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REPORT

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Authors Bradley Justin Pease, COWI Mette Rica Geiker	**Sign.**
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Summary

This report provides an overview of several international code requirements and recommendations from technical committees concerning impact of cracks on durability of reinforced concrete. Most requirements and recommendations include design values for crack width at the concrete surface and concrete cover thicknesses. As presented in this report, requirements and recommendations from different international agencies may vary.

Indexing terms	**Stikkord**
Concrete	*Betong*
Reinforcement	*Armering*
Cracks	*Riss*
Requirements	*Requirements*

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Preface and Acknowledgements

This manuscript was prepared based on an existing draft chapter entitled " Chapter 8 - Code requirements and recommendations" dated June 2011 to the unpublished state-of-the art report from the technical committee RILEM TC-CCD "Concrete Cracking and its Relation to Durability: Integrating Material Properties with Structural Performance". The draft chapter was by Brad J. Pease (DTU, at that time), Mette Geiker (DTU, at that time), Kei-ichi Imamoto (Tokyo University of Science) and Patrick Fontana (German Federal Institute for Materials Research and Testing (BAM)). Contributions from Kei-Ichi Imamoto and Patrick Fontana to the draft chapter are acknowledged.

The existing draft chapter has been updated by Brad J. Pease, now of COWI A/S, in connection with the Norwegian Public Roads Administration (NPRA) Ferry-free coastal route E39 project, WP 7.1.1. Relevance of crack width and decompression requirements (limits) due to durability aspects of conventional reinforcement and the Norwegian public/private funded research project Durable advanced Concrete Solutions (DaCS) - Design and construction for coastal and arctic regions, NFR project 245645. Comments from Terje Kanstad, NTNU, are acknowledged.

Durability-related crack width and concrete cover requirements and recommendations from reinforced concrete design codes

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Durability-related crack width and concrete cover requirements and recommendations from reinforced concrete design codes

1 Introduction

This report provides an overview of several international code requirements and recommendations from technical committees concerning impact of cracks on durability of reinforced concrete. Most requirements and recommendations include design values for crack width at the concrete surface and concrete cover thicknesses. As presented in this report, requirements and recommendations from different international agencies may vary. However, due to an apparent lack of background information (e.g. effect of limit states on lifetime), difference between and critique of requirements and recommendations cannot be explained here.

It is beyond the scope of this report to summarize various code's methods/equations to design (i.e., limit) crack widths at the concrete surface and such information is available elsewhere [1]. However, the accuracy of crack width predictions may result in crack widths in actual structures to vary from the design values. As explained in [1], "*most equations predict the probable maximum crack width, which usually means that about 90% of the crack widths in the member are below the calculated value*." Fig. 1, which plots design crack widths using the 1978 CEB/fib Model Code versus measured crack widths of actual cracks, indicates modelled outcomes may vary widely from reality. For example, assuming a designed crack width of 0.20 mm was specified, measured crack widths ranged between approximately 0.05 mm and 0.5 mm. Multiple primary cracking (i.e., crack frequency or spacing), concrete cover thicknesses, stress level of the reinforcing steel, element type, and crack morphology all influence the surface crack width [1], making estimation of surface crack width difficult and inherently inaccurate. Nevertheless, controlling concrete surface crack widths and cover thicknesses has become the norm to minimize the impact of cracks on structural service life, as presented in the following sections.

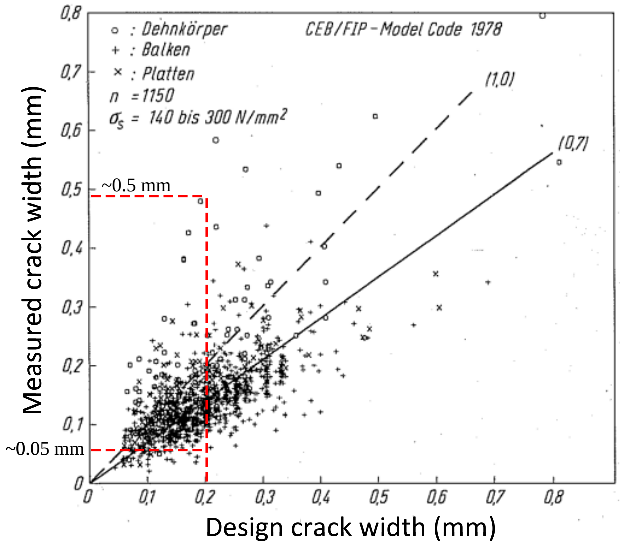

Fig. 1. Measured and calculated crack width comparison [2]. Calculated crack width in accordance with CEB/fib Model Code 1978 [3].

2 Reinforced concrete

Design values for crack width and concrete cover thickness from codes and technical committees for reinforced concrete are summarized in Table 1. It is noted that definitions of concrete cover thickness and means for calculating the design crack widths vary amongst codes.

For example, definitions from AASHTO LRFD [11] and EN 1992-1-1 [4] are as follows:

- AASHTO LRFD [11] defines concrete cover as "The specified minimum distance between the surface of the reinforcing bars, strands, post-tensioning ducts, anchorages, or other embedded items, and the surface of the concrete."

- EN 1992-1-1 [4] defines concrete cover as "the distance between the surface of the reinforcement closest to the nearest concrete surface (including links and stirrups and surface reinforcement where relevant) and the nearest concrete surface."

Durability-related crack width and concrete cover requirements and recommendations from reinforced concrete design codes

Table 5.12.3-1 of AASHTO LRFD [11], which is used to fill Table 1 below, provides cover for unprotected main reinforcing steel. AASHTO LRFD [11] allows "Cover to ties and stirrups may be 0.5 in. [12 mm] less than the values specified in Table 5.12.3-1 for main bars but shall not be less than 1.0 in [25 mm]." As expressed in the EN 1992-1-1 cover definition, no such allowance exists in the European code.

Table 1 includes requirements from the Norwegian National Annex to EN 1992-1-1 [13] and DIN 1045-1 [5], indicating covers from EN 1992-1-1 [4] are modified by certain local annexes. A recent systematic review of national annexes to Eurocodes [15, 16] shows that very few of the countries accept durability-related cover thickness from [4] as is. While it is noted that [5] is superseded by [14], many structures have been constructed according to [5].

Table 1. Crack width limitations from various codes/technical committees for reinforced concrete

Code / Committee Document (Country of Origin)	Assumed Service Life	Environmental Conditions / Situation		Element Description	Nominal (Design) Cover Thickness	Designed Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
EN 1992-1-1 (Eurocode 2) [4][1)]	50	No risk of corrosion or attack	X0 - Very Dry	--	20	0.4
		Corrosion induced by carbonation	XC1 - Dry or permanently wet	--	25	0.4
			XC2 - Wet, rarely dry	--	35	0.3
			XC3 - Moderate humidity	--	35	0.3
			XC4 - Cyclic wet and dry	--	40	0.3
		Corrosion induced by chlorides	XD1 - Moderate humidity	--	45	0.3
			XD2 - Wet, rarely dry	--	50	0.3
			XD3 - Cyclic wet and dry	--	55	0.3
		Corrosion induced by chlorides from seawater	XS1 – Exposed to airborne salt but not in direct contact with sea water	--	45	0.3
			XS2 – Permanently submerged	--	50	0.3
			XS3 - Tidal, splash and spray zones	--	55	0.3
		Concrete abrasion (Optional)	XM1 - Moderate abrasion	--	Add 5 mm to $c_{min,dur}$	Crack width controlled by attack type
			XM2 - Heavy abrasion	--	Add 10 mm to $c_{min,dur}$	
			XM3 - Extreme abrasion	--	Add 15 mm to $c_{min,dur}$	

Code / Committee Document (Country of Origin)	Assumed Service Life	Environmental Conditions / Situation		Element Description	Nominal (Design) Cover Thickness	Designed Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
DIN 1045-1 (Germany) [5][2)]	50	Carbonation induced corrosion	Dry or permanently wet	--	10 (+10)	0.4
			Wet, rarely dry	--	20 (+15)	0.3
			Moderately moist	--	20 (+15)	0.3
			Alternating wet and dry	--	25 (+15)	0.3
		Chloride induced corrosion	Moderately moist	--	40 (+15)	0.3
			Wet, rarely dry	--	40 (+15)	0.3
			Alternating wet and dry	--	40 (+15)	0.3
		Chloride induced corrosion from seawater	Salty air, no direct contact with seawater	--	40 (+15)	0.3
			Under water	--	40 (+15)	0.3
			Tidal, splash, and spray areas	--	40 (+15)	0.3
		Wear-resistance	Moderate wear stresses	--	Add 5 mm	Crack width controlled by attack type
			Heavy wear stresses	--	Add 10 mm	
			Extreme wear stresses	--	Add 15 mm	
JSCE (Japan) [6]	--	--	Moderate	--	--	0.005*Cover
		--	Aggressive	--	--	0.004*Cover
		--	Extremely aggressive	--	--	0.0035*Cover

Code / Committee Document (Country of Origin)	Assumed Service Life	Environmental Conditions / Situation		Element Description	Nominal (Design) Cover Thickness	Designed Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
AIJ (Japan) [7] 3)	--	--	Outdoor	Standard, long term, and very long term	30 (+10)	0.3
		--	Indoor		40 (+10)	0.3
New Zealand Standard (New Zealand) [8]	--	--	Soil with protective membrane	--	--	0.4
		--	Air	--	--	0.3
		--	Tidal, splash, and spray zone, or aggressive soil	--	--	0.2
ACI 224R-01 [1], Table 4.1 (USA) 7)	Not considered	Dry air or protective membrane		--	Cover thicknesses not addressed	0.41
		Humidity, moist air, soil		--		0.3
		Deicing chemicals		--		0.18
		Seawater and seawater spray, wetting and drying		--		0.15
		Water-retaining structures		--		0.1
AASHTO LRFD (USA) [11] 4)	Not stated	--	Direct exposure to salt water	--	100	See 5)
		--	Cast against earth	--	75	
		--	Coastal	--	75	
		--	Exposure to deicing salts	--	60	
		--	Deck surfaces subject to tire stud or chain wear	--	60	
		--	Exterior other than above	--	50	
		--	Interior other than above	≤ No. 36 bar	40	
		--		No. 43, 57 bar	50	
		--	Bottom of cast-in-place slabs	≤ No. 36 bar	25	
		--		No. 43, 57 bar	50	

Code / Committee Document (Country of Origin)	Assumed Service Life	Environmental Conditions / Situation		Element Description	Nominal (Design) Cover Thickness	Designed Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
AASHTO LRFD (USA) [11] 4)	Not stated	--	Precast soffit form panels	--	20	See 5)
		Noncorrosive	Precast reinforced piles	--	50	
		Corrosive Env.		--	75	
		Noncorrosive	Cast-in-place piles	--	50	
		Corrosive Env.		General and protected	75	
		--		Shells	50	
		--		Auger-cast, tremie concrete, or slurry construction	75	
		--	Precast concrete box culverts:	Top slabs used as a driving surface	60	
		--		Top slabs with less than 2 ft (~610 mm) of fill not used as a driving surface	50	
		--		All other members	25	
NS-EN 1992-1-1:2004/ NA:2008 (Norway) [13] 8)	50	No risk of corrosion or attack	X0 - Very Dry	--	$c_{min,b} + \Delta c_{dev}$	0.4
		Corrosion induced by carbonation	XC1 - Dry or permanently wet	--	25	$0.3\ k_c$
			XC2 - Wet, rarely dry	--	35	$0.3\ k_c$
			XC3 - Moderate humidity	--	35	$0.3\ k_c$
			XC4 - Cyclic wet and dry	--	35	$0.3\ k_c$

Code / Committee Document (Country of Origin)	Assumed Service Life	Environmental Conditions / Situation		Element Description	Nominal (Design) Cover Thickness	Designed Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
NS-EN 1992-1-1:2004/ NA:2008 (Norway) [13] 8)	50	Corrosion induced by chlorides	XD1 - Moderate humidity	--	50	0.3 k_c
			XD2 - Wet, rarely dry	--	50	0.3 k_c
			XD3 - Cyclic wet and dry	--	50	0.3 k_c
		Corrosion induced by chlorides from seawater	XS1 – Exposed to airborne salt but not in direct contact with sea water	--	50	0.3 k_c
			XS2 – Permanently submerged	--	50	0.3 k_c
			XS3 - Tidal, splash and spray zones	--	60	0.3 k_c

1) Nominal covers, c_{nom} are presented as cnom = $c_{min,dur}$ + Δc_{dev} with Δc_{dev} assumed to be 10 mm and using Structural Class S4. It is noted that in certain cases, e.g., when casting again blinding, prepared ground or uneven surfaces, higher values for Δc_{dev} are recommended in [4]. For reinforced concrete, crack widths are calculated using quasi-permanent load combinations.

2) For DIN 1045-1, the minimum cover depth c_{min} is shown with an allowance, Δc in parentheses. It is noted that DIN 1045-1 [5] is superseded by [14].

3) If effective protective coating(s) is/are applied, cover depth can be -10 mm.

4) The current edition of AASHTO LRFD [11] is not yet available in the international system of (SI) units. Therefore, covers are taken from the fourth edition of AASHTO LRFD [12]. The conversion of covers for the precast concrete box culverts, which did not exist in [12], are based on conversions from other situations with equivalent covers between [11] and [12].

Cover to ties and stirrups may be 12 mm less than the values specified above for main bars but shall not be less than 25 mm. AASHTO LRFD specifies cover modification factors based on water-to-cement ratio as follows:

For w/c $\leq$ 0.40 0.8

For w/c $\geq$ 0.50 1.2

Finally, decks exposed to tire studs or chain wear, additional cover shall be used to compensate for the expected loss in depth due to abrasion. Section 2.5.2.4

Code / Committee Document (Country of Origin)	Assumed Service Life	Environmental Conditions / Situation		Element Description	Nominal (Design) Cover Thickness	Designed Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]

of AASHTO LRFD indicates an addition 0.5 in (10 mm in [12]). to compensate for thickness loss due to abrasion.

5) Control of cracking by distribution of reinforcement by satisfying a reinforcement spacing limit per Equation 5.7.3.4-1 in AASHTO LRFD [11] in the layer closest to the tension face. Equation 5.7.3.4-1 in AASHTO LRFD is based on a physical crack model that considers exposure conditions through an exposure factor.

Exposure factor, γ_e for Class 1 (upper bound) is 1.00 and corresponds to surface crack width of approximately 0.43 mm, for Class 2 (decks and substructures exposed to water) γ_e is 0.75 and corresponds to surface crack width of approximately 0.33 mm, other values for γ_e can be specified by Owner.

7) According to [1], the crack widths presented are: "*a general guide for what could be considered reasonable crack widths at the tensile face of reinforced concrete structures for typical conditions. These reasonable crack width values are intended to serve only as a guide for proportioning reinforcement during design. They are to be used as a general guideline along with sound engineering judgment.*"

8) Nominal covers, c_{nom} are presented as $c_{nom} = c_{min,dur} + \Delta c_{dev}$ with Δc_{dev} assumed to be 10 mm and 50-year service life. It is noted that in certain cases, e.g., when casting again blinding, prepared ground or uneven surfaces, higher values for Δc_{dev} are recommended in [13]. For reinforced concrete, crack widths are calculated using quasi-permanent load combinations in all cases except XD3 and XS3 where frequent load combinations are used. The term k_c in the design crack width column is explained further in Section 5.

3 Prestressed/post-tensioned concrete

Design values for crack width and concrete cover thickness from codes and technical committees for prestressed and post-tensioned concrete are summarized in Table 2. The differences amongst the codes in methods for crack width calculation and cover thickness definitions mentioned in Section 2 should also be noted in relation to values presented in Table 2.

Table 2. Crack width limitations from various codes/technical committees for prestressed and post-tensioned concrete

Code/ Committee (Country of Origin)	Assumed Service Life	Environmental Conditions/Situation		Element Description	Nominal (Design) Cover Thickness	Design Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
EN 1992-1-1 (Eurocode 2) [4] 1)	50	No risk of corrosion or attack	X0 - Very Dry	Prestressed - bonded	20	0.2
				Prestressed - unbonded		0.4
		Corrosion induced by carbonation	XC1 - Dry or permanently wet	Prestressed - bonded	35	0.2
				Prestressed - unbonded		0.4
			XC2 - Wet, rarely dry	Prestressed - bonded	45	0.2 2)
				Prestressed - unbonded		0.3
			XC3 - Moderate humidity	Prestressed - bonded	45	0.2 2)
				Prestressed - unbonded		0.3
			XC4 - Cyclic wet and dry	Prestressed - bonded	50	0.2 2)
				Prestressed - unbonded		0.3
		Corrosion induced by chlorides	XD1 - Moderate humidity	Prestressed - bonded	55	Decompression
				Prestressed - unbonded		0.3
			XD2 - Wet, rarely dry	Prestressed - bonded	60	Decompression
				Prestressed - unbonded		0.3
			XD3 - Cyclic wet and dry	Prestressed - bonded	65	Decompression
				Prestressed - unbonded		0.3
		Corrosion induced by chlorides from sea water	XS1 - Exposed to airborne salt but not in direct contact with sea water	Prestressed - bonded	55	Decompression
				Prestressed - unbonded		0.3
			XS2 - Permanently submerged	Prestressed - bonded	60	Decompression
				Prestressed - unbonded		0.3
			XS3 - Tidal, splash and spray zones	Prestressed - bonded	65	Decompression

Code/ Committee (Country of Origin)	Assumed Service Life	Environmental Conditions/Situation		Element Description	Nominal (Design) Cover Thickness	Design Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
				Prestressed - unbonded		0.3
New Zealand Standard (New Zealand) [8]	xx	--	Soil w/ protective membrane	Prestressed	--	0.3
		--	Air	Prestressed	--	0.2
		--	Tidal/splash, spray zone, or aggressive soil	Prestressed	--	0.1
				Prestressed	+ 5 mm	
				Post-tension - unbonded	+ 5 mm	
			Heavy wear stresses	Post-tension - bonded	+ 10 mm	
				Prestressed	+ 10 mm	
				Post-tension - unbonded	+ 10 mm	
			Extreme wear stresses	Post-tension - bonded	+ 15 mm	
				Prestressed	+ 15 mm	
				Post-tension - unbonded	+ 15 mm	
AASHTO LRFD (USA) [11]	Not stated	See Table 1 for descriptions of environments and design cover thicknesses. According to AASHTO LRFD [11], "*Cover for pretensioned prestressing strand, anchorage hardware, and mechanical connections for reinforcing bars or post-tensioned prestressing strands shall be the same as for reinforcing steel*." AASHTO LRFD also stipulates cover to metal ducts for post-tensioning tendons as not less than: • That specified for main reinforcing steel, or • The radius (one-half of the diameter) of the duct.				Note [8)]

Code/ Committee (Country of Origin)	Assumed Service Life	Environmental Conditions/Situation		Element Description	Nominal (Design) Cover Thickness	Design Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
NS-EN 1992-1-1:2004/ NA:2008 (Norway) [13] [3]	50	No risk of corrosion or attack	X0 - Very Dry	Prestressed - bonded	$c_{min,b} + \Delta c_{dev}$	0.40
				Prestressed - unbonded		$0.30\ k_c$ [5]
		Corrosion induced by carbonation	XC1 - Dry or permanently wet	Prestressed - bonded	35	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [5]
			XC2 - Wet, rarely dry	Prestressed - bonded	45	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [5]
			XC3 - Moderate humidity	Prestressed - bonded	45	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [5]
			XC4 - Cyclic wet and dry	Prestressed - bonded	45	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [5]
		Corrosion induced by chlorides	XD1 - Moderate humidity	Prestressed - bonded	60	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [6]
			XD2 - Wet, rarely dry	Prestressed - bonded	60	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [6]
			XD3 - Cyclic wet and dry	Prestressed - bonded	60	$0.30\ k_c$ [5]
				Prestressed - unbonded		Decompression [5]
		Corrosion induced by chlorides from seawater	XS1 - Exposed to airborne salt but not in direct contact with sea water	Prestressed - bonded	60	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [6]
			XS2 - Permanently submerged	Prestressed - bonded	60	$0.30\ k_c$ [4]
				Prestressed - unbonded		$0.20\ k_c$ [6]
			XS3 - Tidal, splash and spray zones	Prestressed - bonded	70	$0.30\ k_c$ [5]
				Prestressed - unbonded		Decompression [5]

Code/ Committee (Country of Origin)	Assumed Service Life	Environmental Conditions/Situation		Element Description	Nominal (Design) Cover Thickness	Design Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
DIN 1045-1 (Germany) [5] [7)]	50	Corrosion induced by carbonation	XC1 - Dry or permanently wet	Post-tension - bonded	20 (+10)	0.2 [5)]
				Prestressed		0.2 [5)]
				Post-tension - unbonded		0.4 [4)]
			XC2 - Wet, rarely dry	Post-tension - bonded	30 (+15)	0.2 [6)]
				Prestressed		0.2 [6)]
				Post-tension - unbonded		0.3 [4)]
			XC3 - Moderate humidity	Post-tension - bonded	30 (+15)	0.2 [6)]
				Prestressed		0.2 [6)]
				Post-tension - unbonded		0.3 [4)]
			XC4 - Cyclic wet and dry	Post-tension - bonded	35 (+15)	0.2 [6)]
				Prestressed		0.2 [6)]
				Post-tension - unbonded		0.3 [4)]
		Corrosion induced by chlorides	XD1 - Moderate humidity	Post-tension - bonded	50 (+15)	0.2 [6)]
				Prestressed		0.2 [9)]
				Post-tension - unbonded		0.3 [4)]
			XD2 - Wet, rarely dry	Post-tension - bonded	50 (+15)	0.2 [6)]
				Prestressed		0.2 [9)]
				Post-tension - unbonded		0.3 [4)]
			XD3 - Cyclic wet and dry	Post-tension - bonded	50 (+15)	0.2 [6)]
				Prestressed		0.2 [9)]
				Post-tension - unbonded		0.3 [4)]

Code/ Committee (Country of Origin)	Assumed Service Life	Environmental Conditions/Situation		Element Description	Nominal (Design) Cover Thickness	Design Crack Width
	[years]	Attack Type	Description of Environment		[mm]	[mm]
DIN 1045-1 (Germany) [5] [7)]	50	Corrosion induced by chlorides from seawater	XS1 - Exposed to airborne salt but not in direct contact with sea water	Post-tension - bonded	50 (+15)	0.2 [6)]
				Prestressed		0.2 [9)]
				Post-tension - unbonded		0.3 [4)]
			XS2 - Permanently submerged	Post-tension - bonded	50 (+15)	0.2 [6)]
				Prestressed		0.2 [9)]
				Post-tension - unbonded		0.3 [4)]
			XS3 - Tidal, splash and spray zones	Post-tension - bonded	50 (+15)	0.2 [6)]
				Prestressed		0.2 [9)]
				Post-tension - unbonded		0.3 [4)]

1) Nominal covers, c_{nom} are presented as cnom = $c_{min,dur} + \Delta c_{dev}$ with Δc_{dev} assumed to be 10 mm and using Structural Class S4. It is noted that in certain cases, e.g., when casting again blinding, prepared ground or uneven surfaces, higher values for Δc_{dev} are recommended in [4]. For prestressed members with unbonded tendons crack widths are calculated using quasi-permanent load combinations, while prestressed members with bonded tendons are calculated using frequent load combinations.

2) Per Table 7.1N in EN 1992-1-1, in addition, decompression should be checked under the quasi-permanent load combinations.

3) Nominal covers, c_{nom} are presented as $c_{nom} = c_{min,dur} + \Delta c_{dev}$ with Δc_{dev} assumed to be 10 mm and 50-year service life. It is noted that in certain cases, e.g., when casting again blinding, prepared ground or uneven surfaces, higher values for Δc_{dev} are recommended in [13]. The term k_c in the design crack width column is explained further in Section 5.

4) Crack widths are calculated using quasi-permanent load combinations

5) Crack widths are calculated using frequent load combinations.

6) Crack widths are calculated using frequent load combinations, in addition, decompression should be checked under the quasi-permanent load combinations.

7) For DIN 1045-1, the minimum cover depth c_{min} is shown with an allowance, Δc in parentheses.

8) Where cracking is permitted under service loads, crack width, fatigue of reinforcement, and corrosion considerations shall be investigated in accordance with the provisions of Articles 5.5, 5.6, and 5.7 of AASHTO LRFD [11].

9) Crack widths are calculated using infrequent load combinations, in addition, decompression should be checked under the frequent load combinations.

4 Discussion of code requirements

Fig. 2 shows selected requirements of design crack width and minimum cover depth for reinforced concrete structures from Table 1. Fig. 2(a) shows requirements categorized by the specifying code, while Fig. 2(b) shows requirements from several codes (AASHTO, AIJ, DIN 1045-1, and Eurocode 2) categorized by environmental condition. It is acknowledged that, as described in Section 2, cover thickness definitions and crack width calculation approaches vary in the various design codes. Nevertheless, Fig. 2 provide a basic comparison of these code requirements.

In Fig. 2(a) values for AASHTO assume and exposure factor of 0.75 and for DIN 1045-1 assume chloride-induced corrosion from seawater. Using these assumptions, Fig. 2(a) highlights two distinct concepts exist in the various codes – concept 1 sets a single design crack width for all exposures but varies minimum cover depth and concept 2 varies both values based on exposure conditions. AASHTO is an example of concept 1, while Eurocode 2 and DIN 1045-1 follow concept 2.

Fig 2(b) groups selected requirements from various codes in terms of the exposure conditions. The green region and data points indicate the cover depth and crack width requirements for structures with either no risk of corrosion or carbonation-induced corrosion (considered to be the least severe exposure conditions) while the orange region and data points highlight requirements for marine and deicing salt exposures. Design crack width requirements clearly narrow as exposure conditions increase in severity. While outputs from cracking models are highly variable (see Fig. 1), the desire to reduce crack widths to improve durability is apparent. Minimum cover depths also tend to increase with exposure severity.

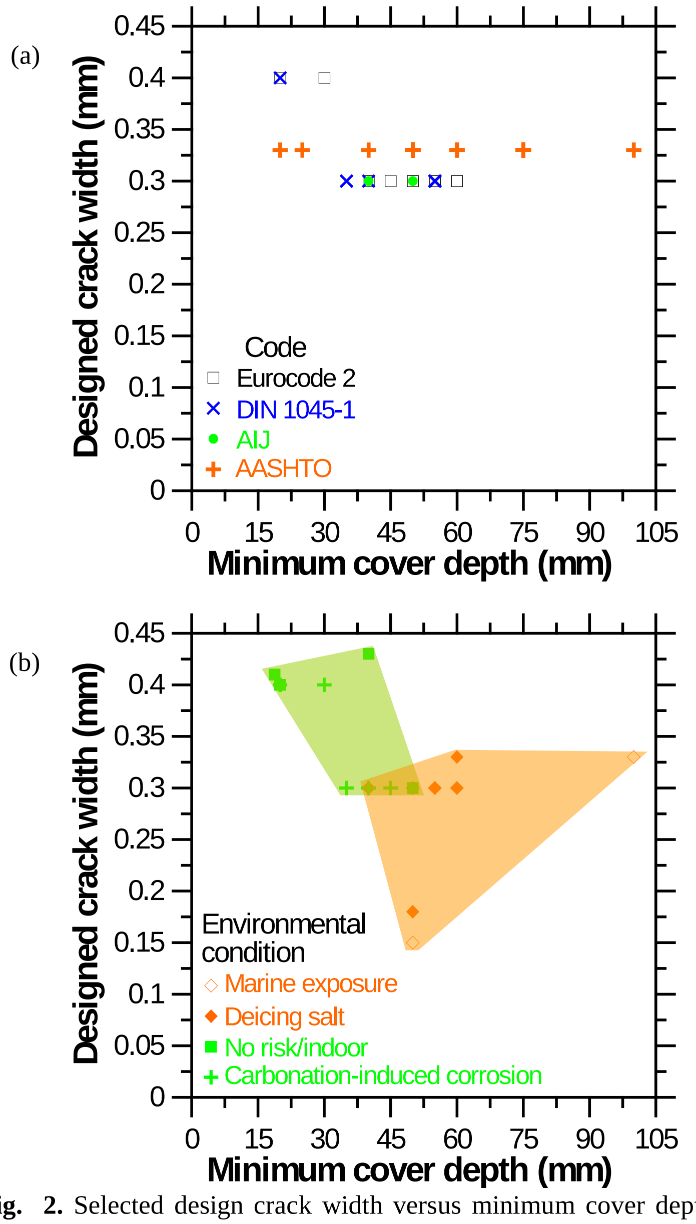

Fig. 2. Selected design crack width versus minimum cover depth requirements from various codes (a) grouped by code (assumptions: AASHTO – exposure factor of 0.75, DIN 1045-1 – chloride-induced corrosion from seawater) and (b) grouped by general environmental conditions. Notes: The definitions for cover thickness vary amongst codes, See Section 2. Further, requirements from [13] are not included due to the applied k_c-factor, See Section 5.

5 Examples of code requirements for crack width with large concrete covers

Both AASHTO LRFD [11] and the Norwegian National Annex to EN 1992-1-1 [13] permit adjustments in calculations to control cracking when large covers are used. These adjustments are useful to mitigate reinforcement congestion, which can lead to difficulty in placing and achieving an adequate compaction (consolidation) of concrete.

In Section 5.7.3.4 of the 2016 interim revisions of AASHTO LRFD [11], it is clarified that the value d_c (i.e., "*thickness of concrete cover measured from extreme tension fiber to center of the flexural reinforcement located closest thereto*") need not be taken larger than 2 in. (50 mm) plus the bar radius for calculation purposes. Further, a minimum required bar spacing, s of 5 in. (125 mm) is set for the control of flexural cracking. The code commentary explains:

"*In certain situations involving higher-strength reinforcement or large concrete cover, the use of Eq. 5.7.3.4-1 can result in small or negative values for s [bar spacing]…Where large concrete cover is used, past successful practice suggests a value of d_c not greater than 2.0 in. plus the bar radius for calculation purposes*."

Section NA7.3.1(5) of the Norwegian National Annex to EN 1992-1-1 [13] introduces the factor k_c, seen in Tables 1 and 2, to account for nominal covers (c_{nom}) exceeding the minimum durability-related cover requirement ($c_{min,dur}$). The factor k_c is expressed as:

$$k_c = c_{nom}/c_{min,dur} \leq 1.3$$

For example, the nominal cover (c_{nom}) from Table 1 for XD2 is 50 mm, based on a $c_{min,dur}$ of 40 mm plus a 10 mm Δc_{dev}; yielding k_c = 1.25. The resulting crack width limit for the XD2 exposure condition (0.30 mm x k_c) is 0.375 mm.

6 References

1. ACI Committee 224, “Control of cracking in concrete structures (ACI 224R-01),” American Concrete Institute, Farmington Hills, MI, USA, May 2001, 45 pp.
2. Scheissl P, Wölfel E (1986) Konstruktionsregeln zur Beschränkung der Rissbreite – Grundlage zur Neufassung DIN 1045, Abschnitt 17.6 (Entwurf 1985). *Beton- und Stahlbetonbau* **81**(1):8-15
3. CEB/*fib* Model Code for Reinforced concrete and prestressed concrete structures (1978)
4. Eurocode 2: Design of concrete structures, Part 1, General rules and rules for buildings (BS EN 1992-1-1:2004)
5. DIN 1045-1, Concrete, Reinforced concrete and prestressed concrete structures, Part 1: Design and construction, (DIN 1045-1: 2008-08), Berlin, August 2008
6. JSCE, Standard Specifications for Concrete Structures (2002)-Structural Performance Verification- (in Japanese)
7. AIJ, Recommendations for Practice of Crack Control in Reinforced Concrete Buildings (Design and Construction), 2006.2 (in Japanese)
8. New Zealand Standard: Concrete Structure, Part1-The Design of Concrete Structures (NZS3101: Part 1: 1995)
9. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)," American Concrete Institute, Farmington Hills, MI, USA, September 2014, 519 pp.
10. German Committee on Reinforced Concrete (DAfStb). Guideline waterproof concrete constructions, November 2003 (supplementing DIN 1045-1 [5])
11. AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 7th Edition, 2014, with 2016 Interim Revisions
12. AASHTO LRFD Bridge Design Specifications, SI Units, 4th Edition, 2007
13. Norsk Standard, "Eurocode 2: Design of concrete structures Part 1-1: General rules and rules for buildings (NS-EN 1992-1-1:2004+NA:2008)" pp. 252, 2008
14. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings; German version EN 1992-1-1:2004 + AC:2010, 2011.
15. Ignatiadis, A.: Analysis of the National Annexes of Eurocode 2, DAfStb, 27.11.2013, CEN/TC 250/SC 2/WG 1 N 118 (26 pages)
16. Ignatiadis, A. Analysis of NDPs in EN 1992-1-1 (state in November 2013), DAfStb, 27.11.2013, CEN/TC 250/SC 2/WG 1 N 119 (290 pages)