This paper presents an evaluation study of crack limit states according to design codes and previous research. It aims primarily to relate research findings to design code similarities. Cracks in reinforced concrete structures are still a challenging problem for researchers, especially in one-way plate structures where there is still a lot of damage and corrosion in the reinforcement due to cracks. Finding the right formula will make it easier for practitioners to design these structures, and the problem of durability in reinforced concrete plates can be overcome. From this research, an approach is proposed on how to predict the maximum crack width formula in one-way reinforced concrete slabs with different thicknesses. Plates use a variety of thicknesses, including 125 mm, 150 mm, 175 mm, and 200 mm. The test specimens have the same dimensions and steel reinforcement, a slab width of 0.6 m and a length of 2 m. From a literature study of prediction formulas from previous research works and codes, namely $w_{max(prop)}=7.5*10^{-3} f_s h^{-0.333}$, it was found that thickness (h) has little influence on maximum crack width. The results from both approaches in this analysis are overall in accordance with the observed experimental tests and the proposed formula. Based on these observations, increasing the thickness of the reinforced concrete slab has significantly reduced the maximum crack width so that the experimental formula is obtained, namely $w_{max(exp)}=0.32*f_s h^{-1.113}$. Therefore, a constant is needed to evaluate the influence of thickness parameters for slabs with a thickness less than 200 mm on the maximum crack width formula for reinforced concrete slabs, and a special approximation formula has been obtained. In practical use, the crack width formula can only be used for one-way slabs

Keywords: flexural crack width, one-way slab, reinforced concrete, slab thickness

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IDENTIFYING THE EFFECT OF THICKNESS ON CRACK WIDTH IN ONE-WAY REINFORCED CONCRETE SLAB STRUCTURES

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1. Introduction

In reinforced concrete (RC) design, structural optimization technology is still very important, and structural safety assessment for service limit states (SLS) is becoming increasingly significant. Keeping cracks from interfering with the aesthetic or function of the structure is an important component of this inspection. Current design codes do not adequately represent the reality of relevant crack behavior for all types of structural elements or composites. Although they have little effect on the strength of reinforced concrete elements, cracks reduce the structure's longevity and aesthetic appeal. However, some experts state that manipulating the length and width of cracks is a simple technique to use in engineering practice.

Crack widths show significant heterogeneity, and design regulations provide various recommended formulas [1]. Therefore, it should be emphasized that the topic of microcracks and cracks in concrete and structures built from this material is important in several aspects, especially the costs associated with the potential repair of damaged structural elements as well as the safety and comfort of building occupants [2]. Additionally, it is well known that one of the biggest problems that a reinforced concrete structure may face during its service life is corrosion. Prescriptive solutions to this problem often involve limiting the width of cracks that are allowed to form during the service life of the structure [3]. So, using a more accurate crack width formula can increase the durability of the structure.

The history of the crack width calculation model in Japanese, American, English, Eurocode, 2010 Model Code, and Japanese code has been researched. In terms of aesthetics, structures are ranked according to the level of prestige they possess, and the allowable crack width is determined [4]. The fact that there are several methods, constraints and structural classifications makes current knowledge possible to calculate mechanically reasonable maximum crack widths [5].

Thus, the analysis and prevention of cracks in one-way RC slabs have scientific relevance to structural design optimization technology.

2. Literature review and problem statement

The computation is based on the idea that the crack width can be found by multiplying the fracture distance by the variation in the average strain of the reinforcement and concrete. The disparate outcomes of the two formulations of the rule can be observed in the work [6], which serves as an inspiration for the comparison of the findings obtained for crack width and crack distance for bending and tension. In this work, there are variations in concrete cover but there is a problem that has not been explored, the effect of beam height on reinforced concrete. Perhaps the beam height parameter in this research has not been considered an influential parameter because the varied cover is not very significant.

According to research [7], the parameter $\varnothing/\rho_{p,ef}$ had a minimal effect on the crack distance, but the thickness of the concrete cover layer had a considerable influence. In this work, there are also variations in concrete cover on the specimens and there is also literature analysis of previous studies regarding bond behavior and slip on size effects, but the problem of the influence of the beam height is still not explained where the problem of concrete height parameters should have an impact on the specified concrete cover.

In [8], numerical simulations discuss problems related to RC slabs in the form of thermal and shrinkage effects on concrete cracking. This study does not discuss the influence of large slab thicknesses, only examines plates with small thicknesses. Perhaps this work focuses on something that is rarely researched, namely the non-physical influence of reinforced concrete on cracking. Whereas in practice, the thickness of the plate will affect the hydration and shrinkage of reinforced concrete.

The research [9] provides corrections to the MC 2010 and EN 2004 regulations regarding the effects of stress distribution in flexural and tension structures, the effects of casting position, then describes in more detail the effective concrete area by considering the effective height of reinforced concrete beams and then providing the effect on curvature to beam crack width. However, this research has not detailed the direct effect of beam height on crack width, only mentioning the curvature effect, the value of which is not very significant and is ultimately influenced by the concrete cover. Perhaps this is because the researchers focused on the beam structure in the same way as the researchers described previously.

The average distance between primary and secondary cracks can be predicted using the model [10]. However, only primary cracks are considered when analyzing crack width. Macro cracks in reinforced concrete elements are contingent upon the sort of stress applied, whereas micro cracks are specific to a certain scenario [2]. In these two studies, the influence of beam height on crack width for both primary and secondary cracks was found. In the case of low beam height, only primary cracks are found. The research object for beams with low height is only one object and several more objects are needed to better explain the effect of beam height on primary crack width, especially in slab structures.

The experimental results [11] provide evidence that the crack width in plain reinforcement is significantly higher than in deformed reinforcement. In this research, the influence of beam height and concrete cover thickness on cracking of reinforced concrete is known, but it is limited to tension structures and it has not been explained how this applies to flexural RC beams or slabs.

According to experimental findings [12], there is a positive correlation between higher crack width and lower concrete compressive strength values. In addition, tests show that in test specimens with poor concrete quality, the reinforcement stress value greatly influences the crack width. In this research, plates are used as pavement, which uses sub-grade soil elastic supports and it has not been explained what the effect would be if using simple supports such as on the deck of bridges.

The results of the experiment [13] significantly reduce the crack width that occurs in high-strength reinforced concrete beams (RC beams) and improve the concrete's quality. This is demonstrated by the effect of split tensile strength on the crack width ($w_{\max}$) of beams with the formula approach: $w_{exp}=3.74\, f_{tf}^{\ -1.513}$, $w_{prop}=0.19\, f_{tf}^{\ -0.022}$. In this study, there is evidence that high-quality concrete has different formulations for bond behavior, but the specimens are only limited to non-full-scale specimens.

The most used crack width calculation uses the relationship between crack spacing and concrete-steel strain deference. For parameter study, we need to see every formula that was created before. The formula [14] uses the parameters such as crack spacing (s_{rm}), bond stress (τ), concrete tensile strength (f_{ct}), steel reinforcement diameter (ϕ), concrete strain (ε_c), and steel strain (ε_s). This formula was created by classical theory about crack width on concrete. Just like other research, in this study, the beam height parameter is only used as a curvature effect on reinforced concrete cracking.

In parameter modeling, the study also needs to review each parameter in crack behavior based on the design code. The empirical based crack width calculation models were developed mostly for building codes. The American Concrete Institute (ACI) code [15] uses simpler parameters such as concrete cover (c), and effective concrete tension area ($A_{c.eff}$). This formula may become the most used in practice, but it must consider that material, manpower and environment have ideal condition according to other criteria from ACI. The Australian Standard (AS 3600-2000) [16] contains complex parameters using a combination formula by the classic calculation formula with the ACI code, but it has an additional parameter such as nodular ratio (n).

Several codes adopt simplified or semi-analytical ways to make the crack width computation model less complex or more user-friendly. In East Asia, a Japanese Society of Civil Engineers (JSCE) code is used [17]. JSCE uses parameters and factors together, this code uses the parameters of concrete cover (c), steel diameter (ϕ) and its spacing (s) and the factors of steel bars surface geometry, reinforcement layer, and concrete grade. The most common in Europe are CEB/FIP Model Code 2010 (MC2010), and Eurocode 2 (EC2). The formula [18] uses classical calculation and many other parameters and then uses factors. The same as MC2010, the formula [19] besides using almost all parameters mentioned before uses many factors such as type of surface bars, type and duration of loading and national annex coefficient. The MC 2010 and EC2 formula is suitable for any condition of material, manpower and environment. The same as in the research work in the crack formulation from the code parameter, the height of the beam is only used as a curvature effect on reinforced concrete cracks.

From the formulas from previous research and codes that are often used, we cannot provide a solution on how to formulate the crack width if applied to slabs with a small thickness compared to a large thickness, whereas it is known that basically slabs with a low thickness can cause significant cracks. So, all this allows us to emphasize that it is advisable to carry out a study of the crack width (w) in RC slab structures in terms of slab's thickness parameters (h), both small and thick. The study starts with the analysis of the literature data and then compares them with experimental results.

3. The aim and objectives of the study

The aim of the study is to identify the effect of thickness for a new specific formula for predicting one-way RC slab maximum crack width.

To achieve this aim, the following objectives are accomplished:

– to identify crack behavior from previous researcher work and most used building code;

– to identify the effect of steel stress (f_s) and slab thickness (h) on the RC slab's maximum crack width from an experimental study;

– to obtain the slab's thickness factor (k_h) to evaluate the proposed RC slab's crack width formula.

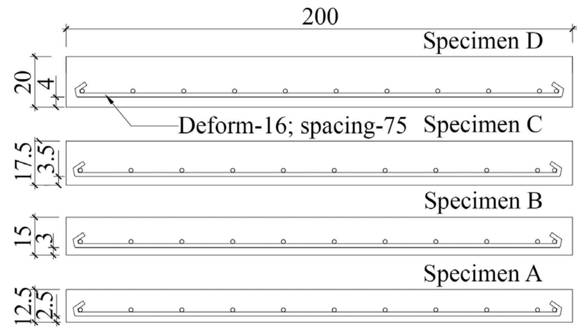

Fig. 1. Details of reinforced concrete slab specimens

4. Material and methods

In the experimental method, the object of this study is reinforced concrete slabs, which have the same reinforcement (strength; fy, and type: deformed steel reinforcement, which has 16 mm of diameter (ϕ)), section width; b, concrete strength; $f'c$. Specimens A, B, C, D have the values of h as follows: 125 mm, 150 mm, 175 mm, and 200 mm. The values of the crack width were calculated at the same steel stress level (fs=250 MPa). Concrete strength was considered as fc=22 MPa and the clear cover=(0.2h) mm. Table 1 shows the data sheet of the specimens. All specimens were made in East Java, Indonesia on the Southeast Asian continent. So, the specimen uses concrete-forming materials from there, such as sand from the city of Lumajang, gravel from volcanic crushed stone from Mount Semeru and cement of Indonesian production.

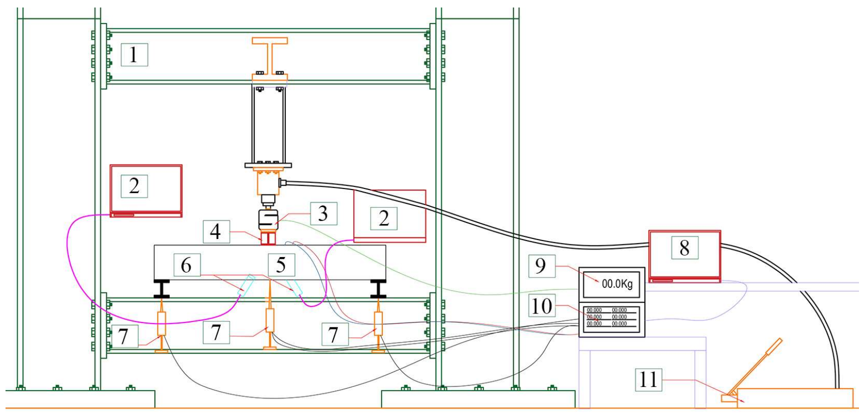

Fig. 2. Experiment setup: 1 — loading frame; 2 — microscope's computer; 3 — load cell; 4 — spreader beam; 5 — strain gauge; 6 — digital microscope; 7 — LVDT; 8 — data logger's computer; 9 — load meter; 10 — data logger; 11 — hydraulic jack

The research object is shown in Fig. 1. There are 4 slab specimens with concrete covers of 25 mm (A), 30 mm (B), 35 mm (C), 40 mm (D). All specimens use 7pc tensile steel reinforcement. For transverse reinforcement, plain reinforcement with a diameter of 8 mm with a reinforcement spacing of 200 mm is used.

The test load uses line loading using a spreader beam at the point of maximum moment. In this study, two microscope cracks were used, which were placed on the right and left sides of the plate or in other words at the end of the load line so that the accuracy of observing the crack width was higher. For steel reinforcement, strain ε_s is measured using a strain gauge. All data are recorded by a data logger and personal computer step by step according to the test control method, as follows in Fig. 2 for details.

Table 1

Specimen specifications

h (mm)	A (125)	B (150)	C (175)	D (200)
Cover (mm)	25	30	35	40
A_c (mm^2)	60,000	72,000	84,000	96,000
ϕ (mm)	16	16	16	16
A_s (mm^2)	1402	1402	1402	1402
ρ	2.34 %	1.95 %	1.67 %	1.47 %

The main research hypothesis in this study is that reinforced concrete slab structures can reduce the flexural crack width (w) by increasing the thickness of the RC slabs. The flexural capacity of reinforced concrete will increase if the distance between the center of gravity of the concrete compression force and the tensile force of the steel reinforcement is greater. So, by increasing the thickness of the plate, the distance will be greater. This will cause a decrease in the flexural crack width (w) in the RC slab element at the same service load.

There are several assumptions used in this research, namely:

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

– uses a simple support type structure;

– uses static line load equally distributed across the slab.

This research adopted several simplifications, including:

– does not take into account the bond stress value of reinforced concrete;

– does not take into account the size of the secondary crack that occurs;

– does not take into account cracks caused by heat and shrinkage processing.

5. Results of research on the effect of thickness on crack width in one-way reinforced concrete slab structures

5. 1. Finding a new proposed maximum crack width formula ($w_{\max\text{-}Prop}$)

This paper presents the proposed formula based on the literature study from the codes [15–19] and previous works [5, 9, 14]. The graph in Fig. 3 shows the relationship between the maximum crack width w_{max} and the values of steel stress f_s.

Fig. 3 shows the results obtained from the prediction formula from literature studies where the largest slope is in the formula from [20] while the smallest slope is in [15]. So, in this case we make the proposed formula based on the f_s parameter, namely:

$$w_{\max(proposed)}=0.0013\,f_s. \qquad (1)$$

After that, we see the relationship between the maximum crack width w_{max} and the values of steel stress f_s and slab thickness h shown in Fig. 4.

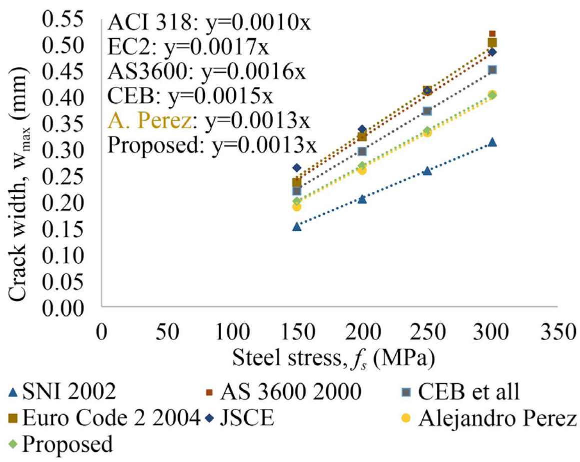

Fig. 3. Relationship between f_s and w_{max} using the formula from researcher works and codes

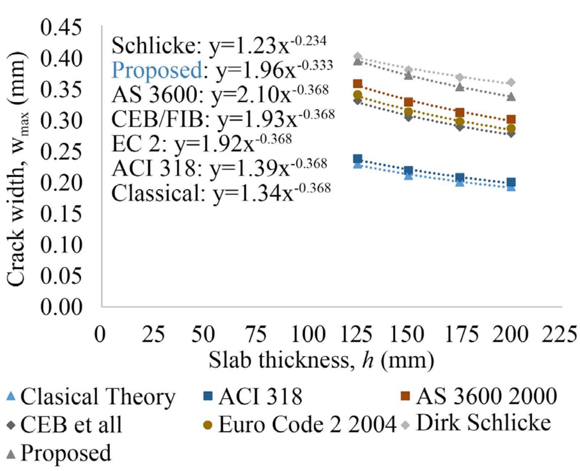

Fig. 4. Relationship between h and w_{max} using the formula from researcher works and codes

From Fig. 4, all prediction formulas have relatively the same influence on the thickness parameters. The results of the prediction formula obtained from literature studies show that the largest value is found in the formula [5] while the smallest value is found in the formula [15]. So, in this case we make the proposed formula based on the h parameter, namely:

$$w_{\max(proposed)}=1.97\,h^{-0.333}, \qquad (2)$$

where f_s – reinforcement steel stress, and h – thickness of the concrete slab. From the two regression formulas (1), (2) we obtained a combined formula with the constant convergence theorem for each proposed variable. So, the proposed formula for the maximum crack width on the RC slab surface obtained from previous researcher's literature studies and codes given by (3) and the calculation using specimen's specifications in Table 1 are presented in Table 2.

$$w_{\max(proposed)}=7.5\ 10^{-3}\,f_s\,h^{-0.333}\ \text{(mm)}. \qquad (3)$$

Table 2

Predicted w_{max} from the proposed formula

f_s (MPa)	h (mm)			
	(A)125	(B)150	(C)175	(D)200
200	0.28	0.26	0.25	0.24
250	0.35	0.33	0.31	0.30
300	0.42	0.39	0.37	0.36
350	0.49	0.46	0.43	0.42

In Table 2, the maximum crack width values are presented by entering data on the specimens in this study in (3). These values are the first step in formulating the thickness factors, which if compared with laboratory results, will show facts that reveal the truth regarding the effect of thickness on the maximum crack width value of one-way reinforced concrete slabs.

5. 2. Effect of steel stress (f_s) and slab thickness (h) on the experimental maximum crack width ($w_{max-Exp}$)

The experimental data will be described in terms of the relationship between steel stress or strain and plate thickness parameters with maximum crack width. Fig. 5 shows a comparison of the maximum crack width that forms in the reinforced concrete slab due to the stress of reinforcement steel (f_s) on a 200 mm thick slab specimen by the experimental results in Table 3 and the proposed formula in Table 2.

Table 3

Experimental results of reinforced concrete slab's maximum crack width

f_s (MPa)	h (mm)			
	(A)125	(B)150	(C)175	(D)200
200	0.29	0.24	0.20	0.17
250	0.38	0.31	0.26	0.22
300	0.46	0.35	0.33	0.28
350	0.57	0.41	0.43	0.32

Fig. 6 shows a comparison of the maximum crack width that forms in the reinforced concrete slab due to the slab thickness (h) according to the experimental results and the proposed formula (3) at the serviceability limit state (SLS) of the reinforced concrete slab, which has 250 MPa of steel stress (f_s).

Just like looking for the proposed formula, now we look for the experimental crack width formula by taking the regression formula for each crack width value with variations in f_s and h from Table 3, Fig. 5, 6, which is as follows:

$$w_{\max(exp)}=0.0009\,f_s, \qquad (4)$$

$$w_{\max(exp)}=81.8\,h^{-1.113}. \qquad (5)$$

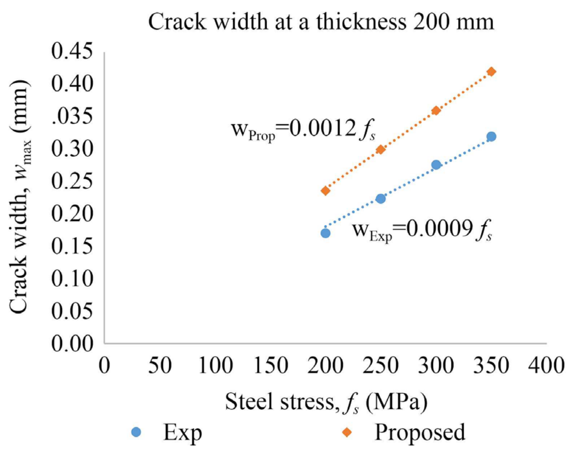

Fig. 5. Relationship between f_s and w_{max} for comparison of the experiment and the proposed formula

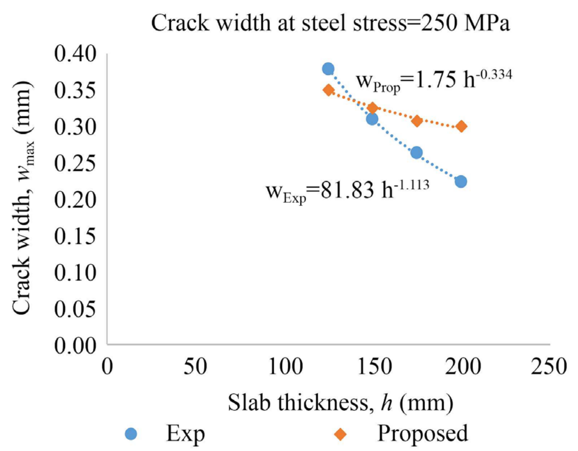

Fig. 6. Relationship between h and w_{max} from the experiment and the proposed formula

From formula (4) and (5) we can modify it to the final formula (6):

$$w_{max(exp)}=0.32\, f_s\, h^{-1.113}\ \text{(mm)}. \qquad (6)$$

And we must know about the comparison from the proposed and predicted formula and then the experimental results. So, Table 4 shows the results of the experimental specimens, including the measured maximum crack widths and the predictions according to the code predictions [15–19] and from researcher prediction by [5, 14] and (3).

Table 4

Comparison of w_{max} from the experimental results and predicted formula

Specimen (slab thickness)		A (125)	B (150)	C (175)	D (200)
Experimental results		0.379	0.310	0.263	0.223
Code prediction	EC2	0.308	0.277	0.260	0.249
	ACI 318	0.224	0.201	0.188	0.181
	JSCE	0.441	0.396	0.372	0.357
	AS3600	0.282	0.253	0.237	0.228
Researcher prediction	Dirk Schlicke	0.401	0.374	0.360	0.352
	H. Marzouk	0.317	0.284	0.266	0.255
	Proposed	0.339	0.330	0.313	0.296

In Table 4, the values obtained from the formula from the literature study are presented, and the proposal is to enter all the parameters in the specimen by entering the stress value of the steel reinforcement in the SLS condition, namely 250 MPa and comparing it with the experimental results. If all approaches provide the same conclusion according to the hypothesis, then the final formula will be obtained.

5. 3. Finding the thickness factor of crack width in one-way RC slabs and providing a new final crack width formula

Some parameters of concrete thickness (h) in the slab can be considered as a second important factor influencing crack width, but their efficiency is considered in different ways in building regulations. And now, we can obtain the thickness factor by dividing the extrapolated crack width from the experimental value w_{exp} by the resulting value from the proposed formula w_{prop}. So, the relationship between slab thickness and thickness factor can be seen in Fig. 7.

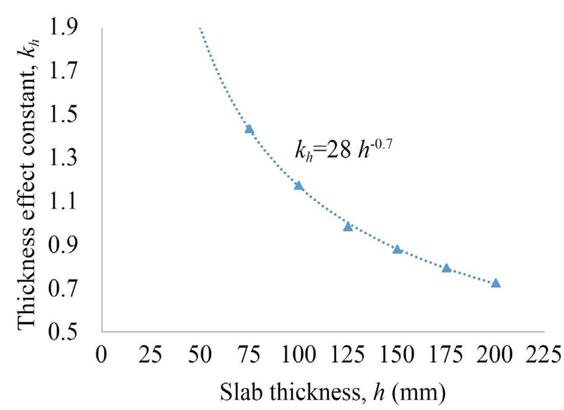

Fig. 7. A coefficient of the effect of thickness on the maximum crack width according to the proposed formula

After obtaining the proposed formula and comparative tests with the experimental results, this is the final part of the work in this research, namely finding a new formula for one-way slab structures by adding a thickness factor from Fig. 7 to (3) and obtaining the final formula (7).

$$w_{max}=7.5\ 10^{-3}\, k_h f_s\, h^{-0.333}\ \text{(mm)}, \qquad (7)$$

where:

$$k_h=28h^{-0.7};\ \text{for } (h)<200\ \text{mm}, \qquad (8)$$

0.7; for (h)>200 mm.

Formula (7) and the thickness factor (8) are only effective if used in slab structures where the thickness compared to the width is small. Therefore, the provisions of the k_h factor will be influenced by the thickness of the plate if the thickness is below 200 mm, and if the slab thickness exceeds 200 mm the structural behavior is more like the behavior of the beam, so that k_h becomes a constant, so formula (7) is no different from the formula in the previous formula in the codes.

6. Discussion of the literature study and experimental results on the effect of thickness on crack width in one-way reinforced concrete slab structures

Fig. 3 describes the relationship between f_s and $w_{\max}$ using formulas from the researchers' work and codes. It can be seen in the graph that all the lines show a positive linear relationship, only the slope values differ. The code from America [17] shows the lowest value, this is due to the use of this code for practical purposes and there are not too many parameters in it, while the highest crack width value is in [19], which is known to have various parameters from important assumptions that is in the physics and mechanics of concrete structures. So, in this research the approach formula for f_s is taken as the average of the two codes. And then from Fig. 4, the relationship between h and $w_{\max}$ can be seen using formulas from the researcher's work and codes. All graphs from several formulas agree with the statement, namely that adding thickness to a reinforced concrete structure will reduce the maximum crack width. The formula given by [5] has the highest value for crack width, while the lowest value is again given by the formula [15]. So, both f_s and h parameters [15] provide the lowest crack width values. From all the graphs, the influence of thickness on maximum crack width is not very significant.

Table 2 is obtained from the proposed formula (3) while Table 3 is obtained from experimental results. Both tables use the same specifications as in Table 1. There are significant differences in the experimental results and formula (3) indicating that there is a correction to the previous formula regarding its application to one-way plate structures. Fig. 5 depicts the relationship between f_s and $w_{\max}$ for comparison of experimental results and the proposed formula for a plate with a thickness of 200 mm. Both approaches have the same characteristic, namely they are linear. From the graph, it is also known that increasing the stress in the steel will increase the crack width. The graph from formula (3) gives a higher value compared to the value from the experimental graph, namely (4). Based on Fig. 6 and Table 4 at a slab thickness of 200 mm, we can see the effectiveness of using the proposed formula to predict crack widths in one-way slab structures from the experimental results on each test object.

Table 4 shows the experimental results of slab specimens, including the measured and predicted maximum crack widths according to prediction codes [15–17, 19] and from researchers' predictions by [5, 14]. The proposed formula in (3) compares the results of crack width calculations for specimens A, B, C and D whose cross-sectional thickness increases sequentially, it is found that the crack width value has decreased in all observations. This is given by the code equation [17]. As h increases, the effective area of the concrete increases, and as a result the crack width decreases. However, according to all approaches, an increase in h will only affect the crack location factor (in reinforcement or on the surface). Formula (3) [14–16, 19] shows the crack width value below the experimental value, while formulas [5, 17] shows a value that is greater than the experimental value. It can also be seen that the largest relative error is in the formula [15] followed by other regulations, while the formula given by the researcher provides a better match to the experimental results. This indicates that in the case of wide cracks in slab structures, it is more likely to use the formula from (3) [5, 14].

From Fig. 8, it is known that for reinforced concrete structural components that have h less than 200 mm, there is a significant difference in crack width values, however, for h greater than 200 mm the influence of thickness must really be considered in the most widely used components such as beam structures. In other words, if a one-way plate structure usually has h less than 200 mm, then in formulating the crack width, the plate thickness must be considered as a necessary parameter. From the proposed empirical formula, a coefficient can be obtained that considers the influence of h on reinforced concrete slabs that have a thickness of less than 200 mm. Look at Fig. 7 and let's call k_h the coefficient that refers to the thickness to convert the proposed empirical formula (3) into the final empirical formula (7). A new formula can be a solution to the problem of cracks in slabs, but its use is only limited to one-way structures with thicknesses that tend to be small.

The results obtained can be applied to reinforced concrete slab structures both in buildings and truss bridge decks, especially in structures built in coastal areas where sea water will greatly damage the reinforcement in reinforced concrete due to corrosion if cracks occur. In this case, the mass reinforced concrete building work carried out will make it easy to control the service life and age with certainty. Thus, the expected potential impact of use is reduced cracking that occurs in reinforced concrete slab structures so that reinforced concrete structures not only remain strong but also maintain the beauty of the building until the planned service life and costs for structural repairs and overall costs can be minimized.

In this research, there are several weaknesses, which can later become references or novelties for further research, namely the loading is not fully line load due to deformation in the spreader beam, then there is deformation of the test frame, which is only partially controlled. From this research, we suggest that for further research we can focus on the effect of steel area (A_s), concrete cover (c), rebar diameter (ϕ), tension steel reinforcement layer (n) and bond behavior (τ) between tensile reinforcement and concrete.

7. Conclusions

1. The proposed formula was found from several design codes and researchers give the same conclusion, namely that increasing the tensile stress (f_s) value of steel will increase the crack width (w) linearly, and increasing thickness (h) from 125 mm to 200 mm (60 %) will reduce the crack width (w) by 16 %. However, the proposed formula is in good agreement with all previous formulas.

2. The crack width (w) parameters governing the models were categorized, and an extensive background study of each model resulted in the decision of the appropriate model for cases with large concrete thickness (h). However, from this experimental result it is known that increasing thickness by 60 % decreased crack width (w) by 42 %. So, thickness (h) has a significant effect on the maximum crack width ($w_{\max}$) of reinforced concrete plates in the case of small thickness (h).

3. For the case of one-way slabs, where there is a small ratio between the thickness and width of the slab structure, we need to consider the influence of thickness parameters and k_h was provided. So, from this research we can use this new formula well for RC slabs that have h less than 200 mm, and for RC slabs that have h greater than 200 mm we can use formulas from the most widely used codes and from other

prediction formulas. This new formula can be used as a solution to prevent cracks in one-way plate structures.

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

The 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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