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A modelling approach for joint rotations of segmental concrete tunnel linings

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ABSTRACT

This paper presents an approach to determine the nonlinear bending moment – rotation relations for longitudinal joints of segmental concrete tunnel linings with flat concrete contact areas based on the rules for confined concrete and partially loaded areas according to Eurocode 2. It is demonstrated that the resulting bending moment – rotation relations show better agreement with experimental data than other approaches from the literature. The proposed approach allows to establish the bending moment – rotation relations for both serviceability limit state (SLS) and ultimate limit state (ULS) and thereby a tunnel lining design consistent with Eurocode 2. The practical implications for the design concept of tunnel linings are discussed.

1. Introduction

The effect of the joints in precast segmental concrete linings has been studied extensively in the literature. Muir Wood (1975) proposed a formula to account for the effect of the joints in uncoupled lining rings by an equivalent bending stiffness of a continuous ring. This formula is often used in engineering practice. Other correction factors to approximate jointed tunnel lining rings by continuous rings were proposed e.g. by Lee and Ge (2001). Blom (2002a, 2002b) and El Naggar and Hinchberger (2008) proposed analytical models for segmental tunnel linings with consideration of the joints. Explicit consideration of the joints by means of rotational springs in bedded beam models for tunnel linings has become wide-spread (e.g. Duddeck and Erdmann, 1982; ITA WG Research, 2000; Koyama, 2003; Grübl, 2006; Do et al., 2013). Three-dimensional shell-spring models with explicit consideration of the joints have been used e.g. by Klappers et al. (2006) and Arnau and Molins (2012). In beam and shell models, the joint behaviour is often modelled by nonlinear rotational springs based on the expressions by Leonhardt and Reimann (1965) and Janssen (1983) or Blom (2002a, 2002b). Several authors have investigated the effect of the joints by 2D and 3D continuum models of tunnel linings (e.g. Wittke, 2007; Chen and Mo, 2009; Arnau and Molins, 2011; El Naggar and Hinchberger, 2012).

In this paper, the existing analytical expressions by Leonhardt and Reimann (1965) and Janssen (1983) and by Blom (2002a, 2002b) to describe the bending moment – rotation relation of the joints are briefly presented in Sections 2 and 3. A new analytical approach to describe the bending moment – rotation relation based on the rules for confined concrete and partially loaded areas according to Eurocode 2 is presented in Section 4 and validated in Section 5 by comparison with experimental data and the aforementioned existing approaches.

2. Janssen's approach

Based on the assumption of a joint deformation zone with a total length s equal to the joint height l (Fig. 1) such that

$$\Delta s = \varepsilon_{e1}\cdot l \quad (1)$$

and based on the assumption of linear elastic behaviour such that the stress at edge 1 is

$$\sigma_{e1} = E_c\cdot\varepsilon_{e1} \quad (2)$$

Leonhardt and Reimann (1965) derived the following equation for the joint rotation φ as a function of the normal force N, the bending moment M, the Young's modulus of the concrete E_c and the joint height l

$$\varphi = \frac{8N}{9\left(1-2\frac{M}{N\cdot l}\right)^2 E_c\cdot l} \quad (3)$$

Eq. (3) applies to opened joints (joint opening $l_o > 0$ and compressed joint height $l_c < l$), i.e. in case $M > N\cdot l/6$. The authors demonstrated good agreement of this relation with various experimental data.

Janssen (1983) completed the formulation

$$\varphi = \frac{12M}{E_c\cdot l^2} \quad \text{for} \quad M \leqslant \frac{N\cdot l}{6} \quad (4)$$

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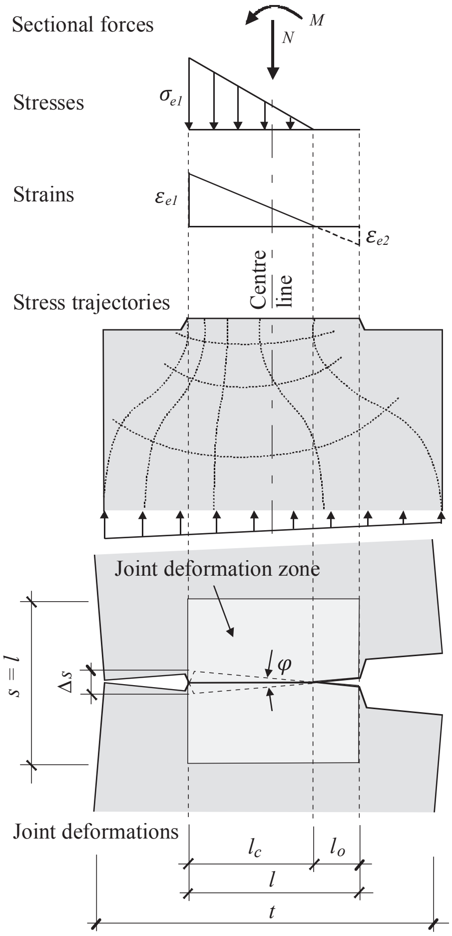

Fig. 1. Janssen's approach.

$$\varphi = \frac{8N}{9\left(2\frac{M}{N\cdot l}-1\right)^2 E_c\cdot l} \quad \text{for} \quad M > \frac{N\cdot l}{6} \tag{5}$$

and derived corresponding expressions for the rotational stiffness. In the remainder of this paper, Eqs. (4) and (5) will be referred to as Janssen's approach.

3. Blom's approach

Blom (2002a, 2002b) proposed an approach based on the bi-linear stress-strain relation in order to consider the compressive strength of concrete f_{ck}. This approach represents a refinement compared to Janssen's approach as it considers a more advanced stress-strain relation (Fig. 2). The compressive strength f_{ck} and the ultimate strain ε_{cu3} are basic material parameters as defined e.g. in Eurocode 2 (CEN, 2004).

Using the same assumption of a joint deformation zone as in Janssen's approach, the rotation can be defined by

$$\varphi = \frac{\varepsilon_{c3}\cdot l}{x_1} = \frac{f_{ck}\cdot l}{E_c\cdot x_1} \leftrightarrow x_1 = \frac{f_{ck}\cdot l}{E_c\cdot \varphi} \tag{6}$$

Then, the stress resultants R_1 and R_2 can be written as

$$R_1 = \frac{f_{ck}\cdot x_1}{2} \quad \text{and} \quad R_2 = N - R_1 \tag{7}$$

With R_2, the length x_2 is obtained as

$$x_2 = \frac{R_2}{f_{ck}} \tag{8}$$

Equilibrium of bending moments results in

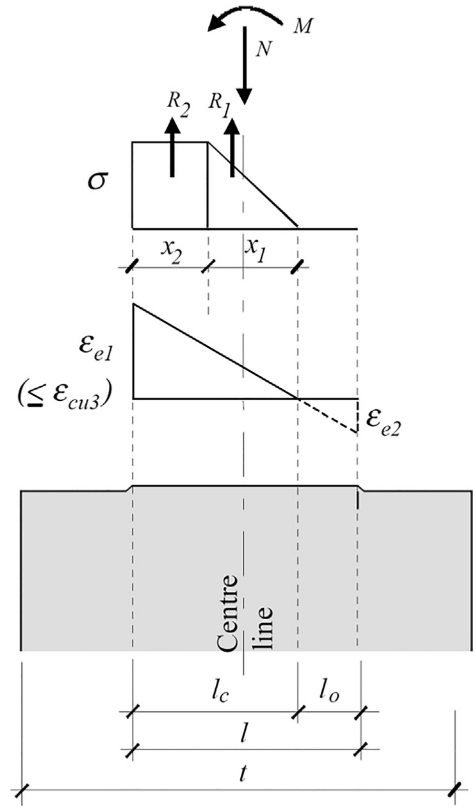

Fig. 2. Blom's approach.

$$M = N\frac{l}{2} - R_1\left(\frac{x_1}{3} + x_2\right) - R_2\frac{x_2}{2} \tag{9}$$

Finally, the maximum strain is determined as

$$\varepsilon_{e1} = \frac{f_{ck}\cdot(x_1 + x_2)}{E_c\cdot x_1} \tag{10}$$

The bending moment – rotation relation according to Blom's approach consists of three parts, the first part defined by Eq. (4), the second part defined by Eq. (5) until $\varepsilon_{e1} = f_{ck}/E_c$, and the third part defined by Eq. (9) until ε_{e1} according to Eq. (10) becomes $\varepsilon_{e1} = \varepsilon_{cu3}$. Blom's approach allows to determine both SLS bending moment – rotation relations based on f_{ck} as well as ULS bending moment – rotation relations based on $f_{cd} = f_{ck}/\gamma_c$ with the partial safety factor γ_c defined in Eurocode 2.

4. Proposed approach

Compared to Blom's approach, the following further refinements are made in the proposed approach:

- The parabola-rectangle stress-strain relation is used to provide a better representation of the actual stress-strain relation of concrete.
- An increase of the compressive strength and the strain limits is considered according to the rules for partially loaded areas and confined concrete in Eurocode 2.

4.1. Eurocode basic equations

As indicated in Fig. 1, the load transfer through a longitudinal joint represents the situation of a partially loaded area. For partially loaded areas, Section 6.7 Eq. (6.63) in Eurocode 2 allows to increase the compressive strength of concrete according to