in only one instance did the maximum crack occur between two blocks whose sum is maximum.

It was suggested in [13] that future SLS designs have more standardized processes. Clarifying the use of the term durability in the code language and separating the requirements for crack width for aesthetic reasons from those for durability and tightness are deemed important. The literature study raises concerns about the research that went into developing the tightness and leakage prediction formulae that are in use today. It is discussed that treating crack widths more consistently and limiting them will be made easier by differentiating the crack width through a cross section.

The findings of the study [14] supported the notion that the genesis and propagation of cracks are stochastic processes. Comparing the maximum crack widths computed using the suggested formula to those computed using Eurocode 2, the results were conservative. It was also established that the loading method has no bearing on the separation between cracks. Therefore, the state of reinforced concrete elements can be evaluated using the density function that describes the distribution of distances between cracks. This study is good at presenting experimentally the behavior of reinforced concrete beams but does not explain in detail whether it can be applied to RC slab structures.

According to experimental results [15], reinforced concrete slabs experience flexural damage, causing a fracture pattern starting from the bottom of the slab. At the same stress, the fracture width decreases as the slabs thickness increases. This fact supports that the influence of slab's thickness will be significant on slab structures or two-dimensional structures. The experiment [16] indicates that coarse aggregate type and compressive strength have less of an effect on flexural behavior than the reinforcing ratio. Every single one-way slab exhibits flexural cracking patterns consistent with previous design work, whereas failure modes are indicated by reinforcement providing way first and then crushing concrete without any spalling on the concrete's compressive zone. One study employed lightweight concrete, while the other used slab specimens with a three-point load on an elastic foundation.

The horizontal crack next to the top side rebar significantly affects the slabs' punching shear capacity, as demonstrated by the [17] test results, and it is established that the width of the horizontal crack is correlated with the reinforced concrete slab's punching shear capacity. It also reveals that once the width of the horizontal fracture reaches a particular point, coated concrete above the crack will no longer function as intended. Thus, the influence of the reinforcement ratio is significant on RC slab cracking, while the concrete cover does not have a significant effect.

It is discovered that the early-age fracture width calculation approach based on Eurocode 2 (EN 1992-2, 2005) was presented to estimate the early-age crack width for an RC slab bridge, according to [18] experimental data. The given technique is viable to evaluate the early-age crack width, as evidenced by the good agreement between the estimated and measured crack widths and the very small errors between them. Therefore, the calculation formula of early-age crack width is reasonable for the assessment of the early-age crack width. From the research of RC slab, which have early crack with bearing capacities are 48 %, 32 %, and 67 % for flexural, shear, and flexural shear cracks up until the slab fails; additionally, there are 54 %, 35 %, and 63 % for displacement and 42 %, 28 %, and 50 % decrease for absorbed energy, according to the Extended FEM method's crack analysis of the RC Slab structure from [19] Analysis. Flexural-shear cracks, flexural cracks, and shear cracks (which seldom ever occur in buildings) are the three most harmful kinds of slab cracks. So, from the research it was found that the most dangerous cracks are flexural cracks. This approach defines a singularity at the crack's tip, necessitating the use of a certain kind of element. Many of the challenges and restrictions of the previous techniques have been addressed by the new Extended Finite Element Method, which makes use of special elements, then this data requires experimental data for validation.

Each parameter in crack behavior based on the design code must be reviewed as part of the parameter modeling research. The models for calculating crack width based on empirical data were primarily created for building regulations. The ACI-318 code [20] uses two simpler parameters: concrete cover (c) and effective concrete tension area ($A_{c\,eff}$) and consider $w_{\max}$=0.0010f_s, $w_{\max}=1.665\,A_s^{-0.269}$. This formula may be the most practical when applied, but it also requires that the environment, labor, and materials be in optimal condition based on other ACI criteria. The Australian Standard (AS 3600-2000) [21] consider that $w_{\max}$=0.0016fs, and $w_{\max}= 77.745\,A_s^{-0.76}$.

Several algorithms employ semi-analytical or simplified approaches to reduce the complexity and improve the usability of the crack width computation methodology. The Japanese Society of Civil Engineers (JSCE) code is used throughout East Asia [22]. The JSCE code utilizes both parameters and factors in tandem. Concrete cover (c), steel diameter (ϕ) and its spacing (s), and factor of steel bars surface shape, reinforcing layer, and concrete grade are used in order of precedence, so from this code consider that $w_{\max}=7.291A_s^{-0.416}$. The most widely used in Europe are EC2:1992-1-1:2004 and *fib*MC-2010. formula [23] that uses a factor after a few additional parameters and a traditional computation and consider that $w_{\max}$=0.0015 f_s, and $w_{\max}=48.974A_s^{-0.706}$. Like *fib*MC-2010, the [24] formula makes use of several variables, including the kind of surface bars, the kind and length of loading, and the national annex coefficient, in addition to practically all the parameters previously discussed, this code consider that $w_{\max}$=0.0017 f_s and $w_{\max}=5.126A_s^{-0.366}$, so, from literature study list formula give the average value formula from the effect of steel stress is called maximum crack width analysis formula; $w_{\max\,(Analisis)}$=0.0013 f_s, and from effect of steel area is that $w_{\max\,(Analisis)}=5.344A_s^{-0.4}$ from combination last two formula give the analysis formula using convergence methods that $w_{\max\,(Analisis)}=0.015f_sA_s^{-0.4}$ using millimeter unit.

It is rarely to provide a solution for calculating the crack width when applied to RC slabs or two-dimensional structure using the formulas from earlier research and mostly used codes, even though it is well known that slabs with a small thickness can generally result in significant cracks. Determining the influence of steel area on crack width in two-dimensional structures has not been fully studied because in slab structures there are irregular supports which constitutively change the stiffness at the edges of the structure. So, this makes it difficult for the slab structure to predict its deformation and crack behavior. The main role of minimum reinforcement in slab structures is to resist cracking due to concrete shrinkage. These two parameters make the crack width formulation need furthermore studied. All of this enables to stress how important it is to investigate the crack width (w) in RC slab structures in relation to the steel area of the thin RC slab for bridge deck. The literature review is analyzed at the beginning of the investigation, and the outcomes of the experiments are then compared.

3. The aim and objectives of the study

The aim of this study is identifying the influence of reinforcement steel area to maximum crack width one-way reinforced concrete slab. This will allow for more precise and accurate practical use in designing reinforced concrete slab structures regarding crack control.

To achieve this aim, the following objectives are accomplished:

– to identify one-way RC slab crack width (w) from the different of steel stress (f_s) and steel area (A_s) from the experimental study;

– to obtain a new predicted formula of one-way RC slab maximum crack width from the effect of steel area.

4. Material and methods

This research object uses replica specimen data or with variations that are different from research [15, 16] which have been explained in section 2. In this research specimen using simple supported restraint and each specimen have the same reinforcement (strength: f_y, and type: deformed bars which have diameter; ϕ=16 mm), section width: b=600 mm, thickness: h=175 mm, concrete cover: c=35 mm, Specimen A, B, C have varied in section steel area A_s. Values of A_s were: 1000 mm^2, 1200 mm^2, 1400 mm^2. Specimen using normal concrete that have 22 MPa of compressive strength without superplasticizer or others additive and have proportion 1 cement:1.5 sand and 2.5 crushed stone with 0.45 W/C ratio. Table 1 shows variation detail of the specimen and Fig. 1 shows the location of steel reinforcement with strain gauge inside concrete slab to measure strain of steel.

The main research hypothesis in this study is that reinforced concrete slab structures can reduce the flexural crack width (w) by increasing the steel area (A_s) of the RC slabs. By increasing the steel area, the contact area between concrete and steel will increase. By increasing the contact area between steel and concrete, the adhesive force will increase so that the slip that occurs will be smaller and will reduce RC slab crack width.

Table 1

Specimen specification

Specimen name	A (1000)	B (1200)	C (1400)
num. of bars	5	6	7
A_s (mm^2)	1000	1200	1400
ρ	1.20 %	1.44 %	1.67 %
ρ_{eff}	2.38 %	2.86 %	3.33 %
ϕ/ρ_{eff}	672.00	560.00	480.00

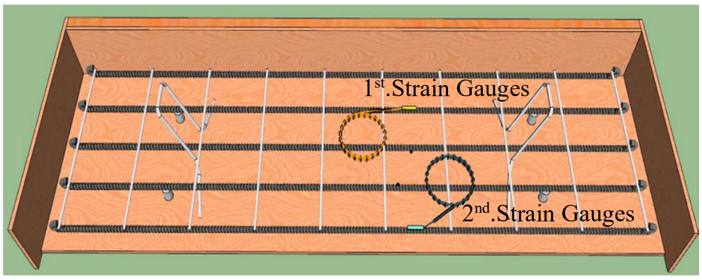

Fig. 1. 3D model of steel reinforcement with strain gauge on RC slab specimen

This study makes several assumptions, including the following:

– the transverse reinforcement has no influence on the RC slab flexural crack width;

– the structure is of the simple support type;

– the static line load is spread evenly throughout the slab. Additionally, this study used several simplifications, such as omitting the bond stress value of reinforced concrete, the size of the secondary fracture that develops, and cracks brought on by heat and shrinkage processing.

As shown in Fig. 2, all hardware is presented, and a personal computer is used to record the crack width using Dinocapture software. Reinforced concrete structures use full scale so that all parameters are well maintained so that the model can be analyzed without having to make copy specimens.

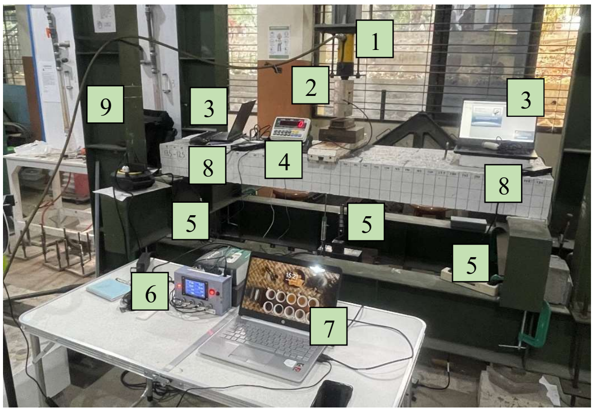

Fig. 2. Experiment setup: 1 —hydraulic jack; 2 — load cell; 3 — microscope's computer; 4 — load meter; 5 — LVDT; 6 — data logger; 7 — data logger's computer; 8 — digital microscope; 9 — loading frame

The sequence of the experimental research process is as follows:

1. Configuring all research-supporting equipment, such as strain gauge cables installed on data recorders, hydraulic jacks, load cells, and LVDTs. Fig. 2 shows how the tools are set up on the test frame.

2. Using steel H-beams to model the line load.

3. The crack detector is turned on right away at the first crack site to take a picture of the crack as soon as it becomes apparent.

4. After loading every specific multiple, the spot where the first fracture occurs is imaged using a crack detector. A video recording of the load measurements and data logger will be made during each test. To obtain the data immediately, a computer can also be linked to the data logger.

5. Strain gauge readings for reinforcement can be seen in the data logger. Strain gauges were installed on the tensile reinforcement in the center and at the edge.

6. Observations continue to be made with increasing load multiples until the serviceability limit state of the slab specimen is obtained

5. Result research the effect of steel area to crack width behavior in one-way reinforced concrete slab structure

5. 1. Experimental result of the effect of steel stress (f_s) and reinforcement steel area (A_s) to maximum crack width ($w_{\max\text{-}Exp}$)

The experimental results will be explained in terms of the relationship between steel stress or strain and area parameters with maximum crack width. At the serviceability limit state (SLS) of the reinforced concrete slab, from this research which has 250 MPa of steel stress (f_s), in Fig. 3, the maximum crack width in a reinforced concrete slab as a function of steel area (A_s) in the experiment results is compared with the analysis formula. Comparing the maximum crack width that occurs in a reinforced concrete slab due to the stress of the reinforcing steel (f_s) on a A_s=1400 mm^2, results value using analysis formula that consider from section 2 ($w_{\max ANA}$) at Table 2 and experiment result at Table 3 are shown in Fig. 4.

Table 2

The value of RC slab crack width from analysis

f_s (MPa)	A_s (mm^2)		
	A (1000)	B (1200)	C (1400)
150	0.17	0.16	0.15
200	0.23	0.21	0.20
250	0.28	0.26	0.25
300	0.34	0.31	0.30

Table 3

Experimental result of the effect of reinforcement steel area to RC slab maximum crack width

f_s (MPa)	A_s (mm^2)		
	A (1000)	B (1200)	C (1400)
150	0.26	0.19	0.18
200	0.32	0.26	0.21
250	0.34	0.30	0.28
300	0.40	0.35	0.35

Finding the experimental crack width formula is like finding the analysis formula. To do this, it is possible to use the regression formula from Table 3, Fig. 3, 4 for each crack width value with changes in f_s and A_s. This formula is as follows:

$$w_{\max(\exp)} = 0.0011\, f_s, \tag{1}$$

$$w_{\max(\exp)} = 26.45 A_s^{-0.630}. \tag{2}$$

It is possible to change formula (1) and (2) to get the final formula (3), which is:

$$w_{\max(\exp)} = 0.11 \cdot f_s A_s^{-0.630}. \tag{3}$$

Additionally, it is necessary to understand how the analysis formulas compare, followed by the experiment's result. The results of the experimental specimens are displayed in Table 4, together with the measured maximum crack widths and the predictions made in accordance with most used codes and $w_{\max ANA}$.

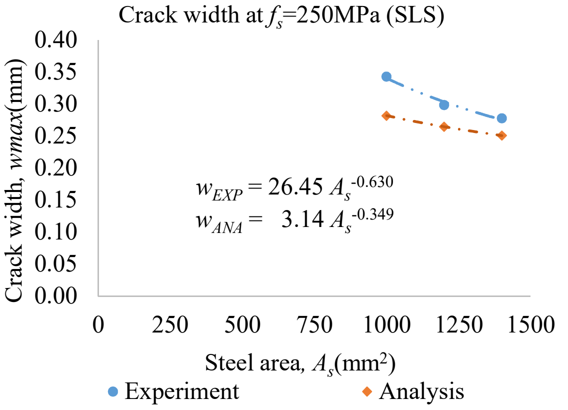

Fig. 3. Relationship between A_s and $w_{\max}$ comparison from experiment and analysis

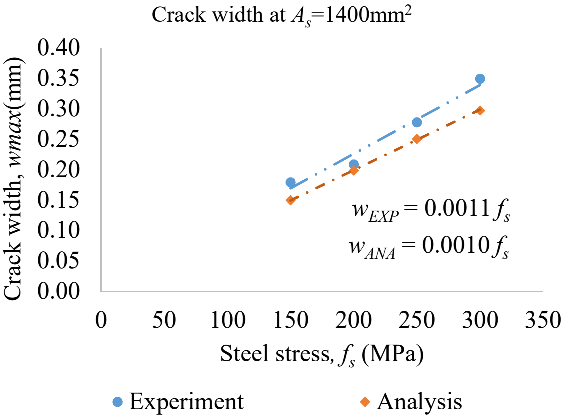

Fig. 4. Relationship between f_s and $w_{\max}$ for comparison of experiment and Analysis

Table 4

Comparison $w_{\max}$ from experiment and predicted formula

Specimen (steel area)		A (1000)	B (1200)	C (1400)
Experiment result		0.343	0.299	0.278
Code prediction	EC2	0.296	0.274	0.260
	ACI 318	0.207	0.196	0.188
	JSCE	0.331	0.300	0.280
	AS3600-2000	0.311	0.269	0.237
Analysis		0.282	0.265	0.251

The values derived from the research literature formula are shown in Table 4, and the suggestion is to enter all the parameters in the specimen by using the steel reinforcement's stress value in the SLS condition, which steel stress at 250 MPa, and comparing it with the experimental result. It is possible to achieve the final formula if all ways yield the same conclusion based on the hypothesis.

5. 2. Obtaining a new crack width final formula from the effect of steel area

This is the last section of the study effort, which involves establishing a new formula for one-way slab structures by adding a thickness factor to analysis formula and producing the final formula from the effect of steel area (5), after obtaining the suggested formula and doing comparison tests with the experimental findings.

$$w_{\max} = 1.5 \cdot 10^{-2} k_h f_s A_s^{-0.4} \ \text{(mm)}, \tag{4}$$

where:

$$k_h = \begin{cases} 40h^{-0.7} \text{ for } (h) < 200 \text{ mm}, \\ 1 \text{ for } (h) > 200 \text{ mm}. \end{cases} \tag{5}$$

The effectiveness of using formula (7) is influenced by the steel area and is also influenced by the thickness of the slab so that the k_h factor (8) from previous research [3] will be adopted in forming the final formula from this research.

6. Discussion crack width behavior on one-way reinforced concrete slab structure on different steel area

The experimental findings differ significantly, and analysis formula ($w_{\max.ANA}$) suggests that the prior formula must be corrected when used to one-way slab configurations. The relationship between f_s and $w_{\max}$ is shown in Fig. 3 so that the experimental findings and the analysis formula may be compared on a 1400 mm^2 steel area. The similarity between the two methods is that they are both linear. It is also evident from the graph that a rise in steel stress causes a corresponding increase in crack width. this is verified by [3, 5] research at flexural RC member results. The value obtained from analysis formula from section 2 ($w_{\max ANA}$) is less than the value obtained from the experimental graph, which is (3). The usefulness of the analysis formula in predicting crack widths in one-way slab constructions from the experimental findings on each test item is demonstrated by Fig. 4 and Table 4 at 1400 mm^2 steel area.

The experimental findings for slab specimens are displayed in Table 4, together with the maximum crack widths that were measured and projected based on prediction codes. additionally, When the results of the crack width calculations for specimens A, B, and C whose steel area rises successively are compared using $w_{\max ANA}$, it is discovered that the crack width value has reduced in every observation. As A_s increases, the bonding area of the steel and concrete increases, and as a result the crack width decreases. However, according to all approaches, an increase in A_s will only affect the crack location factor (in reinforcement or surface).

From the experimental results on crack width, there is good agreement with the results of the analysis formula from the study literature, however the values are significantly different where the results from the experiment give a crack width that is greater than the results from the analysis formula. The research results are supported by the results of [15, 16] which both show results where the effect of steel area has a significant effect on the crack width of reinforced concrete slabs using the same specimen or replica, only using different variations. This result is made possible by the influence of the thickness and steel area of the slab structure which gives different behavior to the beam structure in the analysis formula, so this is the basis for evidence that the slab structure is a specific case. so that this research is proven to be convergent and further research can be carried out by replicating the specimens in this study using more complex parameters. If to use the conventional formula, the cracks that occur in the slab will be larger and may exceed the allowable cracks under service load conditions. These findings can be a reference in the practical planning of reinforced concrete slabs. This finding is particularly useful for structures built near the coast, where seawater can severely corrode reinforced concrete reinforcement and cause cracks, resulting in a reinforced concrete structure that is strong and aesthetically pleasing over its planned service life. hence, the amount of money needed for overall structural repairs.

Shortcomings of this research is the provision of the test frame is only partially controlled, and the loading is not completely evenly distributed due to distortion of the spreader beam, so that the crack width at the midpoint of the slab will be different from the edge, so in future research it can also be measured at the midpoint of the slab span. In this research, there are limitations to its application on bridge decks that use dynamic loads, so the solution in this research is limited to static loads and does not consider the age of the slab structure due to repeated loads. Based on our findings, it is possible to recommend that future research should concentrate on the aspect ratio of two-dimensional structures. especially testing the width of the concrete slab (*b*). So, in further research, a formula will be developed and found for the width of reinforced concrete cracks in slab structures with various parameters and with various loads so that the formula can be used in the process of planning the production of reinforced concrete slabs.

7. Conclusions

1. The results of this experiment were that a 40 % increase in steel area resulted in a 19 % drop in crack width (w). Therefore, in the case of small thickness of slab, the influence of steel area (A_s) has a substantial effect on the maximum crack width ($w_{\max}$) of reinforced concrete slabs.

2. Because the effectiveness of the final formula depends on both the steel area and the slab thickness, the *kh* factor from previous research will be used to build the final formula from this study. In addition to the most used code, it is also possible to apply prediction formulas from other codes. This innovative formula may be used, for practice, to prevent fractures in one-way slab constructions.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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