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Splitting force of bottle-shaped struts with different height-to-width ratios

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ABSTRACT

A bottle-shaped strut is a common kind of strut in the structures, whose compression disperses, resulting in a splitting force at some distance away from the load plate. Considering characters of the geometric and physical boundary conditions which are different from previous studies, a new mathematical equation for the infinite isostatic lines of the compression (ILC) is obtained and a corresponding equation of transverse stresses distribution is derived. Then theoretical formulae to calculate the resultant splitting forces and their location in a bottle-shaped strut are proposed. Based on the principle of superposition, different compression dispersion models for the struts with different height-to-width ratios are individually formulated and simplified. A recommendation for EN1992 is presented. The transverse stresses distribution and the equations for the resultant splitting force and their locations are validated by the test and FEM results. The results show that the proposed equations have good agreements with the test and FEM result, which can provide accurate predictions for the magnitude and location of the resultant splitting force.

1. Introduction

A strut and tie model consists of struts, ties and nodes [1]. It has been thought as an effective tool for modelling disturbed regions in structural concrete members [2]. A bottle-shaped strut is a common kind of strut in the structures such as deep beam and pile caps. In this type of strut, the load is applied to a relatively small area of the member, which inevitably results in the compression stress dispersing with a convex outer profile like a bottle as shown in Fig. 1. To maintain static equilibrium, a transverse tensile force has to be developed to balance the later component of the inclined compressive forces. Consequently, as the applied load increases, those strains in the struts exceed the tensile resistance of concrete and a dominant splitting crack is formed along the strut axis.

To date, efforts to build a better splitting force formula for a bottle-shaped strut have been made by some researchers. The transverse splitting tension in disturbed region (D-region) was discussed at first by Guyou [3], who used isostatic lines of compression (ILC) to investigate the dispersion of loads in post-tensioned anchorage zones. He creatively sketched the basic configuration of a compression-dispersion model (CDM). Sahoo et al. [4] presented a mathematical description of this model for bottle-shaped struts and derived an equation for estimating the splitting force. However, some researchers [5,6] think the theoretical model proposed by Sahoo is questionable. The transverse compressive stress below the anchor plate is equal to zero, which is not in a agreement with the result of FEA and Breen's conclusion [7]. Therefore, He et al. [6] modified the physical boundary conditions and proposed a revised CDM. Brown [8] calculated the splitting force in terms of the slope of dispersion of compression and the efficiency factor. Zhou [9] introduced the boundary condition of the three and four order derivative of the equation of ILCs, and derived a sixth-order polynomial equation, and then the bursting force formula was obtained. Ghanei and Aghayari [10] investigated the effect of height-to-width ratios on the dispersion of compression, and they found the location of maximum tensile straining and the dispersion angle of compression are dependent on the height-to-width ratios of the bottle-shaped strut. It indicates that current ACI 318-14 recommending a 2:1 fixed dispersion model may underestimate the splitting force of a bottle-shaped strut whose height-to-width ratio (h/b) is less than 2 as shown in Fig. 1(a), but suitable for a bottle-shaped strut whose height-to-width ratio (h/b) is greater than 2 as shown in Fig. 1(b). In EN 1992-1-1 2004 [11], an equation for full discontinuity subjected to $h/b < 2$ has already provided for calculating splitting forces in bottle shaped strut as follows:

$$T_b = \frac{1}{4}\left(1-1.4\frac{a}{h}\right)P \tag{1}$$

However, as the height-to-width ratio becomes smaller and smaller, one equation cannot consider D-region superposition effect of the

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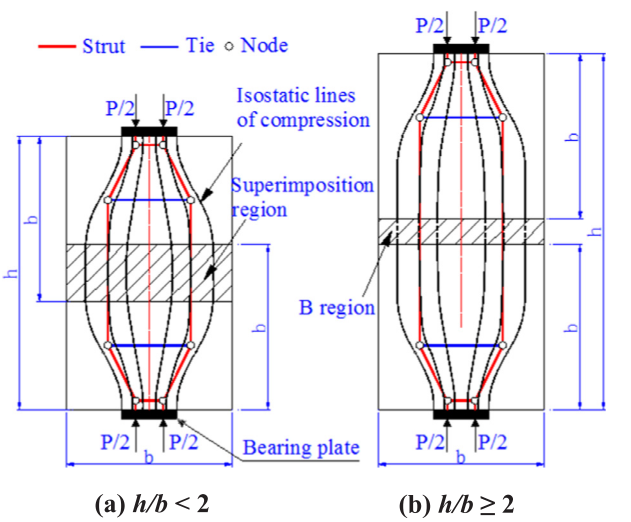

Fig. 1. Isostatic lines of compression and STM model for bottle-shaped struts.

bottle-shaped struts under different scenarios.

Seen from reviewed literature mentioned above, the present research hotspots still put focus on how to reasonably define the assumptions of the geometric and physical boundary conditions of the ILCs. They remain assuming the first order derivative of the equation of ILC is equal to zero at $x = 0$ even if the load plate is considered in their models. And no one considers the significance of the turn point where the transverse stresses change from the tension to the compression. So there is still controversy among different researchers, and further studies are still necessary. Furthermore, current theories do not cover all conditions, especially for a bottle-shaped strut with height to width ratio less than 2. The superposition effect should be considered to calculate the splitting force of a bottle-shaped strut.

2. Research significance

In this paper, a new quantitative compression-dispersion model, considering the different assumptions based on the previous researches, is established by mathematical and explicit describing the equation of ILCs. This model accurately reflects the characteristic behaviour of a bottle-shaped strut, and is able to provide an overall view and an adequate theoretical basis of internal stress distributions within a bottle-shaped strut. Splitting force formulae for the struts with different load area ratios and height-to-width ratios are obtained individually aiming to make some improvement in this topic. The proposed formulae are critically validated using test and FEA results, and a comparison with Code [1,11,12], Sahoo's method [4], and He's method [6] is also carried out, and the results will show which method is closer to the test and FEA results.

3. Splitting force analytic model

3.1. ILC equation in one end of bottle-shaped struts

Previous researches [4–6,9] tell us to describe the compression stresses in an elastic body subjected to a point load (or a distributed load on a finite dimension) can be represented by isostatic lines. Sahoo [4] first presented a mathematical description of these isostatic lines using a differential equation. So similar to those eminent previous research works, we still try to establish the polynomials equations of isostatic lines of compression in bottle-shaped struts. According to Saint-Venant's principle, the stresses distribution in a bottle-shaped strut is disturbed within a distance approximately equal to the strut width. Therefore, under a concentrated load, plane $b \times b$ can be defined as the dispersion zone. Fig. 2(a) shows the dispersion of compression in the region of the struts under a concentrated load. Obviously, there are infinite ILCs throughout the disturbed region of the struts, which constituted a CDM under the concentrated load. To calculate the transverse stresses, the CDM is defined as the mathematical model of principal compressive-stress trajectories. Three assumptions on geometric and physical boundary conditions of the ILCs of the CDM are given as follows.

Assumption 1. The ILCs are uniform distributed in both sections A-A′ and B-B′ as shown in Fig. 2(a). Based on geometric similarity theory, if for an ILC with a vertical coordinate of y_i at section B-B′, the vertical coordinate at section A-A′ can be determined by times a/b (loading area ratio), which can be written as

$$y|_{x=0} = y_i \cdot a/b, y|_{x=b} = y_i \tag{2a}$$

Assumption 2. The ILCs must be perpendicular to the section B-B′, which means the slope of the ILCs equal to zero, that is

$$\left.\frac{dy}{dx}\right|_{x=b} = 0 \tag{2b}$$

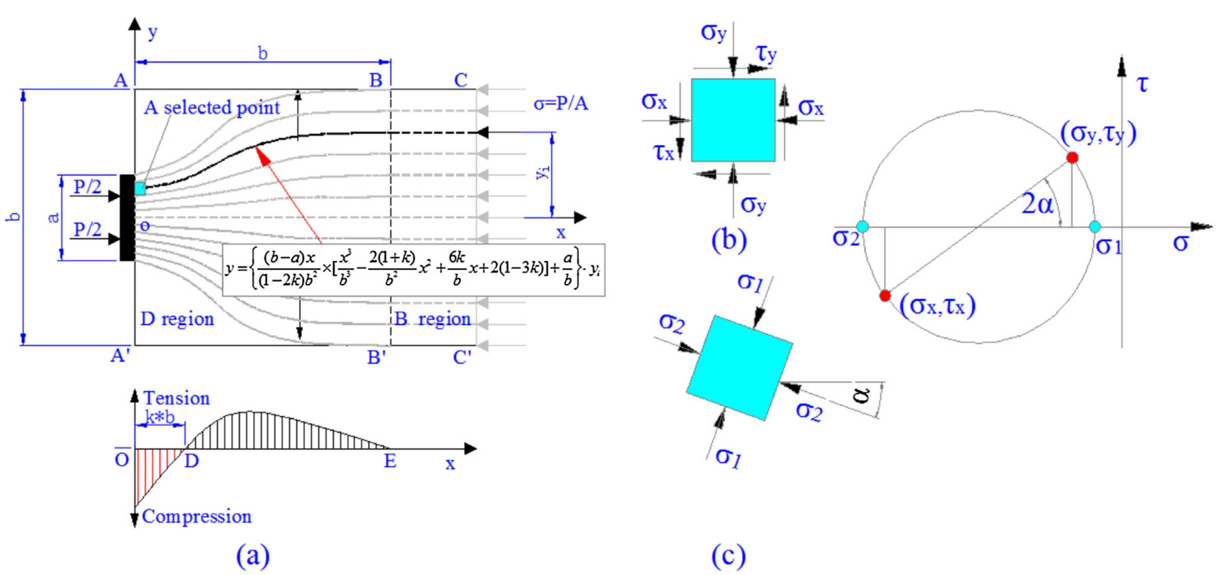

Fig. 2. Calculation model for ILC equations.