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CONTROL OF CRACKS IN THE DESIGN OF NUCLEAR SAFETY-RELATED STRUCTURES IN THE UK

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ABSTRACT

Nuclear safety related concrete structures have inherently large margin of capacity between the ultimate and serviceability limit state, mainly due to the requirement to remain essentially elastic in the event of a design basis earthquake. Despite this, cracking can occur from either direct loading, restraint or imposed deformations, including early-age thermal cracks due to temperature differential or externally restrained thermal strain. This paper presents an overview of current UK practice for control of cracks in nuclear safety-related concrete structures and provides a discussion of the provisions of ACI 349-13, ASME BPVC 2013 Section III, Division 2 (ACI 359-13), the European Pressurised Reactor Technical Code for Civil Works (ETC-C) and Eurocode 2 (BS EN 1992). This is followed by recommendations for design.

INTRODUCTION

Cracking of concrete structures is an unavoidable phenomenon and can occur from different causes, such as direct loading, restraint, imposed deformations and early-age thermal effects due to temperature differential or externally restrained thermal strain. The occurrence of cracks is generally acceptable and recognised by most modern engineering design codes and standards. Crack control is normally considered for serviceability but it can also be important in terms of safety if it becomes adverse to the function of a safety-critical Structure, System or Component (SSC). Design codes and standards normally limit cracks, explicitly or implicitly, to an extent that will not impair the durability of the structure, cause some form of structural malfunction (e.g. leakage) or cause the appearance of the structure to be aesthetically impaired. Although there are differences between different codes and standards in the way crack control is addressed, for design, usually a minimum required amount of bonded reinforcement is prescribed to limit crack width and spacing, in addition to specifications for detailing.

Nuclear safety-related concrete structures, such as Reactor Building structures and Reinforced Concrete Containment Vessels (RCCVs), have inherently large margin of capacity between the ultimate and serviceability limit state. This is mainly due to the requirement to remain essentially elastic in the event of a design basis earthquake and consideration of other infrequent, extreme and accidental loading for design basis and beyond design basis performance, such as aircraft impact. Despite this, nuclear safety-related concrete structures are still susceptible to cracking. Furthermore, although concrete elements may be heavily reinforced due to high demands, the generally larger cross section dimensions of nuclear safety-related structures than those found in normal building structures can have significantly higher temperature differentials during hardening. This can result in high demands for control of early thermal cracking.

In the UK, several different nuclear-specific and non-nuclear specific codes and standards are used for design of nuclear safety-related concrete structures, with often significant differences in the philosophy for crack control. In certain cases the nuclear regulators and relevant stakeholders require enhancement of code provisions associated with crack control with additional justifications to provide confidence in the adequacy of the design to substantiate the nuclear safety case.

This paper presents an overview of current UK practice for control of cracks in nuclear safety-related concrete structures and provides a comparison of the principal codes and standards used for design of nuclear-related concrete structures in the UK: ACI 349-13 'Code Requirements for Nuclear Safety-Related Concrete Structures', ACI 349-13 (2014), ASME Boiler and Pressure Vessel Code (BPVC) 2013 Section III, Division 2 (ACI 359-13), ASME BPVC III-2 (2013), the European Pressurised Reactor Technical Code for Civil Works (ETC-C) 2012, ETC-C (2012), and Eurocode 2 (BS EN 1992), BS EN 1992-1-1 (2014). Recommendations for design are provided.

It is worthwhile to note that all of the aforementioned codes and standards other than BS EN 1992 are nuclear-specific. Although BS EN 1992 is not nuclear-specific it is sometimes used for design of Class 3 structures, as defined by the safety classification of the UK Office of Nuclear Regulation Safety Assessment Principles for Nuclear Facilities, ONR (2014).

SAFETY ASSESSMENT PRINCIPLES AND REGULATORY REQUIREMENTS

The UK Office for Nuclear Regulation (ONR) uses Safety Assessment Principles (SAPs) as a framework for making consistent regulatory judgements related to safety. The SAPs also provide duty holders with information on the regulatory principles against which their safety provisions will be judged. The SAPs apply to assessments of safety at existing or proposed nuclear facilities and relate only to nuclear safety, radiation protection and radioactive waste management.

The choice of the design approach for crack control for nuclear safety-related concrete structures falls under the auspices SAPs ECS.3 and potentially ECS.4, ONR (2014):

- Engineering Safety Assessment Principle ECS.3: Codes and Standards: *Structures, systems and components that are important to safety should be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected to the appropriate codes and standards.*
- Engineering Safety Assessment Principle ECS.4: Absence of Established Codes and Standards: *Where there are no appropriate established codes or standards, an approach derived from existing codes or standards for similar equipment, in applications with similar safety significance, should be adopted.*

It is important to note that the ONR SAPs document further states that:

- *The codes and standards applied should reflect the functional reliability requirements of the structures, systems and components and be commensurate with their safety classification.*
- *Codes and standards should be preferably nuclear-specific, leading to a conservative design commensurate with the importance of the safety function(s) being delivered.*
- *Each code or standard adopted should be evaluated to determine its applicability, adequacy and sufficiency and should be supplemented or modified as necessary to a level commensurate with the importance of the relevant safety function(s).*
- *Appropriate nuclear industry-specific, national or international codes and standards should be adopted for Class 1 and 2 structures, systems or components. For Class 3, if there is no appropriate nuclear industry-specific code or standard, an appropriate non-nuclear-specific code or standard should be applied instead.*
- *The combining of different codes and standards for a single aspect of a structure, system or component should be avoided. Where this cannot be avoided, the combining of the codes and standards should be justified and their mutual compatibility demonstrated.*

Parenthetically, SSCs are classified as Class 1 when they form a principal means of fulfilling a function that plays a principal role in ensuring nuclear safety. Class 2 are any SSCs that make a significant contribution to fulfilling a function that plays a principal role in ensuring nuclear safety, or forms a principal means of ensuring a function that makes a significant contribution to nuclear safety. Any other SSCs contributing to a categorised safety function can be classed as Class 3, ONR (2014).

DESIGN CODES AND STANDARDS

In UK practice it is very common to use the provisions of BS EN 1992 for crack control and crack width calculations of nuclear-related concrete structures. BS EN 1992 and particularly BS EN 1992-1-1:2004, BS EN 1992-1-1 (2014), superseded BS 8110, BS 8110-1 (1997), BS 8007, BS 8007 (1987) and BD28/87, BD 28/87 (1989), which were previously the principal standards for estimating design crack width and spacing of reinforced concrete structures in the UK. BS EN 1992 also forms part of the basis of the ETC-C approach, ETC-C (2012), used for the design of the UK European Pressured Reactor (EPR). CIRIA C660 'Early-Age Thermal Crack Control in Concrete', Bamforth (2007), is commonly used in combination with BS EN 1992 for control of early-thermal cracking.

The following sections provide a brief overview of the current principal codes and standards used in the UK for the design of nuclear safety-related concrete structures, and their philosophy for crack control.

ACI 349-13

ACI 349 is developed and reported by ACI Committee 349 and published by the American Concrete Institute (ACI). The code covers the design and construction of nuclear safety-related concrete structures that form part of a nuclear power plant. However, it does not cover concrete containment structures and RCCVs. The latter type is covered by the scope of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section III, Division 2, dually designated ACI 359. ACI 349 makes significant use of ACI 318 'Building Code Requirements for Structural Concrete' and follows a similar format. The most recent revision of ACI 349 (ACI 349-13) was published in June 2014 and is aligned with ACI 318-08.

ACI 349-13 does not explicitly specify acceptable crack width limits or provide a methodology for calculating crack widths but gives provisions for minimum reinforcement and follows the philosophy of ACI 318. Historically, flexural crack control requirements in ACI 318 were based on the Gergely-Lutz method, Gergely and Lutz (1968), utilising an empirical equation derived from statistical analysis of experimental data from various sources. Since 1999, the philosophy of ACI Committee 318 changed, advocating that it is misleading to purport to effectively calculate crack widths given the inherent variability in cracking of concrete structures, ACI 224R-01 (2001). This is also supported by increased evidence from various researchers that there is little correlation between reinforcement corrosion and crack width. Subsequently, crack control requirements were simplified by limiting provisions for spacing of reinforcement. ACI 349-13 uses the same reinforcement spacing provisions as ACI 318-08.

ACI 349-13 Section 7.12 requires all exposed concrete surfaces to be reinforced in two perpendicular directions and gives minimum reinforcement area provisions. Reinforcement is not allowed to be spaced apart further than 457 mm. Concrete sections which are less than 1.22 m thick are provided with minimum reinforcement of 0.12% of the gross concrete area, in each direction at each face.

For sections equal to, or greater than 1.22 m thick, the minimum area of reinforcement is given by the product of the specified tensile strength of concrete and the effective tensile area of concrete, divided by the stress in the reinforcing steel. The stress in reinforcing steel can be taken as 60% of the specified yield strength. The minimum area of reinforcement does not need to exceed 1% of the effective tensile area of concrete. The minimum reinforcement size is limited to No. 6 bars.

On tension faces of structural slabs and walls, the ratio of reinforcement area at the tension area to the gross concrete area is not allowed to be less than 0.18%, provided that the area of reinforcement at the tension face is at least 1/3 greater than that required by analysis.

The code permits the use of lower cement content in thick concrete members (> 0.61 m) with requirements to help limit or control temperature rise due to hydration and the risk of early thermal cracking. Concrete sections which are as thick, or thicker than 1.83m, are permitted to waive the minimum reinforcement requirements provided that members are constructed by ACI Committee 207 for non-reinforced massive concrete structures.

Other relevant ACI standards and guides that may complement ACI 349-13 are ACI 224R-01, ACI 224R-01 (2001), and ACI 224.4, ACI 224.4R-13 (2013). It is worth noting that ACI 224R-01 ‘Control of Cracking in Concrete Structures’ Table 4.1 suggests maximum acceptable crack widths for concrete structures. For example, a maximum crack width of 0.3 mm is suggested for reinforced concrete structures under service loads and exposed to humidity and moist air, which is comparable to the provisions of BS EN 1992 for similar exposure conditions. More stringent limits are suggested for more severe environmental conditions or sealing requirements.

ASME BPVC 2013, Section III, Division 2 (ACI 359-13)

ASME BPVC 2013 provides rules for the construction of boilers, pressure vessels, and nuclear components and includes requirements for materials, design, fabrication, examination, inspection and stamping. Section III, Division 2, covers prestressed and reinforced concrete containments and includes structural concrete pressure resisting shells and shell components, shell metallic liners and penetration liners extending the containment liner through the surrounding shell concrete.

ASME BPVC Section III Division 2, dually designated ACI Standard 359, is an international standard prepared and continuously developed by the Joint ACI-ASME Technical Committee on Concrete Pressure Components for Nuclear Service, under the sponsorship of ACI and ASME. Currently, there is no UK or European-wide standard specific to the design of RCCVs.

Similar to ACI 349-13, ACI 359-13 does not explicitly specify acceptable crack width limits or provide a methodology for calculating crack widths but makes provisions for minimum reinforcement. Sub-subarticle CC-3535 ‘Concrete Crack Control’ essentially states that:

- When expected cracks are likely to weaken critical elements of the containment, bonded non-prestressed reinforcement is required to carry the total tensile force in concrete.
- A minimum reinforcement of 0.2% of the gross cross-sectional area of a section of the containment shell in each direction at each face of the concrete is required to control surface and membrane cracking from the effects of shrinkage, temperature and membrane tension.
- The minimum reinforcement requirement can be met fully or partially by reinforcement otherwise required to resist loading. It is also allowed to use an integral steel liner to satisfy the requirement for inside face reinforcement. Reinforcing bars used as face reinforcement are not allowed to be more than one-fifth of the total section thickness from the concrete face.

Further control can be achieved through concrete detailing, specifications, and extensive testing requirements. It is worth noting that for concrete containments with leak-tight metallic liners durability, functional and aesthetic requirements that would otherwise be met by an exposed concrete surface have increased reliance on the quality of the metallic liner. Furthermore, it is worth noting that although maximum acceptable crack widths are not specified for design, sub-subarticle CC-6350 ‘Surface Cracking’ of the code requires that for structural integrity testing, patterns of cracks that exceed 0.25 mm in width and 150 mm in length should be mapped before and after containment pressurization testing. This may suggest that a crack width of 0.25 mm may be considered as a significant limit. This is more stringent than the recommended crack width for concrete exposed to humidity and moist air, but significantly less stringent than the acceptable crack width of 0.1 mm for water retaining structures suggested in Table 4.1 of ACI 224R-01.

ETC-C 2012

ETC-C is developed and published by AFCEN, the French Association for Design, Construction and In-Service Inspection Rules for Nuclear Island Components. It was originally developed by Électricité de France (EDF) for EPR safety-classified structures and German Utilities based on provisions of RCC-G ‘Design and Construction Rules for Civil Works’ for French Nuclear Power Plants. EDF first issued ETC-C in 2006 as a reference document for the Flamanville 3 Project. Subsequently, the development of the standard was continued by AFCEN.

During the Generic Design Assessment (GDA) of the UK EPR, the Office for Nuclear Regulation (ONR) accepted the 2010 revision of ETC-C supplemented by a mandatory and UK-specific Companion Document. The latest revision of ETC-C was published in 2012 and incorporates some, but not all of the experience gained during the GDA of the UK EPR. It also incorporates experience gained by the Olkiluoto, Flamanville and Taishan projects. The scope of ETC-C 2012 covers design, construction and testing of all concrete structures of the EPR. Although the 2012 revision is not yet officially used in the UK, it is considered here as it is the most recent version of the standard.

ETC-C 2012 requires crack width assessment consistent with the provisions of BS EN 1992-1-1, which are discussed in the next section, and additional provisions for creep and shrinkage strains. Provisions for minimum reinforcement are also consistent with BS EN 1992-1-1. There is no mention of early-thermal crack control during the design process in ETC-C 2012, similar to the 2010 revision of the code. In the UK Companion Document of the 2010 version it is discussed that early-age effects such as plastic shrinkage and thermal shrinkage of EPR concrete structures shall be controlled by construction measures combined with an appropriate concrete mix. This is backed up by operating experience and feedback from the Flamanville 3 project.

BS EN 1992

BS EN 1992 (or Eurocode 2) is a non-nuclear-specific standard principally applicable to design of conventional structures. The provisions of BS EN 1992 do not necessary and generally reflect the functional reliability requirements of nuclear safety-related SSCs and provisions specific to the design of special structures such as Reactor Buildings and RCCVs are outwith its scope. However, BS EN 1992 can generally be used for design of Class 3 structures.

In the UK nuclear industry, BS EN 1992 provisions for crack control are often used to supplement or enhance design of Class 1, 2 and 3 structures undertaken according to other codes, e.g. ACI 349-13 and ASME BPVC 2013 Section III, Division 2, or when design provisions are potentially less conservative than those of BS EN 1992. Furthermore, the provisions of BS EN 1992-1-1 for crack control are specified by ETC-C 2012 as mentioned earlier.

Because BS EN 1992 does not fully address design for early-age thermal cracking, CIRIA C660, Bamforth (2007), is often used to complement the design. CIRIA C660 is also cited as Non-Contradictory

Complementary Information in the UK National Annex to BS EN 1992-3, BS EN 1992-3 (2006). Experience has shown that the use of BS EN 1992 alone can lead to a significant increase in required minimum reinforcement, particularly with sections that are thicker than 800mm. In other cases the use of BS EN 1992 alone can result in smaller amounts of required minimum reinforcement than that calculated using previous UK standards (e.g. BS 8007 or BD28).

The Eurocode approach for crack control essentially provides estimates of the free contraction in a concrete section and applies a restraint factor to determine the restrained strain. Cracking is assumed to occur when the restrained strain exceeds the tensile strain capacity of concrete.

BS EN 1992-1-1 provides limiting crack widths based on durability, serviceability and appearance requirements. A maximum crack width of 0.3 mm is generally used for reinforced members and prestressed members without bonded tendons of all concrete exposure classes, other than X0 and XC1 as defined in BS EN 1992-1-1, for sustained loading under normal environmental conditions. This is normally expected to be satisfactory with respect to appearance and durability. Stricter limits are specified for more severe environmental conditions and functional requirements (e.g. sealing under hydrostatic pressure). Table 1 below is an extract of Table 7.1N BS EN 1992-1-1.

Table 1: BS EN 1992-1-1:2004 Recommended values of maximum crack width.

Exposure Class	Reinforced Members and Prestressed Members with Unbonded Tendons	Prestressed Members with Bonded Tendons
	Quasi-permanent load combination	Frequent load combination
X0, XC1	0.4 mm	0.2 mm
XC2, XC3, XC4	0.3 mm	0.2 mm
XD1, XD2, XD3 XS1, XS2, XS3	0.3 mm	Decompression

BS EN 1992-3, BS EN 1992-3 (2006) provides more stringent limiting crack widths (0.05 to 0.2 mm) than those of Table 1 for sealing of water retaining structures under hydrostatic pressure.

Bamforth (2007) notes that the crack width limits given in BS EN 1992-1-1 are total crack widths arising from early-age deformations, long-term deformations and loading. However, it has not been common practice in the UK to add calculated early-age crack widths to those arising from structural loading, with no reported impairment of structural performance resulting from this. This may be understood due to the self-equilibrating nature of early-age thermal stresses and that they do not coincide with effects from mechanical loading. Bamforth (2007) states that more research and field observations are required in this field. Experience has shown that for thick sections of nuclear-safety related structures the demand due to early-thermal effects can be significant and the addition of crack widths due to early-thermal deformations, loading and long-term deformations can result in increased requirements for reinforcement.

Crack control to BS EN 1992-1-1 may be generally achieved with, or without direct calculation:

- Limiting the maximum reinforcement diameter without direct calculation, by use of Table 7.2N which provides maximum values of bar diameter for crack control, for different levels of stress in reinforcing steel and different limiting crack width values.

- Limiting the maximum bar spacing without direct calculation, by use Table 7.3N which provides maximum values of bar spacing for crack control, for different levels of stress in reinforcing steel and different limiting crack width values.
- Calculating explicitly crack widths to ensure they are within limits, instead of using Tables 7.2N and 7.3N.

Due to the high demands in nuclear safety-related structures, it is often impractical or uneconomical to adhere to the values presented in Tables 7.2N and 7.3N. Therefore, it is common practice to adopt the explicit approach and calculate crack widths.

It is normal practice to design the reinforcement to meet nominal code requirements for structural loading and then to verify that the steel reinforcement provided is adequate to control early-age and long-term cracking. To control the crack spacing and hence the crack widths, there should be sufficient steel such that when a crack occurs the reinforcement will not yield.

BS EN 1992-1-1 Expression (7.8) estimates the resulting crack width w_k as shown in Equation 1. The crack width is defined as the product of the maximum crack spacing $s_{r,max}$ and crack inducing strain, which is given as the difference between the mean strain in reinforcement ε_{sm} and the mean strain in concrete between cracks ε_{cm}:

$$w_k = s_{r,\max}\left(\varepsilon_{sm} - \varepsilon_{cm}\right) \tag{1}$$

The maximum crack spacing depends on the cover to reinforcement, a coefficient which takes account of the bond properties of reinforcement, a coefficient which takes account of the distribution of strain, the bar diameter and the ratio of the area of reinforcement to the effective area of concrete. In crack width calculations, the cover to reinforcement is taken as the nominal cover to longitudinal reinforcement, in accordance with the UK National Annex to BS EN 1992-1-1.

To verify that sufficient steel is provided when cracks occur, the required minimum area of reinforcement is calculated in accordance with Section 7.3.2 of BS EN 1992-1-1. The minimum area of reinforcing steel $A_{s,min}$ in the tensile zone is given as:

$$A_{s,\min} = \frac{k_c k f_{ct,eff} A_{ct}}{\sigma_s} \tag{2}$$

where k_c a coefficient which takes account of stress distribution within the section prior to cracking and the change of lever arm, k is a coefficient which allows for the effect of non-uniform self-equilibrating stresses, $f_{ct,eff}$ is the mean value of tensile strength in concrete at the time when crack are expected to occur, σ_s is the absolute value of maximum stress permitted in reinforcement immediately after cracking and A_{ct} is the concrete area within the tensile zone. The coefficients k_c, k and the area of concrete in tension are influenced by the nature of restraint. Their values can be obtained by Table 3.1 of CIRIA C660, which provides the conditions in which either external restraint or internal restraint is dominant.

BS EN 1992-3, BS EN 1992-3 (2006) uses different expressions for estimating the magnitude of crack-inducing strain. For continuous edge restraint, the informative Annex M of BS EN 1992-3 assumes that the crack-inducing strain is equal to the restrained-strain. CIRIA C660 proposes the following expression:

$$\varepsilon_{cr} = \varepsilon_r - 0.5\varepsilon_{ctu} \tag{3}$$

where ε_{cr} is the crack-inducing strain, ε_r is the residual strain after cracking and ε_{ctu} is the tensile strain capacity of concrete under sustained loading.

ILLUSTRATIVE COMPARISON OF PROVISIONS FOR MINIMUM REINFORCEMENT

An illustrative comparison of differences between the provisions of minimum reinforcement for crack control during the first 28 days is given below considering BS EN 1992, ACI 349-13 and ASME BPVC 2013, Section III, Division 2. It is worth noting that a thorough and accurate comparative assessment of the provisions of ACI 349-13, ASME BPVC 2013 Section III, Division 2 and BS EN 1992 is complicated as one would need to consider different cross sections, self-equilibrating effects throughout the plastic and hardening state of the structure, the effect of subsequent loading on early cracks, differences in detailing and specifications and the construction process.

It is assumed that $k_c = 1$ for pure tension (BS EN 1992-1-1), $k = 0.65$ (BS EN 1992-1-1) as, generally, walls and slabs of an RCCV structure can be expected to be thicker than 800mm, a concrete grade of C35/45 and $\sigma_s = 400$ MPa.

At 4 days, according to Section 3.1.2 and Table 3.1 of BS EN 1992-1-1:

$$f_{ct,eff}(4) = 2.3 \text{ MPa} \tag{4}$$

At 28 days, according to Table 3.1 of BS EN 1992-1-1:

$$\mathrm{f}_{ct,eff}(28) = 3.2 \text{ MPa} \tag{5}$$

If it is assumed that the neutral axis is at the middle of a section, i.e. $A = 2\times A_{ct}$, where A is the gross cross sectional area:

$$A_{s,min}(4) = 0.0019A \tag{6}$$

$$A_{s,min}(28) = 0.0026A \tag{7}$$

The minimum area of reinforcement to ACI 349-13 for sections 1.22 m thick or thicker can be calculated from:

$$A_s'_{min} = f_t'A/f_s'' \tag{8}$$

where $A_s'_{min}$ is the minimum reinforcement, f_t' is the specified tensile strength of concrete and f_s'' is the stress in steel reinforcement. Taking $f_t' = 3.2$ MPa and $f_s'' = 0.6\times500$ MPa $= 300$ MPa yields:

$$A_s'_{min} = 0.011A \tag{9}$$

Therefore, the minimum area of reinforcement should be limited to 1% of the tensile area according to Section 7.12.2.2 of ACI 349-13.

The ASME BPVC 2013, Section III, Division 2 requirement of 0.2% is slightly more conservative that the BS EN 1992-1-1 requirement at 4 days. At 28 days, BS EN 1992-1-1 is more conservative as it requires an additional 0.06% of the gross cross sectional area to be provided as reinforcement. The ACI 349-13 requirement is significantly more conservative than that of BS EN 1992-1-1, requiring 1% of the effective tensile area of the section.

CONCLUSIONS

This paper presented an overview of current UK practice for control of cracks in nuclear safety-related concrete structures and provided a discussion of the principal codes and standards used for design of nuclear-related concrete structures in the UK. The philosophy of ACI 349-13 and ASME BVPC 2013, Section III, Division 2 for crack control at the design process is commendable and backed up by years of operating experience on numerous nuclear safety-related concrete structures worldwide.

However, the lack of a more quantitative and deterministic justification for crack control may be challenged in UK practice and may not satisfy regulators. Consequently, it is generally recommended in the UK to support the design with additional crack width calculations according to BS EN 1992 and CIRIA C660 to substantiate the design and essentially demonstrate "*a conservative design commensurate with the importance of the safety function(s) being delivered*" as required by the relevant Safety Assessment Principles.

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