

Crack Width Comparison between ACI 318, Eurocode 2 and GB 50010 for Flexural RC Members

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How to cite this paper: Liu, G.Q. and Lu, Z.Y. (2024) Crack Width Comparison between ACI 318, Eurocode 2 and GB 50010 for Flexural RC Members. *Open Journal of Civil Engineering*, 14, 116-126.
<https://doi.org/10.4236/ojce.2024.141006>

Received: February 22, 2024

Accepted: March 24, 2024

Published: March 27, 2024

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Abstract

Comparative research on different countries' structural design codes holds great importance and can gain valuable insights: Awareness of Design Levels, Identifying Code Deficiencies and Optimizing Designs. The crack width of concrete structure is an important design aspect of the civil design. The four highly recognized and widely used crack width theories are systematically summarized. Based on the mentioned theories and project practices, American code ACI system, Eurocode 2 1992-1 and Chinese code GB 50010 have different crack width control requirement and calculation methods. The crack width control method based on ACI system code has evolved from the Z-factor method to the steel bar spacing control method which is simple and easy to be adopted for engineering. Meanwhile, the ACI 224.1R also gives a direct crack width calculation method consistent with the steel bar spacing control method. The Eurocode 2 and GB 50010 based on the bond-slip & no-slip theory consider much more affecting factors than ACI for predicting crack width. Taking the crack width calculation of Tunnel 5 intake as an example, the crack widths of the structure are calculated according to ACI system code, Eurocode 2 and GB 50010 respectively, the results show that the crack width results in various codes are not much different. The EN 1992-1 and GB 50010 results are almost the same which are less than the ACI 224.1R results.

Keywords

Crack Width, Structure Serviceability, Comparative Analysis

1. Introduction

Crack width elevation is one of the serviceability requirements in the structural

concrete design. Control of cracking in concrete structure is important for obtaining aesthetics appearance and for long-term durability. Since there are many factors that affect the width of cracks in concrete structures, the crack control methods and crack width calculations are quite different in various countries design codes. This paper focuses on the crack control method based on American concrete design code ACI 318 and its evolution process [1] [2]. As a supplement, the direct calculation method of the crack width is also described referring to ACI 224.1R [3] and ACI 350 [4]. Furthermore, this paper also points out the crack width calculation methods based on Eurocode 2 [5] and Chinese code GB 5010 [6] as a comparison to the ACI code. At last, various code equations are adopted for prediction and evaluation of AWTIP tunnel 5 intake structure. The adopted crack width calculation method and width limit can provide guidelines for similar project practice.

2. Crack Width Calculation Theory

Since the 1930s, Scholars from various countries have conducted extensive research on the mechanism of crack generation and factors affecting crack width, and have proposed a variety of calculation theories and different calculation methods based on these theories. The highly recognized and widely used crack width theories are as follows: bond-slip theory, no-slip theory, bond-slip & no-slip theory, and experimental-based mathematical statistics method.

2.1. Bond-Slip Theory

The bond-slip theory was proposed by R.Saligar in 1936. The bond-slip theory holds that crack mainly depends on the bonding force between steel bar and concrete. At the cracked section, the bond failure occurs between the steel bar and the concrete. When the steel bar elongates, the concrete rebounds and produces relative slippage. The relative slippage is the width of the crack development [Refer to **Figure 1(a)**].

2.2. No-Slip Theory

The no-slip theory was established in the 1960s. The theory believes that within the allowable crack width range, the relative slip between the deformed steel bar and the concrete can be ignored; assuming that the crack width on the steel bar surface is zero, the strain gradient from the cracked section steel bar to the structure surface is used as the mechanism to calculate the crack. The main factor affecting the crack width is the distance from the calculated point to the nearest steel bar, that is, the thickness of the concrete cover; the surface crack width is only formed by the uneven stress and deformation of the concrete around the steel bar. Therefore, the elastic theory method can be used to calculate the strain difference between the steel bar and a certain position to determine the crack width at that position [Refer to **Figure 1(b)**].

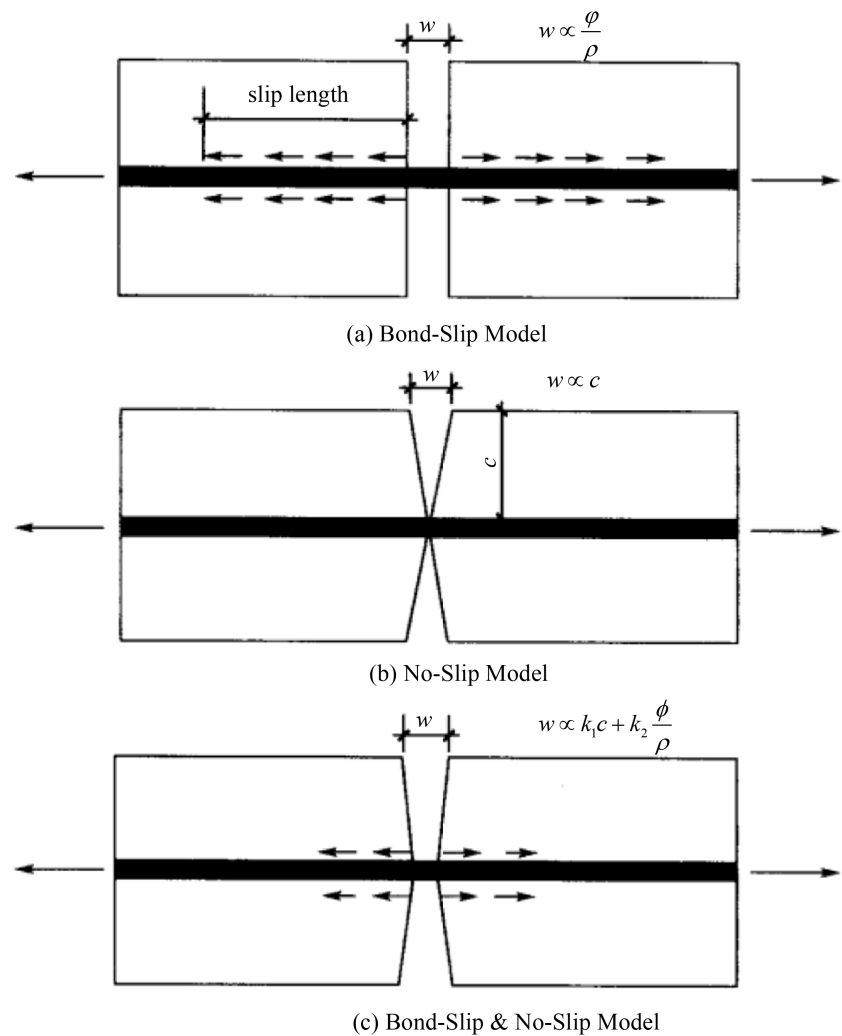


Figure 1. Theoretical model of cracks in reinforced concrete members.

2.3. Bond-Slip & No-Slip Theory

The bond-slip theory and the no-slip theory respectively describe two extreme situations of the crack mechanism of component concrete, and the real situation of the crack is between the two states. Therefore, the British scholar Bee by proposed the bond-slip & no-slip theory. This calculation theory not only considers the effect of strain gradient, but also considers the possible bond slip of steel bars, and puts forward the concept of effective embedding area of steel bars. According to the theory, the crack width on the surface of the component depends on the distance from the crack measurement point to the nearest steel bar (related to the concrete cover and the steel bar spacing). Cracks are caused by the retraction of the concrete around the steel bar, and each steel bar has a certain range of restraint on the rebound of the concrete, that is, the area where the tensile force is diffused to the concrete through the bonding force, and the area that can effectively restrain the rebound of the concrete is called the effective embedding area. In the embedding area, the reinforcement does not control the cracks

outside this area [Refer to **Figure 1(c)**].

2.4. Mathematical Statistics Method

The mathematical statistical method was first proposed by the American scholar Gergely-Lutz in 1968. They conducted statistical analysis on the crack test data of six groups of flexural members to determine the importance of each influencing factor. The main factors that determine the crack width include: the thickness of the concrete cover of the side or bottom edge, the effective cross-sectional area of the tensile concrete, the number of steel bars, the strain gradient from the steel bar to the tensile edge of the section, and the stress of the steel bar, among which the stress of the steel bar is the most important factor.

3. Crack Width Prediction Based on Various Building Codes Provisions

The American code ACI adopts mathematical statistical method and the no-slip theory at different periods while the Eurocode 2 and Chinese code GB 50010 adopt the bond-slip & no-slip theory.

3.1. American Code ACI

In the American code ACI system, the method of crack control in the design of concrete structures mainly comes from *Building Code Requirements for Concrete and Commentary* (ACI 318-19), *Control of Cracking in Concrete Structures* (ACI 224R-01), *Causes, Evaluation, and Repair of Cracks in Concrete Structures* (ACI 224.1R-07) and *Code Requirements for Environmental Engineering Concrete Structures and Commentary* (ACI 350M-06).

3.1.1. ACI 318

In the American ACI 318 code system, the concrete structure crack control method has generally gone through two stages. The z-factor method was used in the editions from 1971 to 1995; ACI 318-99 has been using the steel bar spacing control method since then.

1) Z-factor method

The z-factor method is developed by Gergely and Lutz based on the mathematical statistical method, which is applicable to situations where the thickness of the concrete cover is not greater than 50mm. the equation proposed by the version of ACI 318-95 [1] is as follows:

$$W_{\max} = 0.011\beta f_s \sqrt[3]{d_c A} \times 10^{-3} \quad (1)$$

where W_{\max} is the maximum crack width, mm; β is the ratio of distance between neutral axis and extreme tension face to distance between neutral axis and centroid of steel bar, $\beta = 1.20$ may be adopted in the beams to compare the crack widths obtained in flexure and axial tension; d_c is the thickness of concrete cover measure from extreme tension fiber to centroid of tension reinforcement, mm; A is the effective tension area if concrete surrounding the

flexural tension reinforcement and having the same centroid as that reinforcement, divided by the number of bars or wires, when the flexural reinforcement consists of different bar or wire sizes the number of bars or wires shall be computed as the total area of the largest bar or wire used, mm^2 ; f_s is calculated stress in reinforcement at service loads, MPa.

From Equation (1), the resulting parameter z expression is as follows:

$$z = f_s \sqrt[3]{d_c A} = \frac{W_{\max}}{1.1\beta} \times 10^{-5} \quad (2)$$

A maximum value of $z = 31 \text{ kN/mm}$ is permitted for interior exposure, corresponding to a limiting crack width of 0.41 mm , while a maximum value of $z = 25 \text{ kN/mm}$ is permitted for exterior exposure, corresponding to a limiting crack width of 0.33 mm .

2) Steel Bar Spacing Control Method

Research experiments show that when the thickness of the concrete cover is greater than 50 mm , the accuracy of the crack width result by the z -factor method cannot meet the requirements. Makhlouf found that when the thickness of the concrete cover doubled, the measured crack width increased by 16% , while the value calculated by the Gergely-Lutz equation increased by 86% , which overestimated the influence of the cover thickness on the crack width [7]. In addition, crack widths in structures are highly variable which is difficult to be calculated accurately. Therefore, the ACI 318-19 provisions for spacing are intended to limit surface cracks to a width that is generally acceptable in practice but may vary widely in a given structure. The role of cracks in the corrosion of reinforcement is controversial. Research shows that corrosion is not clearly correlated with surface crack widths in the range normally found with reinforcement stresses at service load levels. For this reason, the Code does not differentiate between interior and exterior exposures.

ACI 318-19 proposed the following equation of maximum spacing of bonded reinforcement in non-prestressed and Class C prestressed one-way slabs and beams for crack control within 0.40 mm :

$$[s] = 380 \left(\frac{280}{f_s} \right) - 2.5c_c \quad (3)$$

$$[s] = 300 \left(\frac{280}{f_s} \right) \quad (4)$$

where $[s]$ is the maximum spacing of reinforcement closest to tension face, mm; c_c is clear cover of reinforcement, mm.

Compare the steel bar spacing s with the calculated $[s]$, if $s \leq [s]$, it indicates that the actual crack width has been limited within the allowable crack width; if $s > [s]$, the crack width is not to meet the code requirements, the diameter of steel bars can be reduced or the number of steel bars can be increased so that $s \leq [s]$ to keep the actual crack width of flexural members can be controlled within

the allowable range.

3.1.2. ACI 224.1R-07 and ACI 350M-06

In the code ACI 224.1R-07, A re-evaluation of cracking data provided a new crack width equation based on a physical model (Frosch 1999). For the calculation of maximum crack widths, the crack width can be calculated as:

$$W_{\max} = 2 \frac{f_s}{E_s} \beta \sqrt{d_c^2 + \left(\frac{s}{2}\right)^2} \quad (5)$$

From this equation, the crack width can be calculated directly. Actually, crack control is achieved in ACI 318 through the use of a spacing criterion for reinforcing steel that is based on the stress under service conditions and clear cover on the bars. This design Equation (3) was based on Equation (5) for some assumptions and simplifications, considering crack widths on the order of 0.40 mm.

The code ACI 350M-06 adopts the same equation as ACI 224.1R-07 but the thickness of clear cover in excess of 50 mm is neglected.

ACI 224R-01 suggests the reasonable crack widths of reinforcement concrete under service loads (as shown in **Table 1**).

3.2. Eurocode 2 1992-1

3.2.1. Crack Width Calculation

The Eurocode 2 provides the following expression for calculate the crack width:

$$W_k = S_{r,\max} (\varepsilon_{sm} - \varepsilon_{cm}) \quad (6)$$

where W_k is the design crack width, mm; $S_{r,\max}$ is the maximum crack spacing, mm; ε_{sm} is the mean strain in the reinforcement under the relevant combination of loads, including the effect of imposed deformations and taking into account the effects of tension stiffening. Only the additional tensile strain beyond the state of zero strain of the concrete at the same level is considered; ε_{cm} is the mean strain in the concrete between cracks, mm.

The mean tensile strain $\varepsilon_{sm} - \varepsilon_{cm}$ is given by the following equation:

$$(\varepsilon_{sm} - \varepsilon_{cm}) = \frac{\sigma_s - k_t \frac{f_{ct,eff}}{\rho_{p,eff}} (1 + \alpha_e \rho_{p,eff})}{E_s} \geq 0.6 \frac{\sigma_s}{E_s} \quad (7)$$

Table 1. Guide to reasonable crack widths.

Exposure condition	Crack width (mm)
Dry air or protective membrane	0.41
Humidity, moist air, soil	0.30
Deicing chemicals	0.18
Seawater and seawater spray, wetting and drying	0.15
Water-retaining structures	0.10

where σ_s is the stress in the tension reinforcement assuming a cracked section, MPa; α_e is the modular ratio E_s/E_{cm} ; k_t is a factor dependent on the duration of the load, 0.6 for short-term loading while 0.4 for long-term loading; $f_{ct,eff}$ is the mean value of tensile strength of the concrete effective at the time when the cracks may first be expected to occur.

$$\rho_{p,eff} = \frac{A_s + \xi_1^2 A'_p}{A_{c,eff}} \quad (8)$$

where $A_{c,eff}$ is the effective area of concrete in tension surrounding the reinforcement, mm²; A'_p is the area of pre- or post-tensioned tendons within $A_{c,eff}$, mm²; ξ_1 is the adjusted ratio of bond strength taking into account the different diameters of prestressing and reinforcing steel.

$$S_{r,max} = 3.4c + 0.425k_1k_2\varnothing/\rho_{p,eff} \quad (9)$$

where c is the cover to the longitudinal reinforcement, mm; k_1 is a coefficient which takes account of the bond properties of the bonded reinforcement: 0.8 for high bond bars while 1.6 for bars with an effectively plain surface; k_2 is a coefficient which takes account of the distribution of strain: 0.5 for bending while 1.0 for pure tension; \varnothing is the bar diameter, mm.

3.2.2. Crack Width Criterion

A limiting calculated crack width, W_{max} , taking into account the proposed function and nature of the structure and the costs of limiting cracking is recommended for relevant exposure classes are given in **Table 2**.

3.3. Chinese Code GB 50010-2010

3.3.1. Crack Width Calculation

In the reinforcement concrete tension, flexural and eccentric compression members and the prestressed concrete axial tension and flexural members with rectangle, T-shaped, inverted T-shaped and I-shaped section, the maximum width of crack (mm), according to the characteristic combination for effects of loads and in consideration of the influence of long-term actions, may be calculated according to the following equations:

Table 2. Recommended values of W_{max} (mm).

Exposure Class	Reinforced members and prestressed members with unbonded tendons	Prestressed members with bonded tendons
	Quasi-permanent load combination	Frequent load combination
X0, XC1	0.40	0.20
XC2, XC3, XC4		0.20
XD1, XD2, XS1, XS2, XS3	0.30	Decompression

$$w_{\max} = \alpha_{cr} \psi \frac{\sigma_s}{E_s} \left(1.9c_s + 0.08 \frac{d_{eq}}{\rho_{te}} \right) \quad (10)$$

$$\psi = 1.1 - 0.65 \frac{f_{tk}}{\rho_{te} \sigma_s} \quad (11)$$

$$d_{eq} = \frac{\sum n_i d_i^2}{\sum n_i v_i d_i^2} \quad (12)$$

$$\rho_{te} = \frac{A_s + A_p}{A_{te}} \quad (13)$$

where α_{cr} is stressed characteristics coefficient of member; ψ is non-uniform coefficient for stain of tensile steel reinforcement between cracks; σ_s is the stress of longitudinal steel reinforcement in reinforced concrete member, MPa; E_s is the elastic modulus of steel reinforcement, MPa; c_s is distance from the outer edge of tensile steel reinforcement in the outmost layer to the bottom edge of tension zone; ρ_{te} is the ratio of steel reinforcement for tensile steel reinforcement calculated according to effective tension sectional area of concrete; A_{te} is effective tension sectional area of concrete, mm²; A_s is sectional area of non-prestressed longitudinal steel reinforcement in tension zone, mm²; A_p is sectional area of longitudinal prestressed steel reinforcement in tension zone, mm²; d_{eq} is equivalent diameter of longitudinal steel reinforcement in tension zone, mm²; d_i is nominal diameter of type ilongitudinal steel reinforcement in tension zone, mm; n_i is number of type ilongitudinal steel reinforcement in tension zone; v_i is relative cohesion coefficient of type ilongitudinal steel reinforcement in tension zone.

3.3.2. Crack Width Criterion

The different crack control levels and the limit values of maximum crack width w_{lim} of structural members shall be adopted from **Table 3**.

4. Application and Comparison of Various Design Code Equations to Real Project Practice

The Angat Water Transmission Improvement Project (AWTIP) aims to improve the reliability and security of the raw water transmission system through partial

Table 3. Crack control levels and limit of maximum crack width.

Environmental categories	Reinforced concrete structures		Prestressed concrete structures	
	Crack control levels	w_{lim} (mm)	Crack control levels	w_{lim} (mm)
I	III	0.30(0.40)	III	0.20
IIa	III	0.20	III	0.10
IIb	III	0.20	II	-
IIIa, IIIb	III	0.20	I	-

rehabilitation of the transmission system from Ipo to La Mesa and the introduction of water safety, risk and asset management plans. 96% of water supplied to Metro Manila, home to approximately 15 million residents, comes from this system, north of Manila. Tunnel 5 project is part of this system is designed to deliver 19 m³/s unimpeded flow from Ipo Dam to Bigte Basin area.

In this paper, the crack widths of Tunnel 5 intake are calculated based on the various design codes. The maximum calculated unfactored moment in orthogonal direction is gotten from the Sap2000 finite element structure calculation results showing in **Figure 2**. The basic parameters of intake members refer to **Table 4** and the maximum crack widths of the members based on the different codes refer to **Table 5**.

From **Table 5**, the Z value is less than 25 kN/mm based on ACI 318-95; the steel bar space configuration is 200 mm less than the calculated maximum space based on ACI 318-19. The calculated crack widths based on ACI 224.1R, EN 1992-1 and GB 50010 are all less than 0.20 mm. The intake members can meet

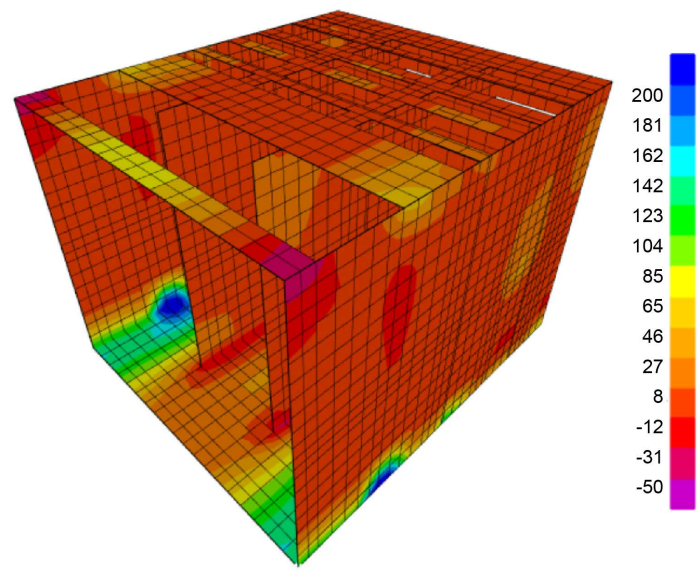


Figure 2. Maximum calculated unfactored moment (COMB-Service).

Table 4. Basic parameters of intake members.

Member	Diameter of rebar	Spacing of steel bar	Thickness of cover	Height of member	Calculated moment
	mm	mm	Mm	mm	kN·m
Base slab	25	200	75	1000	183
Top slab	25	200	75	500	63
Pier	25	200	75	1200	25
Side wall	25	200	75	700	170
Breast Wall	16	200	75	400	2
Outlet Wall	16	200	75	400	1

Table 5. Maximum crack width calculation result of intake members.

Member	ACI 318-95	ACI 318-19	ACI 224.1R	EN 1992-1	GB 50010
Item	Z value	Max. space	Max. Width	Max. Width	Max. Width
Unit	kN/mm	mm	mm	mm	mm
Base slab	19.36	610.57	0.20	0.14	0.13
Top slab	16.88	722.60	0.19	0.09	0.08
Pier	1.41	8676.00	0.01	0.02	0.01
Side wall	17.68	686.59	0.19	0.09	0.09
Breast Wall	0.94	12528.09	0.01	0.01	0.01
Outlet Wall	0.47	25056.18	0.01	0.005	0.002

the requirement of crack width control. Generally speaking, the calculation results of the crack widths in various codes are not much different. The EN 1992-1 and GB 50010 results are almost the same which are less than the ACI 224.1R results.

5. Conclusions

From the above description and comparison of various building codes, the following conclusion may be drawn:

1) There are many complex factors affecting the width of cracks in reinforced concrete members which mainly include the following aspects: the reinforcement steel stress is the most important variable; the thickness of the concrete cover is an important variable but not the only geometric consideration; the area of concrete surrounding each reinforcing bar is also an important geometric variable; the bar diameter is not a major variable and the ratio of crack width at the surface to that at the reinforcement level is proportional to the ratio of the nominal stain at the surface and reinforcement stain.

2) The ACI series codes believe that there is a certain randomness in the crack widths of concrete members, and it is difficult to grasp the actual crack width through calculation. The ACI crack width control method is based on no-slip theory and considers the affecting factors of the tensile steel bar stress, steel bar spacing and concrete cover thickness. The latest steel bar spacing control method is simple and easy to be adopted for engineering.

3) The Eurocode 2 and GB 50010 are all based on the bond-slip & no-slip theory. GB 50010 considers the affecting factors of the steel bar stress, steel bar diameter, steel bar bonding performance, effective steel bar ratio, cover thickness, tensile stiffening effect, component stress characteristics and load duration while Eurocode 2 considers the steel bar stress, steel bar diameter, steel bar spacing, steel bar bonding performance, effective steel bar ratio, cover thickness, tensile stiffening effect, component stress characteristics and load duration.

4) From the crack width calculation results of Tunnel 5 intake, the following conclusion is reached: there are certain differences between the crack widths

calculation methods of ACI system code, European 2 and Chinese GB 50010 in terms of the basis theory, crack width calculation method, crack width limit, affecting factors and load combination. The comparison of the engineering examples of the Tunnel 5 intake given in this paper shows that the results of the crack widths in various codes are not much different, The EN 1992-1 and GB 50010 results are almost the same which are less than the ACI 224.1R results.

5) Cracks in concrete structures are not only caused by load, but also by some non-load causes, for example, temperature change, concrete shrinkage, uneven foundation settlement, early frost heave, Alkali aggregate reaction and steel bar corrosion. For the above reasons that may cause concrete cracks, it is necessary to take corresponding engineering measures and ensure the quality of design and construction quality to avoid cracks caused by the above-mentioned reasons.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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