Annals of Nuclear Energy 92 (2016) 113–126

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Nonlinear analysis of containment structure based on modified tendon model

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ARTICLE INFO

Article history:
Received 16 August 2015
Received in revised form 4 December 2015
Accepted 21 January 2016
Available online 9 February 2016

Keywords:
Containment building
PSC structure
Tendon
Ultimate resisting capacity
FEM

ABSTRACT

This paper proposes a modified stress–strain relation for bonded internal tendon in containment structures on the basis of the tension stiffening effect and the bond characteristics between a tendon and its surrounding concrete. Differently from general approaches for the consideration of bond-slip, which take the double nodes in defining the displacement field, the proposed model indirectly considers the bond-slip effect through the modification for the stress–strain relation of tendon. Since the proposed tendon model takes into account the bond-slip effect without taking double nodes in the numerical modeling of containment structures, it can effectively be implemented into commercialized programs which have a lot of limitation in considering the bond-slip effect at large complex containment structures. The solution algorithm for an un-bonded internal tendon whose structural response is not section-dependent but member-dependent is also introduced. The different structural responses from those in bonded tendon are evaluated by successive iterations and finally considered by the additional modification for the stress–strain relation of tendon. The validity of the proposed tendon model is verified through correlation studies between analytical and experimental results for PSC beams and 1/4 PCCV containment structures.

1. Introduction

Since a nuclear power plant (NPP) containment structure serves as a final barrier to prevent the dissemination of radioactive materials in the case of an accident, the design and construction of a prestressed concrete (PSC) containment structure are strictly guided by related design codes (ACI Committee 349, 2007; ASME, 2007). Furthermore, an exact prediction of its ultimate resisting capacity must also be accomplished to reserve the sufficient safety margin under extreme loadings such as earthquake loading or internal pressure and temperature loading induced from an internal accident (i.e., a loss of coolant accident (LOCA)). In particular, the recent accident of a NPP in Fukushima, Japan highlights the importance of the safety evaluation of the containment structure, because damage to NPP facilities can cause serious and enduring problems.

To trace the nonlinear structural response with an increase of loading and, in advance, to exactly evaluate the ultimate resisting capacity of containment structures, a deep understanding of the structural characteristics of containment structures from the behavior of the constituent materials to the entire structural system is imperative, and comprehensive experimental and analytical studies have been conducted in this regard (Fib, 2001). Notably, many experimental studies (Rizkalla et al., 1984; Twidale and Crowder, 1991; Hessheimer et al., 2003; Kevrokian et al., 2005) have focused on internal pressurization tests to check if newly designed containment structures still maintain the resisting capacity while representing the expected failure behavior even in the case of pressure loading beyond a design basis accident. Moreover, the obtained experimental results have also been used as reference values for numerical analyses to minimize the differences in numerical results depending on the modeling the given of structure. Among scale model experiments of containment structures, a 1/14 scale model of Gentilly-2 in Canada (Rizkalla et al., 1984), a 1/10 scale model of Sizewell-B in UK (Twidale and Crowder, 1991), a 1/4 scale model of Ohi-3 in the US (Hessheimer et al., 2003), and a MAEVA mock-up in France (Kevrokian et al., 2005) are representative experimental studies.

The concrete containment structure usually has a cylindrical shape with a hemispherical dome and has mild steel reinforcement as well as high-strength prestressing tendons in the hoop and longitudinal (vertical in the cylinder, meridian in the dome) directions. Even through many differences can be noted for containment

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http://dx.doi.org/10.1016/j.anucene.2016.01.040
0306-4549/

structures, the most remarkable difference that affects the ultimate resisting capacity and the structural behavior may be the use of bonded or un-bonded internal tendons. The structural behavior of prestressed concrete structures with un-bonded tendons is member-dependent instead of section-dependent, and the stress in un-bonded tendons depends on the deformation of the entire member and is assumed to be uniform at all sections along the span length. This means that the stress cannot be directly determined from a cross-section analysis with the conventional strain compatibility condition, as in the case of bonded tendons. Accordingly, consideration of the slip effect along the tendon together with accurate modeling of damage in concrete due to cracking and associated loss of stiffness must be implemented in the numerical modeling of a structure. Although many numerical models that can simulate the slip effect in PSC structures have been introduced (Baíazs, 1992; Kwak and Kim, 2001b, 2006c; Kwak and Hwang, 2010), regulations that mandate the use of general purpose programs (ADINA, ABAQUS, DIANA etc.) in design and safety evaluation make it difficult to take into account the slip effect induced from the un-bonded internal tendons because the tendon forces are determined in these programs through a section analysis on the basis of the perfect bond assumption.

Furthermore, the use of a one-dimensional link element (CEB, 1996) or a bond-zone element (Kwak and Seo, 2002), which can be adopted in general purpose programs in order to consider the interaction between the concrete and tendon, leads to a considerable increase in the number of degrees of freedom, not only because of doubling the number of nodes along the tendons but also because the mesh has to be refined so that the tendon elements pass along the edges of concrete elements. This means that the complexity of the mesh definition forces the adoption of the perfect bond assumption in complex structures, particularly in three-dimensional models with a large number of degrees of freedom (Kwak and Kim, 2006b). Nevertheless, the slip effect must be considered in the nonlinear analysis of containment structures with un-bonded internal tendons because the resisting capacity of a structure with un-bonded internal tendons is less than that of a structure with bonded tendons (Collins and Mitchell, 1991).

Since the post-cracking behavior of concrete structures, in which bonded reinforcements such as tendons and/or reinforcing steels are embedded, depends on many influencing factors (the tensile strength of concrete, anchorage length of reinforcements, concrete cover and steel spacing) that are deeply related to the bond characteristics between concrete and reinforcements, consideration of the tension stiffening effect on the basis of the bond-slip mechanism is necessary to more exactly evaluate the ultimate resisting capacity (Kwak and Kim, 2001a). In particular, to trace the cracking behavior of structures up to reaching the ultimate state, the tension stiffening effect must be considered regardless of the tendon type (bonded/un-bonded tendon) (Naaman et al., 2002) if the numerical analysis is based on the use of a smeared crack model (Hillerborg et al., 1976). A great deal of research has been conducted to consider the tension stiffening effect (Kwak and Kim, 2001a), and many numerical models have also been introduced (CEB, 1996). Among these models, consideration of the strain softening branch in the tension region of the stress–strain relation of concrete is one of the generally adopted approaches (Maekawa et al., 2003; Kwak and Kim, 2001a,b).

Recently, modification of the stress–strain relation of steel has been emphasized, because reaching the yield strength of a bare bar at a cracked section does not necessarily indicate the complete yielding of steel embedded at a cracked element. The average steel stress at a cracked element still maintains an elastic stress rather than the yield strength (Hsu and Mo, 2010; Kwak and Kim, 2004a,b). In spite of these efforts concentrated on the cracking behavior of concrete structures, a numerical model that can simulate the tension stiffening effect of PSC structures has not been introduced, primarily because of the different bond characteristics of tendons.

Accordingly, to effectively simulate the post-cracking behavior of PSC structures, a modified stress–strain curve of tendon is introduced in this paper to implement the tension stiffening effect and bond-slip between a tendon and concrete. The slip behavior along the un-bonded internal tendon is indirectly taken into account through sequential iteration and correction procedures along the tendon on the basis of the equilibrium condition between a bonded tendon and an un-bonded tendon.

The proposed tendon model makes it possible to consider the slip effect in commercialized software without using any link element that requires double nodes. The validity of the proposed model is established by comparing the analytical predictions with results from an experimental study for two PSC beams with a bonded tendon and a containment structure with an un-bonded tendon.

2. Material models

Since a PSC containment structure is composed of heavily reinforced and prestressed concrete and its interior is lined with thin mild steel plate, constitutive models for the three different materials of concrete, mild steel and prestressing tendon need to be defined to simulate the nonlinear behavior of structure according to the loading history. In spite of the need for an accurate description of material behavior, however, the use of commercialized software to be coincident with the design requirement in practice may cause some limitations in describing the material behavior because of insufficient number of models included. It means that additional considerations must be accompanied in defining the constitutive models of each material, to obtain more reliable numerical results. Because the numerical analyses are conducted with ABAQUS 6.11 (2007), only distinctive characteristics and explanations at each material model are described in this paper, and more details can be found elsewhere (Dassault Systems, 2007).

As a PSC containment structure is one of the shell-type structures and carries out-of-plane loadings, the biaxial stress condition must be taken into account to simulate the exact structural behavior according to the loading history. Under combinations of the biaxial stress, however, the stress–strain behavior of the concrete is different from those under uniaxial loading conditions owing to the effects of Poisson's ratio and micro-crack confinement. Fig. 1 shows adopted the biaxial strength envelope of the concrete under proportional loading. This strength envelope was proposed by Lee and Fenves (1998) and has been defined in ABAQUS 6.11. As shown in this figure, the envelope to define the compression–compression region is slightly different from the Kuper's failure envelope (Kupfer and Gerstle, 1973) obtained through panel test. The difference, however, will not have different effect in the structural behavior because the nonlinear behavior of a containment structure subjected to internal pressure loading is induced from the cracking of concrete by the biaxial stresses placed on the tension–tension region and partially on the compression–tension region. Additional details regarding the envelope curve in tension–tension region can be found in previous study by Kwak and Kim (2004a,b).

In a description of the uniaxial stress–strain relationship of concrete, the model of Kappos (1991), which effectively considers the lateral confinement effect provided by the transverse reinforcement, is used with the equivalent concrete compressive strength and the corresponding tensile strength f_{eq} determined from the biaxial strength envelope of concrete (see Figs. 1 and 2). Essentially, implementation of the tension stiffening effect is achieved