CRACK WIDTH CONTROL IN THE DESIGN OF REINFORCED CONCRETE BEAMS IN MARINE ENVIRONMENTS

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Abstract

Reinforced concrete beams are extensively used in construction, and understanding crack development is essential to ensure the safety and durability of structures, particularly in marine environments. This study investigates the influence of tensile steel reinforcements on crack width in reinforced concrete beams through analytical calculations. The objective is to evaluate crack width behavior under varying amounts and configurations of reinforcement, providing recommendations for optimal load-carrying steel arrangements to limit crack width. The research methodology involves numerical simulations using ETABS and adheres to the design guidelines specified in TCVN 5574:2018, IS 456:2000, and TCVN 9346:2012. The results show that both the quantity and arrangement of tensile reinforcement significantly affect crack formation and width. Notably, the study reveals that meeting both structural strength and crack width requirements for reinforced concrete beams in marine structures is challenging. Ensuring a maximum crack width of 0.05 mm under harsh environmental conditions, such as tidal seawater exposure, poses significant difficulties. These findings offer valuable insights for engineers in designing marine concrete structures and optimizing reinforcement layouts to meet performance and durability criteria under aggressive exposure conditions.

Keywords: *Crack width; reinforced concrete beams; marine structures; IS 456:2000 standard; TCVN 5574:2018 standard; TCVN 9346:2012 standard.*

1. Introduction

Reinforced concrete beams play a fundamental role in the construction industry due to their strength and versatility. When subjected to flexural loading, these beams experience cracking, which can impact the structural integrity and longevity of the concrete structure. Understanding the factors influencing crack development and finding effective ways to control cracks are critical for engineers and designers.

In marine construction, where structures are exposed to aggressive environmental conditions, such as saltwater and moisture, crack control becomes even more critical. Cracks can allow corrosive agents to penetrate the concrete and reach the embedded steel reinforcement, leading to accelerated deterioration [1], [2].

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The number and arrangement of vertical steel reinforcements in reinforced concrete beams are significant factors affecting crack development. This study aims to explore these factors and provide insights into optimizing steel reinforcement placement to minimize cracks and enhance the durability of structures.

Understanding crack development in reinforced concrete beams has been a subject of extensive research, resulting in various standards and guidelines for crack control. Relevant standards include the Indian standard IS 456:2000 [3], European standard EN 1992-1-1-2004 [4], Egyptian standard ECP-203 [5], American standard ACI 318-95 [6], Gergely and Lutz [7], Frosch [8], Vietnamese standard TCVN 5574:2018 [9].

These standards provide methods for calculating crack width and moment resistance. As observed, the calculation procedures for crack width and moment resistance according to the Vietnamese standard TCVN 5574:2018 are more complex than other standards. Besides, IS 456:2000 shows higher crack width than other standards, according to the analysis in [1]. It also provides practical results and it is integrated into structural analysis software like ETABS. Therefore, in this study, TCVN 5574:2018, IS 456:2000 are also chosen to investigate whether the crack width satisfies the limit conditions for marine structures.

2. Crack development in reinforced concrete beams according to TCVN 5574:2018 and IS 456:2000 standard

2.1. Vietnamese standard TCVN 5574:2018

The crack width (A_{crc}) can be determined using the following formula:

$$A_{crc} = \varphi_1 \varphi_2 \varphi_3 \psi_s \frac{\sigma_s}{E_s} L_s \quad (1)$$

where σ_s is the stress in the tensile longitudinal reinforcement at the perpendicular section with cracks induced by the corresponding external forces.

$$\sigma_s = \frac{M(h_0 - y_c)}{I_{red}} \alpha_{s1}; \quad I_{red} = I_{bt} + \alpha_{s1} I_s + \alpha_{s2} I_s^{'} \quad (2)$$

in which I_{red} , y_c respectively denote the moment of inertia and the height of the compression zone of the transformed cross-section, determined considering only the cross-sectional area of the compression concrete zone, the cross-sectional areas of the steel reinforcement under tension and compression, with the conversion factor value of steel to concrete: $\alpha_{s1} = \alpha_{s2} = \frac{E_s}{E_{bt}}$.

For bending beams, $y_c = x$ where x is the height of the concrete compression zone. For a rectangular section with both tension and compression steel reinforcement, the height of the concrete compression zone is determined by the following:

$$x = h_0 \cdot \left(\sqrt{\left(\mu_s.\alpha_{s2} + \mu_s^{'}.\alpha_{s1} \right)^2 + 2.\left(\mu_s.\alpha_{s2} + \mu_s^{'}.\alpha_{s1} \cdot \frac{a'}{h_0} \right)} - \left(\mu_s.\alpha_{s2} + \mu_s^{'}.\alpha_{s1} \right) \right) \tag{3}$$

L_s is the basic distance (regardless of the influence of the type of reinforcement surface) between adjacent perpendicular cracks.

$$L_s = 0.5 \frac{A_{bt}}{A_s} d_s, \quad L_s \geq \{10 d_s, 10\,\text{cm}\},\ L_s \leq \{40 d_s, 40\,\text{cm}\} \tag{4}$$

in which A_{bt} is the cross-sectional area of tensile concrete; A_s is the cross-sectional area of tensile reinforcement; d_s is the nominal diameter of the steel reinforcement.

ψ_s is a coefficient accounting for the irregular distribution of relative strain of tensile reinforcement between cracks; It is allowed to take $\psi_s = 1$, if under this condition, the requirement for $M > M_{crc}$ is not satisfied, the value of ψ_s needs to be determined according to the formula:

$$\psi_s = 1 - 0.8 \frac{M_{crc}}{M} \tag{5}$$

M_{crc} is the crack formation moment, taking into account inelastic deformations of the tensile concrete area. W_{pl} is the elastic bending resistance moment of the section with respect to the outermost layer of concrete under tension. To determine ψ_s, the following quantities need to be determined:

$$\begin{aligned} &M_{crc} = W_{pl} R_{bt,ser} \pm N e_x; \\ &W_{pl} = 1.3 \times W_{red};\ e_x = \frac{W_{red}}{A_{red}}; \\ &W_{red} = \frac{I_{red}}{y_t};\ y_t = \frac{S_{t,red}}{A_{red}};\ A_{red} = A_{bt} + \alpha_{s1} A_s + \alpha_{s2} A_s^{'}; \\ &S_{t,red} = 0.5 \times A_{bt} \times h + (\alpha_{s1} A_s a + \alpha_{s2} A_s^{'} (h - a')) \end{aligned} \tag{6}$$

where y_t is the distance from the most tensile concrete fiber to the centroid of the transformed cross-section, $S_{t,red}$ is the static moment of the transformed cross-sectional area for the more tensile concrete layer.

φ_1 is a coefficient considering the duration of the load, taking the values: 1.0 when there is a short-term effect of the load; 1.4 when there is a long-term effect of the load;

φ_2 is a coefficient related to the surface condition of the longitudinal steel reinforcement, taking the values: 0.5 for ribbed steel bars and cables; 0.8 for plain steel bars;

φ_3 is a coefficient related to the load-carrying characteristics, taking the values: 1.0 for members subjected to bending and eccentric compression; 1.2 for members subjected to tension.

2.2. Indian standard IS 456:2000

The crack width (W_{cr}) can be determined using the following formula:

$$W_{cr} = \frac{3a_{cr}\varepsilon_m}{1+\dfrac{2(a_{cr}-c_{\min})}{h-x}} \tag{7}$$

with $\varepsilon_m = \varepsilon_1 - \dfrac{b(h-x)(a-x)}{3E_s A_s (d-x)}$; $\varepsilon_1 = \dfrac{M.x}{I_C(0.5E_C)}$; $I_c = \dfrac{bx^3}{3} + (mA_{st}(d-x)^2)$

where I_c is moment of inertia of the cracked section; ε_m is average steel strain; a_{cr} is distance from the point considered to the surface of the nearest longitudinal bar; $c_{\min}$ is minimum cover to the longitudinal bar; *h* or *D* is overall depth of the beam; *x* is depth to the neutral axis; E_s is modulus of elasticity of steel; *a* is distance from the compression face to the point at which the crack width is being calculated; A_s is area of the tension reinforcement; ε_1 is strain at the level consideration, calculated ignoring the stiffening of the concrete in the tension zone; *b* = width of the flange; *d* is effective depth (Fig. 1); $m = \dfrac{280}{3R_{bn}}$: Modulus ratio.

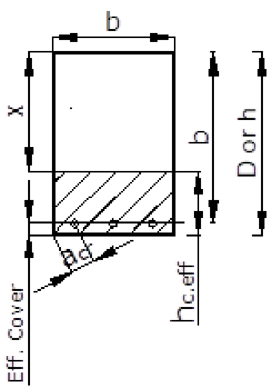

Fig. 1. Cross-section of the beam.

2.3. Material parameters

a) Beam and load

Specifications for the reinforced concrete beam include (Fig. 2):

Length: $L = 6$ m

Cross-section: $b \times h = 250 \times 400$ mm

Cover thickness: $a_{cr} = 25$ mm

Self-weight: Calculated by software (ETABS)

Additional load: Concentrated load at midspan: $P = 58.5$ kN

b) Concrete

Concrete properties are as follows:

Concrete strength: M15 (B20)

Unit weight: 25 kN/m^3

Density: 2548 kg/m^3

Modulus of elasticity: $E_c = 19365$ MPa

Shear modulus: $G = 8068.72$ MPa

Compressive strength of concrete: $R_{bn} = 15$ MPa

c) Steel reinforcement

Steel type: Fe325 (CB300-V)

Unit weight: 77 kN/m^3

Density: 7849.05 kg/m^3

Modulus of elasticity: $E_s = 210000$ MPa

Tensile strength: $R_s = R_{sc} = 345$ MPa

Ultimate strength: $F_u = 450$ MPa

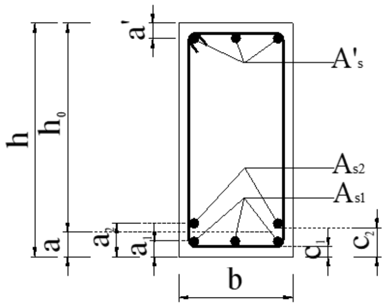

Fig. 2. Arrange steel in beam section.

2.4. Survey problems

a) Steel reinforcement requirement by ETABS

Steel for compression: 2ϕ14 ($A_s^{'} = 3.08$ cm^2). Positive moment (M$^+$) between supports: 100 kNm. Minimum tensile steel area A_s (steel for tension): **16.43** cm^2.

b) Considered problem cases

Case 1: Influence of clear cover

In this case, the clear cover was varied incrementally from 25 mm to 50 mm in steps of 5 mm. The beam section was considered with a width of 250 mm, a depth of 400 mm, and reinforcement consisting of three bars with a diameter of 28 mm, while the applied moment was set at 100 kNm. This setup was used to compare crack width predictions based on different code provisions and models from the literature.

Case 2: Single layer of tensile steel arrangement

Two/three/four steel bars carrying positive moment with diameters ranging from 16 mm to 36 mm would be considered.

Case 3: Double layer of tensile steel arrangement

Four/five/six steel bars carrying positive moment with diameters ranging from 16 to 50 mm would be considered.

3. Calculation results of crack width

3.1. Case 1 - Influence of clear cover

According to [1], only the Egyptian Code 203-2007 predicts a crack width of approximately 0.1 mm, while other codes (BS EN 1992-1-1-2004, ACI, Gergely and Lutz, Frosch, IS 456:2000) estimate crack widths ranging from 0.1 mm to 0.2 mm. For all considered clear cover values, the IS 456:2000 code consistently predicts larger crack widths. Additionally, it was observed that as the clear cover increases, the crack width also increases. The findings in Fig. 3 indicate that the Vietnamese standard TCVN 5574:2018 also produces smaller crack widths compared to IS 456:2000 while still showing a similar trend of increasing crack width with larger clear covers.

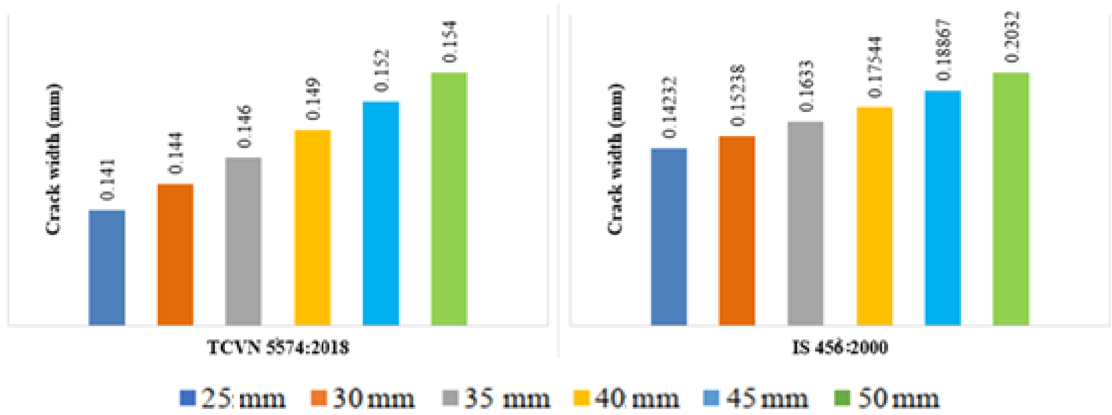

Fig. 3. Impact of clear cover variation on crack width development.

3.2. Case 2 - Single layer for two/three/four steel bars carrying positive moment with diameters changing

Calculation results for crack width (W_{cr} for Indian standard and A_{crc} for Vietnamese standard) with varying steel bar diameters are presented in Tabs. 1-3 for case of two/three/four steel bars respectively. Note that, the Vietnamese standard restricts the diameter of longitudinal steel to 40 mm (Eq. (4)). In addition, although the Vietnamese standard does not specify the maximum steel reinforcement content, for bending members, the standard limits the relative height of the concrete compression zone. Therefore, this content depends on the steel grade and concrete strength class. According to [11], μ_{max} = 2.57%, or A^{s}_{max} = 25.7 cm².

Tab. 1. Crack width (W_{cr} for IS 456:2000 and a_{crc} for TCVN 5574:2018) - case of two steel bars and single layer

Number of bars	ϕ (mm)	A_s (cm²)	W_{cr} (mm)	A_{crc} (mm)
2	16	4.02	0.412	0.673
2	18	5.09	0.404	0.538
2	20	6.28	0.388	0.441
2	22	7.60	0.364	0.369
2	25	9.82	0.315	0.291
2	28	12.32	0.255	0.236
2	32	16.08	0.177	0.185
2	**36**	**20.36**	0.115	0.149
2	**40**	**25.13**	**0.096**	0.123

Tab. 2. Crack width (W_{cr} for IS 456:2000 and A_{crc} for TCVN 5574:2018) - case of three steel bars and single layer

Number of bars	ϕ (mm)	A_s (cm²)	W_{cr} (mm)	A_{crc} (mm)
3	16	6.03	0.390	0.454
3	18	7.63	0.362	0.364
3	20	9.42	0.322	0.299
3	22	11.40	0.275	0.250
3	25	14.73	0.202	0.198
3	**28**	**18.47**	0.139	0.152
3	**32**	**24.13**	**0.079**	0.101

Tab. 3. Crack width (W_{cr} for IS 456:2000 and A_{crc} for TCVN 5574:2018) - case of four steel bars and single layer

Number of bars	ϕ (mm)	A_s (cm²)	W_{cr} (mm)	A_{crc} (mm)
4	16	8.04	0.352	0.344
4	18	10.18	0.303	0.276
4	20	12.57	0.248	0.226
4	22	15.21	0.193	0.172
4	**25**	**19.63**	0.124	0.117

As illustrated in Fig. 4, as the diameter of the longitudinal steel bars increases (resulting in an increased longitudinal steel area), the crack width decreases significantly and tends to a value of 0.1 mm. Vietnamese standards give crack width values significantly higher than Indian standards when the reinforcement diameter is small ($\phi \leq 18$) and in the case of 2 or 3 reinforcing bars. In the remaining cases, the difference between the two standards is quite small. Fig. 3 also illustrates the trend of decreasing crack width as the diameter of longitudinal steel bars increases. In terms of values, when comparing case of two steel bars to case of three/four steel bars, the crack width increases significantly. The more the number of steel bars in a row, the smaller the crack width.

Both standards (IS 456:2000 and TCVN 9346:2012 [10]) stipulate that, in general cases, the crack width should not exceed 0.3 mm in members where cracking is not harmful and does not have any serious adverse effects upon the preservation of reinforcing steel nor upon the durability of the structures. In members where cracking in the tensile zone is harmful either because they are exposed to the effects of the weather or continuously exposed to moisture or in contact soil or groundwater, an upper limit of 0.2 mm is suggested for the maximum width of cracks. For particularly aggressive environment, such as: concrete surfaces exposed to severe rain, concrete completely immersed in seawater or concrete exposed to coastal environment, in general, the allowable crack width is not exceed 0.1 mm. Especially, for outdoor structures exposed to alternating wetting and drying conditions, TCVN 9346:2012 also stipulates that this value should be less than 0.05. Therefore, the crack width limit condition significantly affects the load-bearing steel area of the component and needs attention in the structural design calculations.

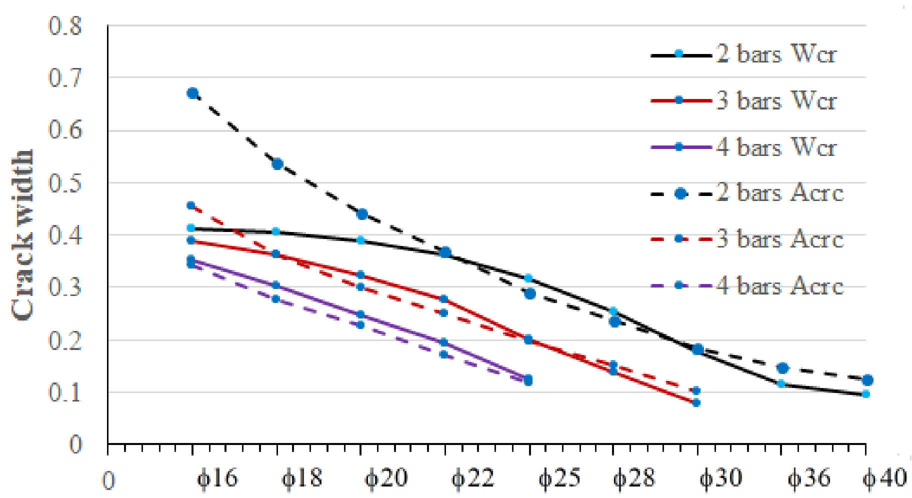

Fig. 4. Crack width variation for IS 456:2000 (W_{cr} - continuous lines) and TCVN 5574:2018 standards (A_{crc} - dashed lines) - case of single layer.

Tables 1-3 demonstrate that, in the case of marine structures, when the crack width limit is set at 0.2 mm, the two standards prescribe an area of steel required for cracking equivalent to that needed for strength in most cases. However, to meet the crack width limit condition of 0.1mm, if a single-layer steel reinforcement is employed, both standards are difficult to meet the requirement. As can be seen, only two options of Indian criteria (2ϕ40 and 3ϕ32) are satisfy to meet both the strength and crack width. The Vietnamese standard poses more challenges in achieving the crack requirement. It should be noted that TCVN 5574:2018 also stipulates that the diameter of the reinforcement bars must not exceed 32 mm and 1/10 of the member width, which is 25 mm in this example. Accordingly, only the arrangement of 4ϕ25 in a single row satisfies the strength requirement; however, this configuration does not meet the crack width limitation.

However, according to other standards such as the European standard EC2 [4], this type belongs to the XS2 grade with a crack width limit requirement of 0.3 mm. In this case, arranging a single layer of steel becomes easier to meet the crack requirement.

3.3. Case 3 - Double layer for four/five/six steel bars carrying positive moment with diameters changing

Figure 5 shows that with the same steel diameter, increasing the quantity of steel significantly reduces the crack width for both standards. Vietnamese standards consistently yield lower crack width values than Indian standards when ϕ ≤ 25 mm. However, when keeping the quantity of steel constant and increasing the steel diameter substantially, the Vietnamese standard does not exhibit a rapid reduction of crack width to zero value, as observed in the Indian standard.

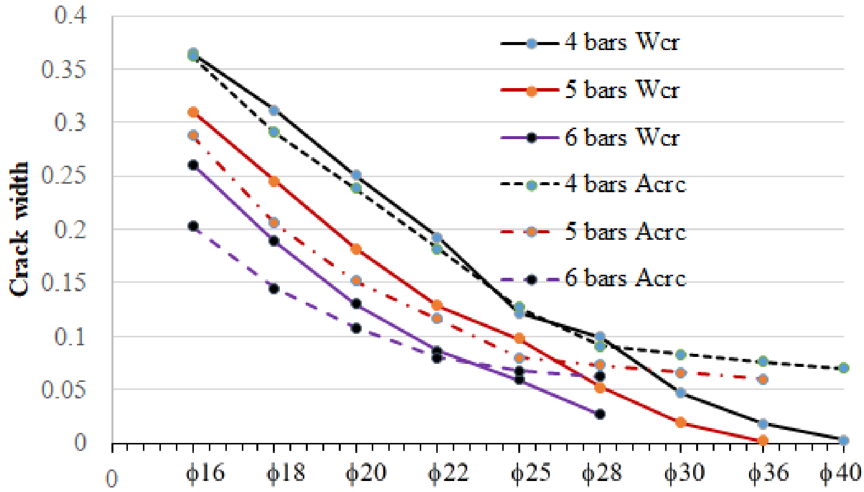

Fig. 5. Crack width variation for IS 456:2000 (W_{cr} - continuous lines) and TCVN 5574:2018 standards (A_{crc} - dashed lines) - case of double layer.

Tables 4-6 demonstrate that as the number of steel bars increases, for both two standards, the diameter of the steel bars decreases to satisfy the strength condition. All options following the Indian and Vietnamese standards easily satisfy the crack width condition more readily than the strength condition in case of using the crack width limit condition of 0.2 mm, but normally after satisfying the strength condition.

Tab. 4. Crack width (W_{cr} for IS 456:2000 and A_{crc} for TCVN 5574:2018) - 4 steel bars - double layer

Number of bars	ϕ (mm)	As (cm^2)	W_{cr} (mm)	A_{crc} (mm)
4	16	8.04	0.365	0.362
4	18	10.18	0.312	0.291
4	20	12.57	0.251	0.238
4	22	15.21	0.193	0.182
4	**25**	**19.63**	0.122	0.127
4	**28**	**24.63**	**0.099**	**0.091**
4	32	28.27	0.047	0.083
4	36	36.32	0.018	0.076
4	40	40.72	0.003	0.070

Tab. 5. Crack width (W_{cr} for IS 456:2000 and A_{crc} for TCVN 5574:2018) - 5 steel bars - double layer

Number of bars	ϕ (mm)	As (cm^2)	W_{cr} (mm)	A_{crc} (mm)
5	16	10.05	0.310	0.288
5	18	12.72	0.245	0.206
5	20	15.71	0.182	0.152
5	22	19.01	0.129	0.116
5	**25**	**24.54**	**0.098**	**0.080**
5	28	30.79	0.052	0.073
5	32	40.21	0.019	0.066
5	36	50.89	0.002	0.060

Tab. 6. Crack width (W_{cr} for IS 456:2000 and A_{crc} for TCVN 5574:2018) - 6 steel bars - double layer

Number of bars	ϕ (mm)	As (cm^2)	W_{cr} (mm)	A_{crc} (mm)
6	16	12.06	0.261	0.203
6	18	15.27	0.189	0.145
6	**20**	**18.85**	0.130	0.108
6	**22**	**22.81**	**0.086**	**0.080**
6	25	29.45	0.059	0.068
6	28	36.95	0.027	0.062
6	32	48.26	0.005	0.056

The arrangement of double layers of steel is more likely to meet the crack width limit requirement of 0.1 mm than the arrangement of single layer of steel. Both standards exhibit a close resemblance in terms of steel arrangement outcomes when opting for a crack width limit of 0.1 mm (refer to the bolted texts in Tabs. 4-6). However, if this limit is reduced to 0.05 mm, compliance with the Vietnamese standard becomes challenging, as the curve depicting crack width against diameter tends to decrease very gradually with an increase in steel diameter (Fig. 4), whereas the Indian standard can still be achieved.

To gain a deeper understanding, it is essential to investigate the influence of the cover thickness, cross-sectional dimensions (b, h), applied bending moment, and other factors. Note that when the clear cover increases the crack width also increases and increasing the cross-sectional dimensions (b, h) can be challenging for marine structures, as it is often associated with material transportation issues. Within the scope of this study, the concrete strength is proposed to explore its ability to meet the crack width limit under challenging environmental conditions on the structure (specifically, when the crack width limit is set at 0.05 mm). Width (b) 250 mm, height (h) 400 mm, cover thickness 25 mm, varying concrete strengths of B30, B40, B50, B60, and different steel arrangements, including single/double layer, multiple diameters, and various numbers of bars, are considered based on Vietnamese standard, to investigate whether the crack width satisfies the limit conditions of 0.1 mm and 0.05 mm.

From Tab. 7, it is evident that achieving crack width limits of 0.1 mm and 0.05 mm for marine structures is not easily attainable, even with increased concrete strength and minimized cover thickness. This condition significantly impacts the longitudinal bar area of the component and requires careful consideration in structural design calculations. The most effective solution may involve increasing the height of the cross-section, which will take more cost.

Tab. 7. Table examining the crack width (A_{crc}) as concrete strength varies

ϕ	B30						B40					
	Single - layer			Double - layer			Single - layer			Double - layer		
	2 bars	3 bars	4 bars	4 bars	5 bars	6 bars	2 bars	3 bars	4 bars	4 bars	5 bars	6 bars
16	0.64455	0.43428	0.32831	0.34578	0.27416	0.19355	0.62089	0.41764	0.31527	0.33214	0.26302	0.18551
18	0.51522	0.34774	0.26322	0.27771	0.19584	0.13841	0.496	0.33418	0.25258	0.26656	0.18775	0.13257
20	0.42217	0.28539	0.21512	0.22736	0.14513	0.10266	0.40618	0.27408	0.20629	0.21809	0.13905	0.09828
22	0.35291	0.23891	0.16387	0.17349	0.11078	0.07843	0.33935	0.22931	0.15706	0.16633	0.10609	0.07505
25	0.27794	0.18851	0.11391	0.12092	0.07722	0.06447	0.26705	0.1808	0.10911	0.11586	0.07392	0.06167
28	0.2584	0.17535	0.10192	0.10845	0.07352	0.06256	0.24822	0.16814	0.0976	0.10389	0.07036	0.05984
32	0.19834	0.11922		0.08262	0.06583	0.05614	0.19036	0.11424		0.07912	0.06299	0.05371
36	0.15767	0.09123		0.07532	0.05989		0.15122			0.07212	0.05732	
40	0.11733	0.07996		0.06703			0.11246			0.06421		

ϕ	B50						B60					
	Single - layer			Double - layer			Single - layer			Double - layer		
	2 bars	3 bars	4 bars	4 bars	5 bars	6 bars	2 bars	3 bars	4 bars	4 bars	5 bars	6 bars
16	0.5983	0.40179	0.30285	0.31918	0.25242	0.17785	0.57933	0.3885	0.29246	0.30833	0.24356	0.17145
18	0.47773	0.32131	0.24248	0.256	0.18007	0.12702	0.4624	0.31054	0.23403	0.24718	0.17366	0.12238
20	0.39103	0.26338	0.19793	0.20934	0.13329	0.09412	0.37833	0.25443	0.19094	0.20202	0.12848	0.09064
22	0.32654	0.22025	0.15061	0.15958	0.10165	0.07184	0.31581	0.21267	0.14523	0.15394	0.09793	0.06916
25	0.2568	0.17353	0.10456	0.11108	0.07078	0.05901	0.24822	0.16746	0.10077	0.1071	0.06816	0.05678
28	0.23863	0.16135	0.09352	0.0996	0.06737	0.05725	0.23062	0.15568	0.09011	0.096	0.06487	0.05508
32	0.18287	0.10955		0.07581	0.06029	0.05137	0.17661	0.10563		0.07303	0.05802	**0.0494**
36	0.14518			0.06908	0.05485		0.14013			0.06652	0.05278	
40	0.10789			0.0615			0.10406			0.05921		

To clarify the influence of steel distribution on the value of crack width for both standards, we will further evaluate how similar steel area distributions affect the difference in W_{cr} and A_{crc} values (Tab. 8). All three cases 1, 2, and 3 satisfy the strength requirement.

The results in Tab. 8 indicate that, to achieve a smaller crack width, it is preferable to select a larger number of steel bars with smaller diameters for double-layer arrangements (6ϕ20) or maximum number and diameter for single-layer arrangements (4ϕ26). This also enhances the load-bearing capacity by increasing the height of the compressed zone. Furthermore, with the same choice of steel bars, a double-layer arrangement slightly reduces W_{cr} (for Indian standard) but not always reduces A_{crc} (for Vietnamese standard) compared to a single-layer arrangement.

Tab. 8. Comparing steel arrangement options

No.	Single layer	A_s (cm^2)	W_{cr} (mm)	A_{crc} (mm)	Double layer	A_s (cm^2)	W_{cr} (mm)	A_{crc} (mm)
1	3ϕ28	18.47	0.139	0.152	**6ϕ20**	18.85	0.130	0.108
2	4ϕ25	19.63	0.124	0.117	4ϕ25	19.63	0.122	0.127
3	**4ϕ26**	21.24	0.105	0.103	4ϕ26	21.24	0.104	0.114

In addition, according to the provisions of TCVN 9346:2012, for conditions involving tidal seawater exposure, B40 concrete requires a protective concrete cover thickness of 70 mm, while B50 concrete requires a thickness of 60 mm. The results are presented in Tab. 9. It can be observed that none of the reinforcement arrangements satisfy the crack width limitation of 0.05 mm.

Tab. 9. Evaluation of crack width (A_{crc}) according to TCVN 9346:2012
for tidal seawater exposure conditions

ϕ	B50, a0=60mm						B40, a0=70mm					
	Single - layer			Double - layer			Single - layer			Double - layer		
	2 bars	3 bars	4 bars	4 bars	5 bars	6 bars	2 bars	3 bars	4 bars	4 bars	5 bars	6 bars
16	0.66711	0.44913	0.33935	0.38282	0.29931	0.21459	0.71541	0.48257	0.36526	0.42132	0.23465	0.23683
18	0.53296	0.35937	0.27186	0.30742	0.21374	0.15344	0.57191	0.38641	0.29283	0.33867	0.17401	0.1695
20	0.43647	0.29474	0.22203	0.25168	0.15838	0.11383	0.46866	0.31714	0.23933	0.27751	0.13292	0.12584
22	0.36467	0.2466	0.16904	0.19208	0.12089	0.08698	0.39181	0.2655	0.18232	0.21196	0.09277	0.09623
25	0.287	0.19444	0.11744	0.13393	0.0843	0.07156	0.30863	0.20953	0.12677	0.14795	0.08825	0.08322
28	0.26677	0.18083	0.10506	0.11996	0.08018	0.06539	0.28695	0.19492	0.11343	0.13255	0.08318	0.0768
32	0.23246	0.14944		0.09746	0.07554	0.05892	0.25018	0.16116		0.13578	0.07877	0.07244
36	0.20462	0.12289		0.09092	0.07151		0.22032			0.11337	0.07489	0.06864
40	0.1817	0.10239		0.08644			0.19573			0.09589		0.0653

4. Conclusion

The control of crack width plays a crucial role in the design of flexural members, particularly in marine structures. It is essential to consider crack width limit during the design process because there are instances where steel arrangements meet the strength requirements but fail to meet the crack conditions.

When arranging the same number of steel layers, an increase in the steel area results in a reduction in crack width. For a given steel reinforcement area meeting strength requirements, choosing a larger number of steel bars with smaller diameters for both single-layer and double-layer arrangements is preferable. The two-layer steel arrangement is easier to meet the strict crack width limit requirements for marine structures than the single-layer steel arrangement.

Finally, satisfying the crack width limit conditions of 0.1mm and 0.05mm in the Vietnamese standard for marine structures requires careful consideration, as it is more challenging to meet compared to the application of other standards.

This study highlights the critical importance of controlling crack width in the design of reinforced concrete beams. By optimizing the arrangement and quantity of tensile reinforcements, engineers and designers can effectively manage crack development and enhance the durability of structures, especially in aggressive environments. Further research will investigate whether, with the replacement of the TCVN 5574:2012 standard by the TCVN 5574:2018 standard, the requirements for corrosion protection in Vietnam's marine environment specified in Vietnamese standard TCVN 9346:2012 remain applicable.

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KIỂM SOÁT CHIỀU RỘNG VẾT NỨT TRONG THIẾT KẾ DẦM BÊ TÔNG CỐT THÉP TRONG MÔI TRƯỜNG BIỂN

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Tóm tắt: Dầm bê tông cốt thép được sử dụng rộng rãi trong xây dựng và việc hiểu rõ sự phát triển của vết nứt là yếu tố cần thiết để đảm bảo an toàn và độ bền cho công trình, đặc biệt trong môi trường biển. Nghiên cứu này tập trung phân tích ảnh hưởng của cốt thép chịu kéo đến chiều rộng vết nứt trong dầm bê tông cốt thép thông qua các phép tính lý thuyết. Mục tiêu là đánh giá sự thay đổi chiều rộng vết nứt theo số lượng và cách bố trí cốt thép khác nhau, từ đó đề xuất các phương án bố trí cốt thép chịu lực hợp lý nhằm hạn chế chiều rộng vết nứt. Phương pháp nghiên cứu bao gồm mô phỏng số bằng phần mềm ETABS, tuân thủ theo các hướng dẫn thiết kế trong tiêu chuẩn TCVN 5574:2018, IS 456:2000 và TCVN 9346:2012. Kết quả cho thấy cả số lượng và cách bố trí cốt thép chịu kéo đều ảnh hưởng đáng kể đến sự hình thành và chiều rộng vết nứt. Đặc biệt, nghiên cứu đã chỉ ra rằng khả năng đáp ứng đồng thời các yêu cầu về độ bền và chiều rộng vết nứt của dầm bê tông cốt thép trong kết cấu công trình biển là một thách thức. Việc đảm bảo chiều rộng vết nứt tối đa là 0,05 mm trong điều kiện môi trường khắc nghiệt, ví dụ như vùng nước biển lên xuống, đặt ra những khó khăn đáng kể. Những phát hiện này cung cấp những hiểu biết có giá trị cho kỹ sư trong việc thiết kế kết cấu bê tông công trình biển và tối ưu hóa cách bố trí cốt thép để đáp ứng các yêu cầu về khả năng chịu lực và độ bền lâu trong môi trường xâm thực mạnh.

Từ khóa: *Chiều rộng vết nứt; dầm bê tông cốt thép; kết cấu công trình biển; tiêu chuẩn IS 456:2000; tiêu chuẩn TCVN 5574:2018; tiêu chuẩn TCVN 9346:2012.*

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