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CREEP AND SHRINKAGE CONSIDERATIONS FOR NUCLEAR SAFETY RELATED CONCRETE STRUCTURES

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ABSTRACT

Current Codes, such as ACI 349 and ASME Section III, Div. 2, require that creep and shrinkage effects be considered for design of concrete nuclear structures. Although such considerations are well understood and applied in case of prestressed structures such as containments, it is not clear how these effects should be included in conventionally reinforced nuclear structures such as those designed per ACI 349 Code. There are no clear guidelines to evaluate creep and shrinkage effects that need to be included in design of conventionally reinforced concrete nuclear structures. To address this issue, this paper reviews the current Code requirements and industry practice related to treatment of creep and shrinkage in design of nuclear power plants in United States. Since creep and shrinkage effects are dependent on structural configuration and geometry, guidelines and criteria based on current ACI Standards for non-nuclear structures is also reviewed to help provide guidance as to when these effects may become significant for conventionally reinforced nuclear structures. In particular, this paper discusses the difference between creep and shrinkage of commonly encountered thick (mass) concrete structural elements (such as basemat, reactor cavity, etc.) with those for relatively slender structural elements such as walls and columns, etc. and industry practice in dealing with them. Also, since nuclear structures generally involve a significant amount of reinforcement, importance of reinforcement to mitigate creep and shrinkage is also discussed.

INTRODUCTION

Creep and shrinkage are two complex and interrelated concrete materials phenomenon that can only be understood when discussed independently as in most industry standards. ACI 209 states that “Shrinkage and creep may occur in three dimensions”. However, most research suggests that total strain, shrinkage, and creep occur in each dimension independently. Creep strain represents the time dependent increase in strain under sustained constant load taking place after the initial strain at loading. It is obtained from the load-induced strain by subtracting the initial strain. The creep strain may be several times greater than the initial strain. Creep strain may be subdivided into a drying and a nondrying component, termed drying and basic creep, respectively.

Creep becomes generally important where concrete sections are subjected to significant sustained compression loads. Under this condition and over a period of time, the concrete continues to deform under constant load while the elastic stress continues to dissipate and transfer to, for example, steel elements within the section. The elements that are generally impacted by creep are the prestressed members, columns of high-rise structures and long-span floors and bridges. In case of prestressed members, the gradual member shortening can result in loss of prestress over time which needs to be accounted for in the design of such members. Conventionally reinforced columns carrying significant compression may also tend to shorten (called as “column-shortening”) compared to, for example, wall elements of the same structure causing floor levelness issues over time. In case of long span and/or heavy concrete floors or bridges, deflections due to creep continue to increase over time and may cause issues with architectural/non-structural components or interfere with daily function or operation of the structure or the surrounding space.

In practice, creep effect is often measured using the creep coefficient, which could be determined using testing, or calculated using empirical equations provided in ACI 349, ACI 209 or other applicable literature.

From practical stand point, creep becomes structurally important at higher stress levels. For example, for a prestressed concrete wall of 100 ft height, considering fc= 4000 psi, prestress =1500 psi and a typical creep coefficient =1.25, the creep deformation will be 0.624 in. On the other hand, a conventional reinforced concrete wall of same size will have about 0.02 in of creep deformation due to its weight.

Shrinkage is volume change (reduction) of concrete that can result from a combination of factors including the basic or autogenous shrinkage due to the hydration process of concrete mixture, moisture loss due to drying and carbonation of concrete when in service over a period of time. The primary and the most significant contributor to shrinkage is the drying shrinkage. Per ACI 209, long-term shrinkage of concrete can vary significantly (from 200 – 800 micro strains) depending upon the concrete mixture, element size and shape and the environment.

NUCLEAR APPLICATION

Nuclear structures are generally box type buildings involving heavily reinforced and thick reinforced concrete sections. As discussed in the previous section, creep becomes important for post-tensioned (PT) sections (such as the containment walls) and heavily loaded vertical elements (columns and walls) and long span floor slabs, if present. The creep effect of PT containments is evaluated in detail both from material as well as design point of view. Concrete mixture is selected with aggregate having relatively low creep properties and a detailed creep evaluation is done to ensure that there is enough prestress left at the end of the life of plant after creep losses are factored in. The design PT force thus includes the creep loss effect of concrete.

Since extreme environmental or accident loads (like seismic and pipe break) control the design of conventionally reinforced concrete elements, the gravity load that they have to carry during the normal operation is small compared to their capacities. Therefore, creep is generally not a concern for such elements. (Also, creep tends to increase the compression in the reinforcement while reducing compressive stresses in concrete for the vertical elements such as walls which may help against the extreme loading events such as SSE). As discussed, since such elements are generally very heavily reinforced, the creep effect is minimized.

Long-span and thick floors may be subject to additional deformations due to creep and shrinkage as stipulated in Section 9.5.2.5 of ACI 349 Code. But slabs of nuclear structure are generally thick and not very long which reduces the initial deformation. Also, presence of reinforcement reduces the creep effect as discussed above. Therefore, for nuclear structures with typical sections and spans, application of the above ACI 349 provisions to determine the long-term deflections is deemed to be appropriate. It should be noted that provisions of Section 9.5 (same as in ACI 318) for deflections were derived for slabs of conventional buildings with typical thicknesses ranging between 4-8 inches. Although not much data exists, it is assumed that deflections of thicker floors would be conservatively predicted with the use of these provisions.

If significant, the creep effect on long-term deflection of slabs or shortening of the vertical elements should be included using the service load combinations (gravity load combinations without load factors) using methods presented by Fintel and Khan (1969), Troxell, et.al. (1958), Elnimeiri and Joglekar (1989) and Neville and Dilger (1970). Note that deformations are checked only using service load combinations.

Shrinkage of nuclear structures is somewhat different from conventional building structures because they involve thick mass concrete pours. Because of the relatively large thickness, the surface of such sections will tend to dry out early compared to the inner parts. This surface drying may cause cracking that will not generally extend through the whole thickness of the elements. Note that in conventional RC building elements such shrinkage cracking generally extends through the thickness because of the relatively thin sections of walls and slabs involved. This is recognized in Section 7.12 of ACI 349 Code, which allows the shrinkage reinforcement to be calculated /reduced for thick/mass concrete sections.

EFFECT OF REINFORCEMENT

It is well known that reinforcement in concrete member restrains creep or shrinkage deformation of concrete, through compatibility and stress redistribution (See Fintel and Khan (1969), Troxell, et.al. (1958), Elnimeiri and Joglekar (1989) and Neville and Dilger (1970)). This restraint due to reinforcement can be approximated by the creep reduction coefficient defined per Neville and Dilger (1970)

$$\alpha_{\rho t} = \frac{1}{1 + \rho n_0 (1 + n_{min} \upsilon_t)}$$

Where
ρ = reinforcement ratio
n_0 = modulus ratio at age of loading
n_{min} =relaxation coefficient
υ_t =creep coefficient

The creep reduction coefficient can be applied to the creep coefficient defined above. Such restrain effect could also be evaluated using compatibility formula between steel and concrete. For a heavily reinforced member with a reinforcement ration of 5%, the creep reduction coefficient could be between 0.5~0.7.

Theoretically, reinforcement whether in tension or compression, is beneficial in reducing creep. But in practice, because significant creep often occurs in the compression zone of a flexure member, compression reinforcement is considered to be more effective in mitigating the creep of flexure members.

Note also that per ACI 349 (same as in ACI 318), the minimum shrinkage and temperature reinforcement of 0.0018 for slabs and 0.0025 for walls should be provided based on the gross section properties for normal shrinkage restraint situations. This provision is often used to account for "normal" temperature and shrinkage of nuclear concrete structures. However, it has been recognized that this provision can, in some cases such as for basemats which are generally 10 ft or more in thickness, result in excessive minimum shrinkage and temperature reinforcement. This issue is addressed in the ACI 350 Code which stipulates that for thicknesses larger than 24 inches, reinforcement need to be provided only based on the 12 inch thickness of concrete on each face. Therefore, use of the above minimum reinforcement provisions of ACI 349 Code which is based on gross section properties requires larger amount of reinforcement for thicker sections involved in nuclear structures. It should also be pointed out that in most cases, the extreme environmental or accident loading results in larger reinforcement especially in slabs and walls which envelopes the minimum shrinkage reinforcement specified above.

As mentioned above, the Code minimum shrinkage and temperature reinforcement (such as 0.0018 for slabs and 0.0025 for walls) is applicable only for normal concrete element configurations built with normal concrete mixes and subject to normal restraint situations encountered in practice such as those involved in conventional structural systems built using conventional construction sequences. They do not apply to situations where the elements are relatively very thin, concrete mix is believed to result in excessive shrinkage or significant restraint is provided to prevent free shrinkage and thermal movement of structural elements. Sections 9.1.3 and 9.2.2 of ACI 349 Code essentially refer to these situations that are not covered within the prescriptive design for shrinkage using minimum reinforcement in Section 7.12. But there is no industry standard or guideline to determine how or whether a structural member meets the prescriptive design for shrinkage. This issue is considered a matter of engineering judgment. Also, review of and industry practice indicates that such additional considerations are rarely considered in typical nuclear power construction. The concern is that such unusual situations may introduce larger forces in to these elements resulting is excessive or wider cracking that need to be controlled by including these forces in the design. The selection of elements subjected to excessive restraint is a matter of engineering judgment and involves identification of unusual building elements, configurations, mix ingredients or construction sequences. Of all the potential contributors to excessive shrinkage, external restraint is, perhaps, the most common reason for concrete distress/cracking due to shrinkage. As an example, a free standing wall constructed over a footing (with dowels from footing lapped with wall reinforcement) would be considered a “normal” restraint situation. However, if the same wall is tied in to pre-existing rigid end blocks/structures that significantly prevent its free shrinkage between the end blocks, it would be considered “excessive restraint” situation. The intent of the Code (ACI 349) is that such excessive restrained elements be evaluated to estimate the expected shrinkage force. This shrinkage force can be calculated using an appropriate expected shrinkage strain for the concrete mixture, volume to surface ratio of the element and environment (see ACI 207 and ACI 209). Such situations requiring additional evaluation for shrinkage are not very common and rarely encountered in typical nuclear power construction involving conventional concrete mixes with normal shrinkage properties.

If deemed to be excessive, the shrinkage force should be included in the factored design load combinations of ACI 349 Code to ensure sufficient reinforcement for crack control. Note that, because of the self-relieving nature of shrinkage forces, these forces need not be included in the severe environmental or accident conditions.

INDUSTRY PRACTICE

To identify the regulatory treatment associated with creep and shrinkage effects in nuclear concrete structures, sixteen existing and current applications for nuclear power plants in United States are reviewed and listed below

<u>Bellefonte Nuclear Plant, Units 1 and 2</u>

The Bellefonte Nuclear Plant is a partially completed nuclear power plant located in Hollywood Alabama. Both Units 1 and 2 have the primary prestressed concrete containment, the secondary reinforced concrete containment, interior steel and concrete structures within the primary containment and other Seismic Category I concrete structures outside of containments.

The long-time effect of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment, which is governed by ASME Division 2 / ACI 359 Code per regulatory concern. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, it is specified in both Section 3.8.3.3.2 and Section 3.8.4.3.2 of Bellefonte FSAR that “Creep has an insignificant effect on the design of relatively massive reinforced concrete structures because of its relation to stress with time and relatively low operating stress conditions and because it primarily serves to relieve stresses without encroaching on structural safety. It is therefore not considered in the design of these structures."

In addition for design of Interior concrete structure and other Seismic Category I reinforced concrete structures, temperature and shrinkage are considered in normal operating case using TVA "Concrete Standard for Temperature and Shrinkage Reinforcement".

Beaver Valley Nuclear Power Station, Unit 1 and Unit 2

Beaver Valley Nuclear Power Plant is located at Shippingport, PA. Both Units 1 and 2 have the conventional concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment. The effect of creep and shrinkage are not considered in the containment design because either it is "of small consequence" or it "results in meridional and radial displacements which are the opposite of the displacements caused by the principal loads, temperature and internal pressure" . Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned.

Crystal River Unit 3 Nuclear Power Plant

The Crystal River 3 Nuclear Power Plant is a closed nuclear power plant located in Crystal River, Florida. CR3 has the prestressed concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment.

The effect of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned.

Davis-Besse Nuclear Power Station

Davis–Besse Nuclear Power Station is a nuclear power plant in Oak Harbor, Ohio. Davis-Besse Plant has the steel containment vessel, the secondary reinforced concrete containment, interior steel and concrete structures within the primary containment and other Seismic Category I concrete structures outside of containments.

For design of the secondary reinforced concrete containment (shield building), creep is not considered while the concrete shrinkage is only mentioned as "Adequate reinforcing is placed in the concrete walls, dome and foundation to control cracking due to concrete shrinkage and temperature gradients"

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

Farley Nuclear Plant, Units 1 and 2

The Joseph M. Farley Nuclear Generating Station is located near Dothan, Alabama. Both Units 1 and 2 have the prestressed concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment.

The effect of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned. Note that it is also specified in Ref [A6] that "Creep tests for concrete were performed for the containment structure only".

Hatch Nuclear Power Plant, Units 1 and 2

The Edwin Irby Hatch Nuclear Power Plant is near Baxley, Georgia. Both Units 1 and 2 have the steel containment vessel, the secondary reinforced concrete containment, interior steel and concrete structures within the primary containment and other Seismic Category I concrete structures outside of containments.

For design of the secondary reinforced concrete containment (shield building), Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned. Requirements are specified in concrete mixture design to minimize shrinkage and creep.

Palo Verde Nuclear Generating Station, Units 1, 2 and 3

The Palo Verde Nuclear Generating Station is a nuclear power plant located near Tonopah, Arizona. All Units 1, 2 and 3 have the prestressed concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment.

The effect of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned. Note that it is also specified in Palo Verde UFSAR that Creep tests are "performed on prestressed structures only".

Turkey Point Nuclear Generating Station, Units 3 & 4

Turkey Point Nuclear Generating Station is a twin reactor nuclear power station located east of Homestead, Florida. Both Units 3 and 4 (site 2) have the prestressed concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment.

The effect of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned.

Wolf Creek Generating Station

Wolf Creek Generating Station is a nuclear power plant located near Burlington, Kansas. It has the prestressed concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment.

The effect of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned. Note that it is also specified in Wolf Creek UFSAR that "Creep tests were normally performed on prestressed structures only".

Millstone Nuclear Power Plant

The Millstone Nuclear Power Station is located in Waterford, Connecticut. It has the prestressed concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment.

The long term effects of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned.

North Anna Nuclear Generating Station, Units 1 and 2

The North Anna Nuclear Generating Station is a nuclear power plant Louisa County, Virginia. Both Units 1 and 2 have the conventional concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containment. The effect of creep and shrinkage are not considered in any design of aforementioned reinforced concrete structures.

Vogtle Electric Generating Plant, Units 1 and 2

The Alvin W. Vogtle Electric Generating Plant is located in Burke County, near Waynesboro, Georgia. Units 1 and 2 were completed in 1987 and 1989, respectively. Each unit has the prestressed concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containments.

The long term effects of creep and shrinkage on prestress loss is considered in the design of the primary prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

For design of Interior concrete structure and other Seismic Category I reinforced concrete structures, the effect of creep and shrinkage is not mentioned.

Vogtle Electric Generating Plant, Units 3 and 4

Units 3 and 4 of Vogtle Electric Generating Plant are both using new generation of AP1000 reactors and currently under construction. Each unit has a steel containment vessel, interior steel and concrete structures within the containment, a reinforced concrete /concrete-filled steel plate (SC) shield building and other Seismic Category I concrete structures outside of containments. The effect of creep and shrinkage are not considered in any design of aforementioned reinforced concrete structures.

Calvert Cliffs Nuclear Power Plant, Unit 3

The Calvert Cliffs Nuclear Power Plant (CCNPP) is a nuclear power plant located on the western shore of the Chesapeake Bay near Lusby, Calvert County, Maryland. Unit 3 of CCNPP is a proposed new unit using the new generation of US EPR reactor. The proposed unit will have a prestressed concrete containment, a reinforced concrete shield building, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containments.

Conservative values of creep and shrinkage are considered in the design of the prestressed concrete containment. Requirements are also specified in concrete mixture design to minimize shrinkage and creep.

It is specified that for design of interior reinforced concrete structure and other Seismic Category I concrete structures that "where the structural effects of differential settlement, creep, or shrinkage may be significant, they are included with the dead load as applicable."

This statement is apparently copied from ACI 349. It is unclear how or whether it will be implemented during the actual design process of this proposed unit.

Economic Simplified Boiling Water Reactor (ESBWR)

The Economic Simplified Boiling Water Reactor (ESBWR) is a passively safe generation III+ reactor designed by GE Hitachi Nuclear Energy (GEH). The proposed application of ESBWR will have the conventional reinforced concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containments.

Neither creep nor shrinkage is mentioned for design of aforementioned reinforced concrete structures per available version of it design control document.

US Advanced Pressurized Water Reactor (US-APWR)

The US advanced pressurized water reactor (US-APWR) is a generation III nuclear reactor developed by Mitsubishi Heavy Industries based on pressurized water reactor technology. The proposed application of US-APWR will have the conventional reinforced concrete containment, interior steel and concrete structures within the containment and other Seismic Category I concrete structures outside of containments.

Effects of creep and shrinkage are considered in the design of the prestressed concrete containment. Neither creep nor shrinkage is mentioned for design of other reinforced concrete structures per available version of the design control document.

Summary of Industry Practice

1. Creep and shrinkage are considered in design of all primary prestressed concrete containments. As mentioned above, creep and shrinkage become important for structures subject to very high levels of sustained stress such as post-tensioned systems. Note that design of these containment structures is governed by ASME Section III, Division 2 / ACI 359 Code.
2. For design of other conventional reinforced concrete nuclear structures designed according to ACI 349 Code, detailed review of industry practice indicted effects of creep and shrinkage are generally determined as insignificant thus not explicitly considered in the design.
3. Creep can be reduced by using appropriate aggregate with low creep properties, using adequate mix design and with additional reinforcement. ACI 207, 209, 318, 349 and 350, and regulatory guidelines (RG. 1.136, RG. 1.142 and RG. 1.55) should be reviewed to mitigate the effect of creep and shrinkage in nuclear power plants.

CONCLUDING REMARKS

Based on the Code requirements and review of the industry practice, the concluding remarks are presented:

1. Given the thickness and amount of reinforcement involved in typical conventionally reinforced concrete nuclear structures, specific evaluation of creep and shrinkage effects is not generally warranted. The requirements of Sections 9.1.3 and 9.2.2 of ACI 349 Code become important where creep and shrinkage is expected to result in excessive forces/deformations which are beyond what may be covered by the prescriptive design and detailing requirements such as minimum shrinkage and temperature reinforcement provisions (Sections 7.12 and 21.7) of this Code.
2. Per industry standards and practice, the only situations where creep should be given consideration is design of post-tensioned elements such as containments, for estimating the potential shortening of heavily loaded sections such as columns and walls and for estimating the long-term deformation of long span floors of conventionally reinforced sections. Note that heavily loaded elements and long-span floors are rarely encountered in nuclear construction. Nuclear structures generally involve thick concrete sections where the sustained load stress is only a fraction of the total capacity of the elements. Also, such sections are generally very heavily reinforced which also helps reduce creep.
3. The minimum shrinkage reinforcement (ratio based on gross section is 0.0018 for slabs/mats and 0.0025 for walls) of ACI 349 Code, which is essentially based on ACI 318 Code for conventional buildings with normal size elements, results in sufficient and sometimes significant reinforcement for nuclear structures. It should also be pointed out that in most cases, the extreme environmental or accident loading results in larger reinforcement especially in slabs and walls which will significantly help reduce creep effects.
4. If significant, the creep effect on long-term deflection of slabs or shortening of the vertical elements should be included using the service load combinations (gravity load combinations without load factors). The shrinkage force should be included in the factored design load combinations of ACI 349 Code involving gravity loads only. Note that, because of the self-relieving nature of shrinkage forces, these forces need not be included in the severe environmental or accident conditions.
5. Sections 9.1.3 and 9.2.2 of ACI 349 Code also relate to the concern that "excessive restraint", if present, can introduce larger forces in to these elements resulting is excessive or wider cracking that need to be controlled by including these forces in design. But review of industry practice indicates that such conditions are rarely encountered in typical nuclear power plant construction.
6. It is well known that reinforcement in concrete member restrains creep or shrinkage deformation of concrete, through compatibility and stress redistribution. For situations where creep and shrinkage need to be considered, the reinforcement provided can be utilized to estimate the reduction on creep and shrinkage, as discussed above.

In summary, creep and shrinkage are not generally a concern for conventionally reinforced nuclear power plant structures involving large section thicknesses, relatively low sustained loads, heavy reinforcement, normal concrete mixes and no significant external restraints.

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