*Transactions*, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Division VI

# PRACTICAL APPLICATION OF REINFORCED CONCRETE DESIGN METHODS FOR THERMAL LOADS IN NUCLEAR STRUCTURES

**James Phillips[1], Ming Tan[2], John Hadfield[3], Jia Jianying[4]**

[1] Principal Engineer, Mott MacDonald, Manchester, UK (james.phillips@mottmac.com)
[2] Technical Principal, Mott MacDonald, Manchester, UK (ming.tan@mottmac.com)
[3] Principal Analyst, Mott MacDonald, Manchester, UK (john.hadfield@mottmac.com)
[4] Principal Engineer, State Key Laboratory of Nuclear Power Safety Monitoring Technology and Equipment, China Nuclear Power Engineering Co. Ltd, China

## ABSTRACT

In nuclear structures, the thermal loading can often be the critical design case for some members and significantly influence the reinforcement design. Considering this, it is important for civil engineers to fully understand the key influential factors to the thermal design and to apply practical approaches to reduce conservatisms in the analysis and design, to enable economy of design. To date there is no consistent internationally recognized approach on how thermal loads can efficiently be catered for in the design of reinforced concrete members, with differing approaches currently adopted across UK nuclear sites.

This paper presents a state-of-art review of different approaches for considering thermal loadings in the design of reinforced concrete structures within the nuclear sector, together with their advantages, disadvantages and conservatisms. The review covers the various approaches within nuclear specific design codes and guidance documents and existing relevant good practice (RGP) within the UK nuclear sector. The established codes and guidance documents reviewed here includes ACI 349-13 (2017), ETC-C (2010) with UK companion document (2012) and RCC-CW (2018).

Using the work undertaken for the Generic Design Assessment (GDA) in the UK for UK HPR1000 [GNSL, 2020], a comparison of the design outcome of using different codified approaches is also presented based upon real design data for thermal loadings for some of the representative date from the reactor building, to establish whether simplified approaches are readily justifiable for adoption in the design of nuclear structures for thermal loadings.

## UK HPR1000

The UK HPR1000 is a Pressurised Water Reactor using the Chinese Hualong technology with electric output of approximately 1180MW. The UK HPR1000 has evolved from a sequence of reactors that have been constructed and operated in China since the late 80s, including the M310 design used at Daya Bay and Ling'ao (Units 1 and 2), the CPR1000, the CPR1000+ and the more recent ACPR1000. The first two units of CGN's HPR1000, Fangchenggang NPP Units 3 and 4, are under construction in China. Fangchenggang NPP Unit 3 is the reference plant for the UK HPR1000.

With the intention to be deployed to the Bradwell 'B' site in the UK, the UK HPR1000 was put forward for GDA in January 2017, to be assessed jointly by the regulators - Office for Nuclear Regulation (ONR) and the Environment Agency. The regulators provided independent scrutiny to ensure that the reactor design is applicable to UK regulatory standards of safety, security and environmental protection.

The GDA for the UK HPR1000 was successfully completed in February 2022, with the issuing of a Design Acceptance Confirmation (DAC) from the ONR and a Statement of Design Acceptability (SoDA) from the Environment Agency [ONR, 2022].

## BACKGROUND

Thermal loads in structural members occur as a result of the restraint of structural members subject to thermal expansion or contraction. Thermal loads can arise in structural members due to a number of thermal exposure conditions typical to nuclear structures, including varying external climate conditions, heating and cooling of internal spaces for user comfort, heat loss or gain from pool water and heat from specific plant and equipment. These thermal loads need to be accounted for in the design of nuclear structures to demonstrate design compliance against the varying design basis events.

The extent of thermally induced reactions within a structural member are not based upon the equilibrium of externally applied loads and internally developed forces and moments, as is the case for other mechanical loads (such as live loading due to plant). Instead, the internal reactions are dependent upon the thermally induced strain distribution in the member and the subsequent resultant stress distribution across the section. The resolution of these stresses gives the thermal loads (axial forces and moments) applicable to the member. As such the extent of thermal loads are driven by the applied thermal strains and the member's stiffness properties (e.g., the cross-sectional area, second moment of area, Concrete Modulus of Elasticity E, etc).

Thermal effects are typically accounted for in the design of nuclear structures by one of the following approaches:

a) Application of temperature effects (mean section temperature change and surface temperature differential) into Finite Element (FE) analysis models to determine the applied temperature strains (see b) below) and the resulting thermal forces and moments within the structural elements - based upon the members shape, material properties, and restraint conditions. The FE analyses may be performed using linear or non-linear analysis methods.
b) Manually calculation of the thermal axial strains ($\varepsilon$) and change in curvature ($\phi$) due to the temperature differential ($\Delta T$) using simplified conservative methods, with $\varepsilon = \alpha \Delta T$ and $\phi = \alpha \Delta T / t$, where t is the section thickness and $\alpha$ is the linear coefficient of thermal expansion (these formulae are the basis of linear FE analysis methods). Based upon a linear stress / strain relationship, conservative stresses and reactions can subsequently be derived.
c) Thermal effects are ignored. This approach is applied where the thermal effects are deemed small and not to govern or influence the design. The influence of thermal effects on serviceability criteria are accounted for by good detailing and design practice.

Each of the above approaches has its advantages, disadvantages, and conservatisms. Therefore, the selection of the approach is usually project dependent based upon the scale of temperatures, structural form, and expected influence of temperature effects.

Adopting linear FE analysis or simple manual calculations to determine thermal forces for reinforced concrete members, typically produces conservative results. As discussed, thermal forces and moment are dependent upon the stiffness properties of the section, so when assuming linear elastic section properties to determine thermal loads, the effects of stress reductions due to cracking of the concrete and other factors such as creep and yielding are not captured. In reality, a small amount of creep, cracking, and deformation can lead to a large reduction in thermal loads from those determine by linear analysis. Subsequently, nuclear specific design codes and other guidance documents and literature provide further approaches to reduce conservative thermal reactions determined using linear elastic assessments.

This paper summarises a review of different methods of how thermal loadings can practically be considered in the design of reinforced concrete structures within the nuclear sector, with reference to established design codes and guidance documents (ACI, ETC-C and RCC-CW) and existing relevant good practice (RGP) within the UK nuclear sector. These reviews were undertaken as part of the GDA works undertaken for the UK HPR1000. Emphasis is placed on reducing conservatisms and providing economy of design - in terms of reducing section sizes and reinforcement requirements, and on adopting practical design approaches. A comparison of the potential reduction in thermal loadings on reinforced concrete members using different approaches is also presented based upon thermal loadings for representative members on the UK HPR1000 design.

The thermal loads and ranges in this assessment are limited to those associated with operating and environmental conditions (normal, accidental and extreme) but does not consider implications due to fire temperatures. In addition, the impact of high temperatures on material properties are out of the scope of this assessment.

## ACI 349 THERMAL STRUCTUAL EVALUATION APPROACH

Structural design information and evaluation approaches for the assessment of thermal loadings on reinforced concrete nuclear structures are captured within Appendix E of ACI 349-13, and in the ACI349.1R-07 (2007) guidance document.

Appendix E of ACI 349-13 provides general discussions related to the application and design of thermal loads on reinforced concrete members and factors that should be considered. However explicit design instructions within ACI 349-13 for assessing thermal loadings are limited. ACI 349.1R-07 presents more detailed discussions on the general behaviour of reinforced concrete (RC) structures under thermal loads as well as providing simplified design-orientated approaches for the consideration of thermal loads on RC structures in alignment with the information within ACI 349-13 Appendix E.

### *ACI 349M-13*

Key discussions within ACI 349M-13 Appendix E related to design of reinforced concrete for thermal loadings include:

- thermal stresses may be self-relieving, due to the mechanisms of cracking, yielding, and creep, etc. (RE.1.2(1))
- Clause E.3.3 states that thermal stresses shall be evaluated considering the stiffness characteristics and the degree of restraint of the structure. The evaluation shall be based on cracked section properties, where; tensile stresses occur greater than the concrete tensile capacity; all concurrent loads are considered; and the internal forces and strains in a section are redistributed to consider cracking.
- Clause RE.3.3 provides guidance on suitable approaches for the resolution of the thermal stress problem, as follows:
  1. Most structural analyses treat thermal loads acting on a monolithic section and evaluate the rigidity of the section and the stiffness of the member based on full uncracked cross sections. Although easy to perform, such an analysis may be overly conservative for moments and forces because it does not consider the self-relieving nature of thermal stress due to cracking and deformation.
  2. Analyses may consider the cracking of concrete for all loads, mechanical and thermal. Although this approach probably is the most accurate and generally results in the largest degree of self-relieving thermal stress, it is complex, involving significant nonlinear analysis and iterative solutions not readily available to the designer; and
  3. The third alternative is to consider the structure uncracked for mechanical loads and only consider the effect of cracking on thermal loads. The difficult part of such an analysis is the determination of

that part of the thermal load that causes cracking, and that part then can be considered acting on a cracked section.

As highlighted above, clause R.3.3 provides three potential approaches to consider thermal loadings; linear elastic analysis; non-linear analysis; and adoption of cracked section properties for the thermal loads only. In all three approaches the degree of restraint of the structure is achieved by the use finite element modelling, however the approach to consider the influence of stiffness varies. The adoption of the linear elastic analysis provides a simple yet overconservative approach for the stiffness and resultant thermal reactions. Non-linear analysis leads to the most accurate stiffness and thermal analysis approach, however, as highlighted, is complex and time consuming and typically unpractical to achieve for the Designer. Consideration of cracked section properties for the thermal loads only, provides a good medium between the simple linear elastic analysis and a non-linear analysis, in terms of time and reducing conservatisms.

ACI 349M-13 provides no direct guidance on how to determine or approximate for reductions in thermal loadings due to cracking, creep, deformation, or yield effects. Simplistic approaches for consideration of cracking and creep are however provided for other loading and design scenarios within ACI 349M-13, such as slenderness assessments and deflection checks. Although these other design approaches are not directed at the reduction of thermal reactions due to cracked section properties or creep, they provide an insight into typical reductions in member stiffness due to cracking and creep. ACI 349M-13 cl. 8.8.2 specifies that where a linear elastic analysis is performed to determine lateral deflections, the assumed stiffness properties can be assumed to be 50% of the gross section properties to account for creep effects. ACI 349M-13 cl. 9.5.2.5 provides factors to increase deflections to capture additional long-term deflections resulting from creep of flexural members; these factors equate to a reduction in concrete modulus of elasticity for long term loading of approximately 0.5 for loadings of 5 years or more, 0.72 for 12 months loading and 0.83 for 6 months loading.

### ***ACI 349.1R-07***

ACI 349.1R-07 is intended to propose simplifications that may be used for structural assessments of reinforced concrete structures for thermal loadings. It permits exclusion of thermal cases with small effect and provides a reduction of thermal effects for a large class of thermal cases without resorting to sophisticated and complex solutions. As a result of the report discussion, the design examples, and graphical presentation of cracked section thermal moments, it is hoped that a designer will better understand how thermal effects are influenced by the presence of other loads, the section properties and the resulting concrete section response. The report regularly refers to the influence of cracking, reinforcement yielding, concrete creep, nonlinear concrete stress-strain, and shrinkage on the thermal reactions and how thermal loads are generally self-relieving.

Some of the key discussions within ACI 349.1R-07 related to design of reinforced concrete for thermal loadings include:

- Chapter 1.2 discusses how ‘Response of a structure to thermal effects depends on the nature of the temperature distribution, end constraints, material properties, and mechanical loads. Stresses in the concrete and reinforcement occur due to restraint of thermal movement and these stresses are generally self-relieving. These thermal stresses are generally small, as most thermal exposures are within prescribed ACI 349 temperature limits. Furthermore, internally generated stresses are complex to analyse given the size and geometry of safety-related concrete structures. As such, structural analyses using manual calculations with simplifying, conservative assumptions (for example, concrete is cracked) are typically considered to be appropriate. Computer-based analysis tools may also be used to determine the effects of thermal exposure and structure response as illustrated in the following paragraphs. It should be noted that a thorough and complete computer-based thermal analysis is much more complicated than a structural analysis of mechanical loads. The difficulty of defining important parameters would also make such computer thermal analyses controversial because differences in parameter ranges may produce significant differences in analytical results. Finally, it is known that ambient thermal effects, in all but very unusual situations (for example major fire events), will have little effect on the ultimate strength of a concrete structure.'

- Chapter 1.3 discusses how 'Stresses resulting from thermal effects are generally self- relieving, that is thermal forces and moments are greatly reduced or completely relieved once concrete cracks or reinforcement yields; as a result, thermal effects do not reduce the strength of a section for mechanical loads' and that 'Design for thermal effects is primarily for serviceability and should address control of cracking'. Further to this the following arguments are provided with regards to being able to ignore thermal effects for a large number of cases:
  - Extreme environmental events are rare occurrences. Serviceability of the structure may not be required after such events. If they occur, high stresses are induced in local areas. Under these stresses, concrete cracks and reinforcement may yield, relieving thermally induced stresses. Thus, it may be too conservative to add the thermal stresses based on elastic analysis to the stresses due to extreme environmental loads. Consequently, the elastically calculated thermal stresses should be reduced considering concrete cracking and reinforcement yield before combining them with the stresses from extreme environmental loads;
  - It would be counterproductive to add reinforcement to mitigate thermal effects because the additional reinforcement would stiffen the structure, thus increasing the stresses due to thermal effects. This is unnecessary because thermal effects typically self-relieve without the need for additional reinforcement. If additional thermal reinforcement is indicated by the design and analysis, the appropriateness of methods and means should be re-evaluated;
  - Thermal gradients should be considered in the design of reinforcement for normal conditions to control cracking. Thermal gradients less than approximately 100 °F (56 °C) need not be analysed because such gradients will not cause significant stress in the reinforcement or strength deterioration. It may cause a small incursion into the nonlinear range for extreme events, but such incursions are not likely to adversely affect the overall behaviour of the structure.
  - A uniform temperature change (Tm – Tb) of 50 °F (28 °C) or less need not be analysed.
- Chapter 1.4. states that 'Elastic FEAs can be used with a reduced elastic modulus for concrete to account in a very simple manner for the various effects of cracking, creep, and yield.' Reference is made to the use of a 0.5 factor on the Concrete Modulus of Elasticity in past practice. No reference or support material is provided for this value and it is only a suggested approach.
- Chapter 1.7 of ACI 349.1R-07 provides a summary, acknowledging the difficulty in accurate analysis of thermal effects, mechanical loads, restraint, concrete cracking, and other stress-relieving effects and stating that the use of a simplified procedure should be adequate to calculate the thermal effects.
- Design guidance for determining reduced thermal moments using cracked section properties is given in Chapter 4 of ACI 349.1R-07 for shell element type structures. Approaches are provided as both formulae and tabulated format. The magnitude of the thermal moment depends on the extent of cracking – which is dependent on the temperature, the section properties, the concrete modulus of elasticity and the applied section forces & bending moments (N & M, with e=M/N). Chapter 4 states that 'the cracked section thermal moments can be considered to represent upper-bound values when compared with those that would result from a nonlinear stress-strain concrete relationship'.

  It is noted that Chapter 4 only provides a methodology for determining reduced thermal moments due to application of a thermal curvature and assumes that any thermal axial forces are included within the mechanical loads.

In summary, three different potential simplified approaches are alluded to in ACI 349.1R-07 for consideration of thermal loadings:

1. Ignoring thermal loadings for ultimate limit state design, where temperatures are within a prescribed limit.

2. Adoption of a reduced elastic modulus (0.5) for concrete to account in a very simple manner for the various effects of cracking, creep, and yield.
3. Detailed manual calculation to determine reduced thermal loadings based upon the expected section stiffness and applied loadings.

The manual calculation methods within ACI 349.1R-07 are derived from first principal formulae assuming linear stress strain relationships, no concrete tensile capacity and the premise that the application of the thermal curvature leads to no change in the axial loading equilibrium across the section. The approach within ACI 349.1R-07 only account for reductions due to cracking and doesn't consider for any reductions due to creep.

Interpretation of the figures provided in ACI 349.1R-07 to derive the thermal loadings indicates that for members with large bending moments relative to axial forces, thermal load reduction factors (RF = cracked case thermal load / non-cracked thermal load) of as low as 0.14 can be achieved for sections with low reinforcement provisions (0.25% Area of steel per face(As)), with the reduction factor (RF) increasing as the reinforcement provisions (As) increase (0.25% As = 0.14 RF, 0.5% As = 0.22 RF, 1% As = 0.42 RF, 1.5% As = 0.59 RF).

The above results are for a relatively low axial load; increases in tensile axial loads lead to further decreases in the reduction factors, whilst an increase in compressive loads leads to increases in the reduction factors. This logic is expected based upon the changes to the extent of cracking from tension and compressive axial loads. It is noted that under high compressive loads, there maybe limited or no reduction in the thermal moments, however due to the presence of compression across the section for these cases, they are rarely the governing case for reinforcement design. Other factors that influence the extent of the thermal load reduction factors are the extent of the thermal and mechanical moment and the area or reinforcement in the section.

It is noted however that shortfalls and limitations with the detailed calculation methodology still exist with regards to the practical application of the methods for nuclear reinforced concrete structure design; which include

- Adoption of the manual calculation methods can be difficult to practically apply in an economical manner for nuclear structures due to the larger number of load case combinations and elements typically considered. Automation of the approach could be viable but would still require extensive computer processing time due to iterative approaches being required and the number of cases, and any software would require a robust validation and peer review for adoption on a nuclear project.
- Conservatisms in the assumed modulus of elasticity of concrete, where the short-term loading value is assumed for all cases. This is potentially due to difficulty in considering different short term and long-term mechanical and thermal loadings using such manual approaches, and the present approach providing conservatisms.
- Lack of a specific quantitative approach for consideration of thermal axial loads. The document currently proposes that any thermal axial loads be added to the mechanical axial loads with any reductions to the thermal axial loads established by adopting cracked section properties in the FEM. However, the assumptions of the cracked section properties for this FEM are not outlined.

## ETC-C THERMAL STURCUTRAL EVALUATION APPROACH

The ETC-C design code, and the UK companion document, is currently utilised for the design of new nuclear power plant construction of the EPR in the UK. The ETC-C and UK companion documents accounts for thermal loads by the use of FEM with modified modulus of elasticity for thermal cases, to account for creep effects, and with the use of generic load reduction factors for thermal reactions, to account for reductions due to cracking and reinforcement yielding.

As outlined in Table 1.3.3-2 bis (2) of the ETC-C UK companion document, the ETC-C approach to thermal loads is conservative compared to the Eurocode recommendations which does not require consideration of thermal loads for ULS calculations for concrete and is not required to be considered as a secondary action in load combinations.

Equations for calculating the modulus of elasticity for different thermal cases are provided within the ETC-C UK companion document which are based on extant formulae from the concrete Eurocodes. The reduction in stiffness from these formulae (with a creep coefficient of 1.17) is presented in Table 1 for the various design load case scenarios.

The reduction factors to be adopted for the assessment of thermal loads are defined in Section 1.4.4.1 of the ETC-C design code. These reduction factors are defined to account for cracking within linear elastic thermal structural analysis results and are applied to the thermal reactions FE results only. The thermal load reduction within this code is presented in Table 1 for the various load case scenarios. These values are valid for reinforced concrete sections with concrete strength $30 \text{ MPa} \leq f_{ck} \leq 60 \text{ MPa}$ and a bending reinforcement ratio $\rho_s < 0.01$.

The cumulative effect of the reduction in concrete modulus and the application of the thermal load reduction factor on thermal loadings derived directly from unmodified linear elastic FE analysis is shown in Table 1 below for different thermal loading cases and indicates the extent of over conservatisms in utilisation of thermal loadings directly from FE analysis or from manual linear thermal stress calculation methods.

Table 1: Overall Effective Reduction Factor of thermal loads using ETC-C

| *ETC-C* | | Load case combination (See table 1.3.3-2 bis) | Concrete Modulus of Elasticity Factor (factor on $E_{cm}$) | Thermal load Reduction Factor | Effective Reduction Factor On FE Results |
|---|---|---|---|---|---|
| Climatic Temperature | normal ($Q_{,k}$) | SLS$_{.f}$ | 0.73 | 0.60 | 0.44 |
| | | ULS$_{.f}$ & SLS$_{.c}$ | 0.73 | 0.50 | 0.37 |
| | | ULS$_{.a}$ | 0.73 | 0.35 | 0.26 |
| | exceptional ($Q_{k,T,Exc}$) | SLS$_{.c}$ | 0.9 | 0.50 | 0.45 |
| Internal Hazards | Normal ($Q_{,k}$) | SLS$_{.f}$ | 0.73 | 0.60 | 0.44 |
| | | ULS$_{.f}$ & SLS$_{.c}$ | 0.73 | 0.50 | 0.37 |
| | | ULS$_{.a}$ | 0.73 | 0.35 | 0.26 |
| | Accidental ($A_{d,T}$) | ULS$_{.a}$ | 0.64 (direct)<br>0.90 (indirect) | 0.35 | 0.22 (direct)<br>0.32 (indirect) |
| Pool Water Temperature | Normal ($Q_{k,T,N}$) | SLS$_{.f}$ | 0.46 | 0.60 | 0.28 |
| | Exceptional ($Q_{,k,T,E}$) | SLS$_{.c}$ | 0.64 (direct)<br>0.90 (indirect) | 0.50 | 0.32 (direct)<br>0.45 (indirect) |
| | Accidental ($A_{d,T}$) | ULS$_{.a}$ | 0.64 (direct)<br>0.90 (indirect) | 0.35 | 0.22 (direct)<br>0.32 (indirect) |

## RCC-CW Thermal Structural Evaluation Approach

The RCC-CW (2018 Edition) design code provides rules for design and construction of Nuclear civil works and was developed by AFCEN. RCC-CW is a further development of the previous ETC-C code. The simplified approach taken within RCC-CW is as per the ETC-C approaches with the only amendments being that exceptional climatic conditions are replaced with accidental climatic conditions with amended parameters accordingly and changes to the Concrete Modulus of Elasticity for Accidental internal hazard cases.

For the accidental climatic condition, the Concrete Modulus of Elasticity decreases from 0.9 to 0.73 and the load is treated as an accidental action reducing the thermal load reduction factor from 0.5 to 0.35, which results in an overall effective reduction factor of 0.26 (compared to 0.45 in ETC-C) for this case. For the accidental internal hazard case, values are not provided for direct and indirect members, as per ETC-C, instead the Concrete Modulus of Elasticity is taken as for the normal operational values (0.73), resulting in a effective overall reduction factor of 0.26.

The RCC-CW also provides an alternative detailed approach for calculating reduced thermal loadings. This approach utilises a slightly different method to those proposed within ACI 349.1R-07 and is based on the premise that the neutral axis remains the same for the mechanical loads and thermal loadings and that a tensile tie effect in the concrete is introduced to maintain equilibrium of axial loads. It is noted that the guidance and examples within RCC-CW for this approach are limited.

## UK RELEVENT GOOD PRACTICE

As part of the review of thermal design methods for nuclear reinforced concrete structures, a review of existing practices for a number of UK nuclear projects and sites were looked at. Approaches for some of these sites are noted below. In general it is noted that there is no common method of relevant good practice (RGP) currently adopted across UK nuclear sites, with approaches dependent on previous site experience, the adopted design codes and the operation of the building.

Historically it has been common practice for UK nuclear structures to not consider temperature loads for reinforced concrete members, unless there is a significant thermal effect due to plant operation or accidental conditions, based upon qualitative arguments on structural behaviour and reference to ACI 349.1R-07 recommendations and other standard building guidance.

The existing approach taken for a major UK nuclear decommissioning site is to consider thermal loadings only for exceptional loadings that are generated by plant and equipment. For these cases, linear elastic thermal structural FE analysis is undertaken with a reduced Concrete Modulus of Elasticity adopted in order to account for both the effects of creep and cracking. Typical factoring of the nominal short-term concrete modulus of elasticity has been in the range of 0.25 to 0.50. This methodology recognises that assumptions are being made in the concrete material's thermal behaviour that is accounted for by factors on the conservative linear analysis.

The new EPR reactor at Hinkley Point uses the EPR specific ETC-C design guide and supporting UK companion document for the analysis and design of the construction of the reinforced concrete civil structures. The ETC-C design code is discussed earlier in this document and uses a factor on the Concrete Modulus of Elasticity in the linear FE analysis, and a thermal load reduction factor, on the FE results.

At another previously planned UK new nuclear power station, thermal effects were only to be considered where the temperature differentials were outside the limits recommended within ACI 349.1R-07. Where thermal effects were to be considered, the thermal reactions were to be determined with a linear elastic thermal structural FE analysis and then post-processed using empirical formulae to consider cracked section properties, as per those outlined in ACI 349.1R-07.

## COMPARISON OF ALTERNATE CODE METHODS

To understand the differences in thermal load reductions using alternate methods; a comparison assessment of the reduced thermal moments due to cracking between the ACI 349.1R07 approach and the ETC-C approach have been undertaken for sample element results from the UK HPR1000 GDA designs. This assessment looked at a series of structural elements to the Spent Fuel Pond which were governed by thermal loading. The governing thermal loads are considered for these assessments, with some load cases resulting in tension across the entire section. Only the reduction of thermal moments Mx and My are considered in the assessments, as consideration of thermal axial forces are not captured within the ACI 349.1R-07 approach, see previous discussions. Table 2 summarises the results obtained from the calculation of thermal loading reduction factors in in accordance with ACI 349.1R-07 and compares it to thermal reduction factors for ETC-C and RCC-CW.

Table 2: Comparison of Thermal Load Reduction Factors determined using ACI 349.1R-07 and ETC-C for elements to the Spent Fuel Pond for the UK HPR1000 design

| **Element** All 2m thick | **Axis** | **Load Combination** | **Section Stress Condition** | **ACI 349.1R approach Thermal Reductional Ratio** | **ETC-C Thermal Reduction Factor** |
|---|---|---|---|---|---|
| 230997 | x | Normal | Tension Only | 0.06 | 0.50 |
| | y | Normal | Tension Only | 0.06 | 0.50 |
| 234018 | x | Accidental | Tension Only | 0.10 | 0.35 |
| | y | Normal | Tension Only | 0.06 | 0.50 |
| 230022 | x | Normal | Tension Only | 0.06 | 0.50 |
| | y | Accidental | Tension Only | 0.07 | 0.35 |
| 219657 | x | Normal | Tension & Compression | 0.13 | 0.50 |
| | y | Normal | Tension & Compression | 0.12 | 0.50 |
| 219651 | x | Normal | Tension & Compression | 0.14 | 0.50 |
| | y | Normal | Tension & Compression | 0.10 | 0.50 |
| 219635 | x | Normal | Tension Only | 0.12 | 0.50 |
| | y | Normal | Tension Only | 0.11 | 0.50 |
| 219625 | x | Accidental | Tension & Compression | 0.12 | 0.35 |
| | y | Accidental | Tension Only | 0.11 | 0.35 |
| 219621 | x | Accidental | Tension Only | 0.08 | 0.35 |
| | y | Accidental | Tension Only | 0.11 | 0.35 |
| 222773 | x | Normal | Tension & Compression | 0.06 | 0.50 |
| | y | Accidental | Tension Only | 0.06 | 0.35 |
| 236248 | x | Normal | Tension & Compression | 0.05 | 0.50 |
| | y | Normal | Tension Only | 0.04 | 0.50 |

The ACI 349.1R-07, adopted in the calculations do not account for effects of a reductions in the Young's Modulus, as reduction of the Young's modulus for the thermal loading in the manual assessments is not directly achievable due to the combination of mechanical and thermal loadings in the expression. The comparison shows that the thermal moment reduction ratios determined with ACI 349.1R-07 methods are significantly lower than the general thermal load reduction factors proposed in ETC-C and RCC-CW. The following observations and comments can be made from these results:

- In these example cases, there is significant conservatism in the adoption of general thermal reduction factors, relative to using the detailed ACI 349M-13 approach.
- The large reduction in thermal moments occurs due to the section thickness, low reinforcement ratios (0.1% to 0.4%) and the presence of tension loads across the section for the enveloping load cases.

- If the sections were subject to compression, this would increase the thermal moment reduction factor; however, it is typically the load case combinations with tension (or lower compression) in the section that govern the reinforcement design, and therefore such case would rarely govern the design.

## CONCLUSION

A review of design codes, guidance documents and existing best practice with regards to the application of design methods for consideration of thermal loadings on reinforced concrete structures was undertaken in support of the qualification of an approach for the UK HPR1000. The summary of these assessments has been presented in this paper. The following conclusions are made from this review, with regards to the practical application of non-conservative design methods for consideration of thermal loadings on reinforced concrete structures:

- Previous UK experience for a number of UK nuclear sites has been to ignore thermal effects due to climatic temperature loading, based on qualitative arguments. Arguments for such an approach are provided within ACI 349R.1 guidance, which discusses stresses for thermal loadings are inherently self-relieving with thermal forces and moments greatly reduced or completely relieved once the concrete cracks or reinforcement yields. As a result, thermal effects do not reduce the strength of a section for mechanical loads and design for thermal effects is primarily for serviceability and should address control of cracking. Therefore, the consideration of thermal loadings in design is a conservative practice that is regularly not considered for ultimate limit state design.
- Adoption of a linear elastic FE analysis to apply thermal loads (temperatures) and to derive the structural forces & moments is deemed RGP and provides simplicity in the analysis and subsequent validation, relative to non-linear analysis.
- The adoption of a short-term (higher) Concrete Modulus of Elasticity for the design against long term thermal loads will lead to conservative results and should be reduced to reduce conservatisms, as recognised in ACI 349-13, ETC-C and RCC-CW and existing practices. Prescriptive approaches for this are not included within ACI 349-13, but are within ETC-C and RCC-CW.
- Direct adoption of linear elastic FE analysis results for thermal loads is overly conservative, as it does not account for cracking of concrete, creep and yielding of reinforcement, which can lead to significant reductions in thermal loads. As such it is recommended that approached are taken where thermal loads are considered to reduce these conservatisms.
- Linear elastic FE analysis for thermal loads, but representing the non-linear affects via factors, is a common and widely accepted industry approach – as stipulated by the established design codes and guidance documents and existing RGP within the UK nuclear sector.
- Prescriptive values for thermal load reduction factors are provided within ETC-C and RCC-CW (0.35 for accidental cases, 0.5 for normal ultimate limit state cases and 0.6 for serviceability cases. ACI 349.1R-07 and existing UK nuclear sites practices are less prescriptive, but reduction factors of 0.5 have been utilised historically, which aligns to reductions for consideration of cracking and creep in other design checks of the ACI 349M-13 code.
- ACI 349.1R-07 and RCC-CW provide more detailed calculation approaches for more accurate assessment of thermal load reductions due to cracking. The application of such approaches can provide greater certainty to the extent of thermal load reduction, however, there remains limitations on the adoption of these, and even with automated design approaches, can be time consuming and complex to process for the expected large number of load case combinations for nuclear projects.
- Comparison of reduction factors determined using ACI 349.1R-07 calculation methods and ETC-C methods was undertaken for a selection of elements to the Spent Fuel Pond for the UK HPR1000 design. This comparison highlighted for these specific members that the adoption of generic thermal load reduction factors remained conservative to the more detailed ACI 349.1R-07 method, with significant reductions in thermal moments when adopting the ACI 349.1R-07 method in the examples taken.

## REFERENCES

ACI Committee 349 (2017). *Code Requirements for Nuclear Safety-Related Concrete Structures* (ACI 349-13) and Commentary, American Concrete Institute, Farmington Hills, MI, U.S.A

ACI Committee 349 (2007) *ACI 349.1R-07 Reinforced Concrete Design for Thermal Effects on Nuclear Power Plant Structures*, American Concrete Institute, Farmington Hills, MI, U.S.A

AFCEN (2010) *ETC-C 2010 EPR Technical Code for Civil Works, AFCEN*, Tour Areva, 92084 Paris la Défense Cedex FRANCE

AFCEN (2018) *RCC-CW 2018 Rules for Design and Construction of PWR Nuclear Civil Works*, AFCEN, Courbevoie FRANCE

EDF SEPTEN (2012) *UK Companion Document to AFCEN ETC-C* revision E

GNSL (2020), Pre-Construction Safety Report, HPR/GDA/PCSR/0016, Rev 001

ONR (2022), https://www.onr.org.uk/new-reactors/uk-hpr1000/dac-soda.htm