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Short communication

Bearing mechanism of composite structure with reinforced concrete and steel liner: An application in penstock

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ABSTRACT

For the composite structure comprised of steel-lined concrete, the inside steel liner and surrounding reinforced concrete are designed to work reliably. The potential sliding between the reinforced concrete and steel liner has a significant effect on the structure bearing mechanism. The Coulomb friction model is employed to simulate the sliding of the steel liner against the surrounding concrete. A concrete damage plasticity (CDP) model is proposed to simulate the surrounding reinforced concrete. The finite element (FE) models of the steel-lined reinforced concrete penstock (SLRCP) located on the downstream surface of a double curvature arch concrete dam are developed, in which the nodes-shared method (NSM) and the friction-contact method (FCM), respectively, are employed. The concrete crack initiation time, concrete crack propagation pattern, penstock deformation, tensile stresses of the steel liner and the reinforcements are presented. The results of the FCM model agree well with the monitoring data, validating that the proposed model could be directly employed in the FE software ABAQUS.

1. Introduction

A composite structure of concrete and steel liner can serve as beam and column when the concrete is poured inside the steel pipe. Additionally, the structure can serve as a pressure vessel when the concrete is reinforced by steel bars and poured along the outside surface of the steel pipe. When the steel liner is laid close to the interior of the reinforced concrete, the composite structure will have superior capability to bear pressure and to prevent seepage [1]. In general, this composite structure is called as steel-lined reinforced concrete penstock (SLRCP) in hydraulic engineering and was applied originally in the former Soviet Union in the 1960s [2]. This combined structure provides the significant benefit of lowering the thickness of steel liner, reducing the difficulties of installation and welding as well as diminishing the risk of accidents. Additionally, the surrounding reinforced concrete can protect the internal steel liner from direct exposure to air and moisture. The SLRCP is routinely employed when the penstock HD (water head H multiplied by pipe diameter D) exceeds 1200 m^2 [2], such as the Dong-Jiang hydroelectric power plants (HPP), the Jin-Shui-Tan HPP, the Wu-Qiang-Xi HPP, the Li-Jia-Xia HPP, and the Three Gorges Project [3–7]. It is demonstrated by well-documented research that reinforced concrete cracking is unavoidable [4–11]. Therefore, the crack widths should be limited to ensure the durability of the reinforced concrete. Before 2000 semi-theoretical and semi-empirical methods were primarily adopted to calculate crack width considering the influence of the mechanic performance, the shape of the rebar surface, rebar diameter and reinforcement ratio [9–11].

Due to the well-known advantages to handling complicated geometries, to presenting colorful illustration, less knowledge background of modeling theory required, etc., the finite element (FE) method gradually became the most popular analysis method instead of model testing and prototype monitoring. A significant number of researches regarding the thickness optimization of the surrounding concrete, cracking performance with the space effect, cross-section shape optimization, crack-controlling techniques, crack model for concrete and the influence of the temperature load, are all well documented [8–10,12]. Unfortunately, the hypothesis that there is no sliding between steel liner and surrounding reinforced concrete is adopted in the above researches, which is apparently contrary to the reality. Since the composite structure is working under asymmetrical conditions, such as the gravity effect

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of internal water pressure (IWP), the constraints at the penstock bottom from the dam concrete, the composite structure experiences slipping between the steel liner and surrounding concrete.

In the following sections, a plastic-damage crack model, which considers the stress degradation and damage evolution law, is presented to simulate the reinforced concrete. An isotropic elasto-plasticity is employed to present the steel behavior. Meanwhile, the Coulomb friction model for surface/surface contact pairs is adopted to simulate the contact behavior between the liner and the surrounding media. Then, the analyses utilizing both the nodes-shared method (NSM) model and the friction-contact method (FCM) model of the SLRCP for the Li-Jia-Xia HPP of China are performed, in which diverse element sizes for surrounding reinforced concrete are adopted. The concrete crack initiation time, concrete crack propagation law, penstock deformation, and the tensile stresses distribution of the steel liner and reinforcement are analyzed. Finally, a short discussion of the influence of the friction coefficients between the steel liner and surrounding concrete on the steel stresses is presented.

2. Modeling of concrete

2.1. Cracking model of concrete

Among the various crack models, the smeared crack model as well as the discrete crack model is primarily used nowadays [12–14]. In the discrete crack model, a geometrical status is attached to a crack and the crack is either pre-embedded in the finite element mesh [15] or realized by continuous re-meshing [16,17]. In the smeared crack model, the geometry as well as the mesh is invariant when the concrete constitutive law is adopted in modeling cracking [13,18].

The discontinuous macrocrack brittle behavior is achieved through the smeared model in this paper. By this means, a single macrocrack is not traced. Instead, the existence of cracks in these calculations is noted by the manner that the cracks influence the stress and stiffness of each material calculation point. In recent years, the plastic-damage model has been widely employed for the nonlinear numerical analysis of concrete structures [12,19–26]. The smeared crack model has shown that it is possible to track the concrete crack initiation and propagation of SLRCP.

2.2. Crack direction assumptions

Three basic crack direction models, such as the fixed, orthogonal crack model; the rotating crack model; and the fixed, multidirectional crack model, have been proposed by various researchers [27]. As a criterion adopted to determine the subsequent cracks, the multidirectional crack model is the least prevalent. Both the rotating crack and fixed orthogonal models have been widely used, even if there can be oppositions against both. Although the issue of orthogonality limitation in the fixed orthogonal crack model is unavoidable, it is thought preferable to the model with rotating cracks in circumstances when the effects of multiple cracks are significant. Hence the fixed orthogonal crack model is employed in this paper using the software program ABAQUS.

In this study, the largest quantity of cracks at the material point is dependent on the quantity of the direct stresses at that point within the model. Once cracks are initiated at that point, the stresses forms of all vectors and tensors are rotated so that they are situated in the element material coordinate system, which is defined along with the crack orientation directions. Crack closing as well as reopening can be presented along the cracks surface while the model ignores the correlated permanent strain. Additionally, the cracks can be closed completely under compressive conditions.

2.3. Crack width estimation

When the reinforced concrete structures are designed, both the strength and ductility should be considered under the ultimate loads as well as under the service loads [28]. The crack widths of the concrete are considered for the service ability as well as the durability and need to be limited to the maximum allowable value, which is proposed by the design codes to avoid aesthetic concerns, excess water loss and rebar corrosion problems.

When the smeared crack model is employed, the width of the cracks could not be achieved directly within the numerical simulation. The crack width of reinforced concrete can be estimated by the empirical formula proposed by EPISPRC [29], as follows.

$$l_f = \left(60 - \alpha_1 \frac{d_s}{\mu_s}\right) v_s \quad (1)$$

$$\omega_{\max} = 2\left(\frac{\sigma_s}{E_s}\varphi_s - 0.7 \times 10^{-4}\right) l_f \quad (2)$$

where l_f refers to the average distance between neighboring cracks, α_1 relies on the stresses state of the structure and is 0.16 when the structure is under axial tension state, $\boldsymbol{d_s}$ represents the steel bar diameter, μ_s denotes the rebar ratio, v_s is the coefficient associated with the steel bar surface shape, $\omega_{\max}$ is the maximum width of cracks, E_s is the steel elastic modulus, φ_s represents the uniformity coefficient of the steel bar and the reinforcement stress σ_s can be directly yielded from the results of ABAQUS.

2.4. Stress-strain relations of concrete

The CDP model is available in software ABAQUS and is used in this study [30], which employs the yield function proposed in [19] and amended in [20]. A non-associated flow rule is followed by the model. The constitutive theory is aimed to grasp the effects of irreversible damage related with the failure mechanisms occurring in concrete or other types of quasi-brittle material under the condition with low confining stresses. The damage and plasticity behavior can result in a decline of the strength and stiffness of the concrete [19,22,31,32]. Damage is often featured by the degradation of the stiffness, which can be expressed by Eq. (3) under uniaxial loading.

$$\sigma = (1 - d)E_0(\varepsilon - \varepsilon^{pl}) \quad (3)$$

where σ, ε and ε^{pl} denote the element stress, total and plastic component of strain, respectively.

The degraded stiffness, E, is given by Eq. (4).

$$E = (1 - d)E_0 \quad (4)$$

The stress–strain relationships of the concrete under tensile and compressive states are presented in Fig. 1.

The effective stress can be presented as Eq. (5).

$$\bar{\sigma} = E_0(\varepsilon - \varepsilon^{pl}) \quad (5)$$

The Cauchy stress, σ, is associated with the effective stress $\bar{\sigma}$ by d as follows.

$$\sigma = (1 - d)\bar{\sigma} \quad (6)$$

When the damage is absent, $d = 0$, the effective stress $\bar{\sigma} = \sigma$.

Damaged states under tension and compression condition are independently represented by $\tilde{\varepsilon}_t^{pl}$ and $\tilde{\varepsilon}_c^{pl}$, as shown as Eq. (7).

$$\tilde{\varepsilon}^{pl} = \begin{bmatrix} \tilde{\varepsilon}_t^{pl} \\ \tilde{\varepsilon}_c^{pl} \end{bmatrix}; \quad \dot{\tilde{\varepsilon}}^{pl} = h(\bar{\sigma}, \tilde{\varepsilon}^{pl}) \cdot \dot{\varepsilon}^{pl} \quad (7)$$