Construction and Building Materials 148 (2017) 10–21

Contents lists available at ScienceDirect

Construction and Building Materials

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

Shear behaviour of geopolymer concrete beams without stirrups

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HIGHLIGHTS

- Shear capacity of geopolymer concrete beams investigated.
- Shear friction behaviour of geopolymer concrete determined experimentally.
- Segmental and FIB approaches able to adequately predict shear failure load.

ARTICLE INFO

Article history:
Received 17 March 2017
Received in revised form 1 May 2017
Accepted 3 May 2017
Available online 10 May 2017

Keywords:
Geopolymer concrete
Shear capacity
Shear friction

ABSTRACT

The environmental impact of Ordinary Portland Cement (OPC) production has driven substantial interest in the development of new types of 'green' concrete, one of which is geopolymer concrete. If geopolymer concretes are to be widely used in practice, either existing design methodologies must be shown to be applicable or new design methodologies must be developed. To address this need, in this paper a recently developed mechanics based segmental approach for predicting the shear capacity of reinforced concrete (RC) beams is extended and applied to reinforced geopolymer concrete beams without stirrups. The results of eight reinforced geopolymer concrete beam tests without stirrups are presented along with the results of four direct shear tests with low levels of confinement. Significantly, the results of the direct shear tests show that the shear-friction properties for the geopolymer concrete utilised in the experimental investigation fall within the range of shear-friction properties of established OPC concrete. Moreover, it is shown that the segmental approach proposed can predict the shear capacity of geopolymer concrete beams with good accuracy and hence can be used as a tool to aid in the development of new design guidelines for geopolymer concrete.

1. Introduction

The production of Ordinary Portland cement (OPC) has been estimated to contribute between 5 and 7% of worldwide greenhouse gas emissions [1]. To reduce the environmental impact of concrete manufacture, it has been suggested that alternatives to OPC requiring the use of fewer natural resources and less carbon dioxide (CO_2) emitting sources of energy are needed [2]. One such approach to reduce the environmental impact of concrete manufacture is through the full replacement of OPC with by-product materials, such as fly ash obtained from burning coal [3], ground granulated slags from a range of metal extraction processes [4], or a combination of fly ash, slags and other natural waste materials [5,6]. As a result, a new material is produced and termed geopolymer concrete [7].

Geopolymer concretes have received substantial research attention recently, with comprehensive studies being carried out at the material level focusing on quantifying the fresh [8,9] and hardened [6,10–12] material properties and long term durability [13–15]. There is; however, a relatively limited number of studies available on the structural behaviour of reinforced geopolymer concrete members [16–18], particularly those failing in shear [19–21]. Moreover, of the work currently available in the literature there is to the authors' knowledge none focusing on predicting the concrete component of the shear capacity.

Due to the complexity of the shear transfer mechanism, shear design procedures have been a point of intense research effort for more than 100 years. Approaches to predict the shear strength of a reinforced concrete beam can be divided into several major categories. Early procedures were based on the 45 degree truss model in which the contribution of the transverse reinforcement to the shear capacity is determined by quantifying the widening of the critical diagonal crack, and the concrete contribution to the shear capacity is considered to be equal to that at which

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.010

diagonal cracks form. The truss model was later improved by through the application of plasticity theory by allowing for a variation in the angle of the critical diagonal crack, and by defining the failure of the section to be that at which the load to cause diagonal cracking coincides with the load to cause sliding along an inclined crack [22,23]. As an alternative to the truss model and plasticity theory, compression field theory [24–26] uses the strain condition in the concrete to determine the inclination of the diagonal crack and allows for the total contribution of the concrete to the shear capacity through the definition of an average principal tensile stress in the cracked concrete, which includes both the stresses at a crack face and between cracks. Most recently, researchers at the University of Adelaide have developed a new mechanics approach for predicting the shear capacity of reinforced concrete [27,28] and prestressed concrete beams [29,30] utilising the sliding failure criteria of Zhang [22] modified based on the mechanics of shear friction theory. In the Zhang's approach, a displacement based analytical technique termed the segmental approach [31], which is based on the Euler-Bernoulli theory of plane sections remain plane but not on the corollary of a linear strain is applied to determine the distribution of internal forces and hence the resistance to sliding failure.

The segmental approach is considered here as it represents a holistic mechanics based approach for the analysis of reinforced concrete, based on the well-established mechanics of partial interaction [32–34] and shear friction [35,36] theories. The model can be applied consistently to determine a wide range of behaviours including: the flexural strength, short and long term deformation of conventionally reinforced and prestressed beams [31,34,37,40] and columns [38]; as well as crack widths and crack spacings [39]. Moreover, as the approach has been developed, it has been widely validated against a total of 1192 shear test results on OPC concrete that have been published in 68 journal papers [27,28,30,39]. These tests have encompassed a very wide range of parameters including: shear span/depth ratios varying from 1.0 to 8.5; beam depths varying from 42 to 1200 mm; cylinder compressive strengths varying from 6.1 to 55.2 MPa; longitudinal tension reinforcement varying from 0.1 to 5.1%; stirrup reinforcement varying from 0 to 1.9%; reinforcement moduli varying from 29.4 to 200 GPa; and the shear capacities varying from 1.9 to 953 kN.

Due to its mechanics basis, as outlined by Oehlers et al. [41], the segmental approach can be used to rapidly develop design guidelines without the need for wide scale member level testing, this can be considered to be important for geopolymer concrete in which there is a need for rapid adoption due to its environmental benefit. Hence the purpose of this paper is not to compare or provide updated design code equations for the prediction of the shear capacity of geopolymer concrete beams, or to develop new material models as these can be refined over time with empirical research. Rather the purpose of this paper is to show how a rational mechanics based approach, such as the segmental approach, can be used to predict the behaviour of new materials, such as geopolymer concrete beams by only performing a limited number of relatively simple and inexpensive material tests and hence how the approach can be used as a tool to develop new design based equations.

1.1. The shear resistance mechanism

Consider the concrete beam in Fig. 1, which is subjected to a transverse load *P*. Potential diagonal shear cracks initiate from the tension region and extend to A in the compression region forming a sequence of potential inclined cracks at an angle β. Shear cracks typically initiate from flexural cracks such as B, C, D which form at a spacing of S_{cr} [29] but in areas of high shear and low moment, such as close to supports in simply supported beams, can form at any angle. It should be noted that while in practice the cracks may form in a curvilinear fashion, for simplicity here they are linearised as shown in Fig. 1.

According to Zhang [22] the shear capacity of a section without stirrups will be reached when the applied transverse load is sufficient to cause the formation of an inclined crack upon which sliding is initiated. Hence in Fig. 2 the load to cause cracking V_{cr} and the load initiate sliding V_{sl} for each potential inclined cracked plane can be considered such that failure will occur at V_{cap} which corresponds to an inclined crack at the critical diagonal crack inclination β_{CDC} where $V_{cr} = V_{sl}$. Hence to predict the shear capacity it is required that the load to cause a diagonal crack V_{cr} and the load to cause sliding V_{sl} be known for any given inclination of potential sliding plane β. The determination of these loads will be treated separately in the following sections.

1.2. Shear to cause a diagonal crack V_{cr}

The free body of a given potential sliding plane in Fig. 1 is shown in Fig. 3. According to Zhang [22] taking moments about point A, the shear load to cause diagonal cracking V_{cr} can be expressed as

$$V_{cr} = \frac{f_{tef} b(h/\sin\beta)^2/2}{a} \tag{1}$$

where *a* is the shear span, *h* is the total depth of the section and f_{tef} is the effective tensile stress and has been defined by Zhang [22] as

$$f_{tef} = 0.156 f_c^{2/3} \left(\frac{h}{0.1}\right)^{-0.3} \tag{2}$$

Hence solving Eq. (1) for each potential crack angle β yields the variation in V_{cr} shown as a dashed line in Fig. 2(a).

It should be noted that for beams to which uniformly distributed load is applied, according to Zhang et al. (2015), the shear span *a* in Eq. (1) can be defined as the ratio of the bending moment to shear force (M_a/V_a) at the critical cross section in Fig. 4.

1.3. Sliding capacity along an inclined plane V_{sl}

Now consider the sliding capacity of a beam subjected to an applied shear V_a and moment M_a as shown in Fig. 4(b) and which has a cross section as in Fig. 4(a). Rotation of the end of the beam segment due to applied load causes the beam end to deform from A-A to B-B inducing forces within the concrete (P_{conc} and V_{conc}) the tensile (P_{rt}) and the compressive (P_{rc}) reinforcement.

From force equilibrium in Fig. 4(b) the concrete compressive region must resist a horizontal force

$$P_{conc} = P_{rt} - P_{rc} \tag{3}$$

and a vertical force

$$V_{conc} = V_a \tag{4}$$

Resolving the horizontal and vertical components of the concrete force, in Fig. 4(c) the force acting to induce sliding along the inclined plane is

$$S_\beta = P_{conc}\cos\beta + V_{conc}\sin\beta \tag{5}$$

and the force normal to the plane is

$$N_\beta = P_{conc}\sin\beta + V_{conc}\cos\beta \tag{6}$$

Sliding failure will occur when the force acting to induce sliding S_β exceeds the sliding capacity of the plane $S_{cap,\beta}$ which can be expressed as a function of the local shear friction capacity τ_N, such that