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Evaluation of Design Methods for Prestressed Concrete Members with Stirrups Using a New Traditional Shear Database

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ABSTRACT

Prestressed concrete (PC) is increasingly used nowadays for the construction of structures subjected to higher loads. Shear design of PC members is complicated and ambiguous as there is no rational and universally accepted shear design procedure. A comprehensive shear database of PC members helps researchers to understand the complicated and ambiguous shear design procedure. In the present study code provisions on shear design based on 45-degree truss analogy (IS 1343:2012 and ACI 318-14), Modified Compression Field Theory (AASHTO LRFD Design Specifications), Variable angle theory (EC-2) have been investigated along with newly proposed shear strength equations. A shear database covering the traditional shear failures of PC beams with stirrups has been developed to assess the shear strength and behaviour of PC beams. Out of 683 shear tests available from the literature on PC beams a total of 274 PC beams with stirrups has been investigated to assess the degree of conservativeness and accuracy of shear design code provisions and shear strength equations. Investigations on the shear code provisions with various variables that govern the shear strength show that serious attention should be given to the prediction of the accurate failure modes for the web-shear and flexure-shear critical specimens. The oversimplifications in the new shear strength equations have also been highlighted in the present study.

1. Introduction

Design procedures should be simple, as well as easy to understand and implement in practice. If empirical equations are used in design procedures, then the understanding of the design procedures becomes complicated. Some shear design procedures for prestressed concrete (PC) members are simple but do not include all the parameters involved in various shear transfer mechanisms. Other shear design procedures are complicated and are used by practising engineers through step-by-step methods without much understanding of their background. This has led to the development of new shear design equations for PC members by various researchers. The two primary modes of traditional shear failure in PC members are web-shear and flexure-shear failure. Cracks develop in concrete when the principal tensile stress in the member reaches the cracking strength of concrete. The cracks are oriented perpendicular to the direction of the principal tensile stress. The principal tensile stresses are parallel to the longitudinal axis of PC members subjected to pure tension or pure flexure. Hence, the cracks in these members are oriented perpendicular to the longitudinal axis of the members. Web-shear cracks, inclined to the member axis, are formed near the centroid of the concrete sections where the shear stress is predominant as shown in Fig. 1(a). Web-shear cracks are also called diagonal cracks. The inclined cracking shear can be calculated by equating the principal tensile stress at the cross-sectional centroid of the member to the tensile strength of concrete. Flexural-shear cracks originate vertically similar to flexural cracks and thereafter become inclined as they propagate to the mid-depth of the section. Typical flexure-shear cracks are shown in Fig. 1(b). Empirical equations are used to predict the flexure-shear cracking force as it cannot be predicted from the principal stresses at the mid-depths of sections. It is essential to have two different shear strength equations for estimating the web-shear and flexure-shear strengths since the failure mechanisms associated with these two failure modes are different. The web-shear and the flexure-shear strengths can also be represented through a single equation through proper implementation of the shear span-to-depth ratio (a/d) that distinguishes between the two types of failure. Thus, the traditional shear failure of PC members can be distinctly classified as web-shear failure (for members with a/d ratio less than 2.5) or flexure-shear failure (for members with a/d ratio greater than 2.5) based on the recommendations of Nawy [1].

Ritter [2] idealised the reinforced concrete member as a truss where longitudinal reinforcement and stirrups are assumed to act as bottom

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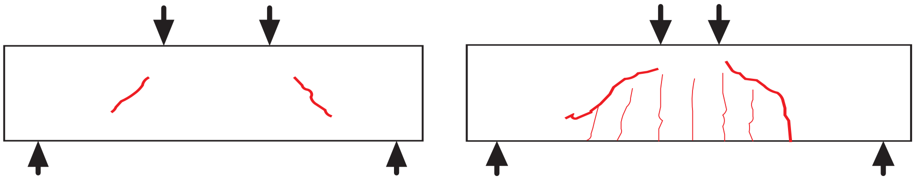
Nomenclature

$V_{ACI\ 318}$	Calculated Shear Strength as per ACI 318-14 Method
V_{AASHTO}	Calculated Shear Strength as per AASHTO LRFD shear strength provisions
$V_{IS\ 1343}$	Calculated Shear Strength as per IS 1343:2012 shear strength equations
$V_{EC\text{-}2}$	Calculated Shear Strength as per EC-2 code provision
V_{UH}	Calculated Shear Strength as UH Method
$V_{Cladera}$	Calculated shear strength as per Cladera's Method
V_{exp}	Experimental Shear Strength
$V_{n,\ max}$	Maximum Shear Strength
V_{cw}	Web-Shear Strength as per ACI 318-14 Method
V_{ci}	Web-Shear Strength as per ACI 318-14 Method
V_{co}	Uncracked shear strength as per IS 1343:2012
V_{cr}	Cracked shear strength as per IS 1343:2012.
V_p	Vertical component of shear strength due to prestress
f'_c	Cylinder strength of concrete
λ	Material strength factor according to ACI 318-14 method.
θ	Strut inclination angle
β	Concrete shear transfer factor as per AASHTO LRFD Method
τ	Design shear stress in concrete calculated as per IS 1343:2012
γ_c	Partial safety factor for concrete
σ_{cp}	Compressive stress due to prestress
ρ_l	Longitudinal reinforcement ratio
$\rho_v f_y$	Shear Reinforcement Index
ζ	size effect parameter
a/d	Shear span-to-depth ratio
A_{sw}, A_{sv}, A_v	Total cross-sectional area of stirrups
b_w	Width of the web
b_v	Width of web adjusted in the presence of ducts
$b_{v,eff}$	Effective width of the web calculated as per Cladera's Method.
c	Neutral axis depth calculated as per Cladera's Method
d_v	Effective shear depth calculated as per AASTHO LRFD Method
D	Overall depth of the section
d, d_t	Effective depth of the beam
z	Depth of lever arm calculated as per EC-2 code provision
f_t	Tensile strength of concrete
f_{cp}	Compressive stress due to prestress
f_p	Characteristic tensile strength of the strand
f_y, f_{yt}	Characteristic tensile strength of the stirrup steel.
K_p	Prestressing factor parameter according to Cladera's Method
M_o	Moment necessary to produce zero stress according to IS 1343:2012
s, s_t, s_v	Spacing of stirrups



(a) Web-Shear Failure (b) Flexure-Shear Failure

Fig. 1. Shear Failure Modes in Prestressed Concrete Members.

and vertical chords, respectively. Concrete elements in between the cracks are assumed to act as diagonal struts carrying compressive stresses. Later in 1922, Morsch [3] extended the discrete truss model approach by Ritter to a continuous truss model approach. Both Ritter and Morsch assumed a 45-degree inclination for the compression strut by neglecting the tensile stresses of cracked concrete. In 1978, the Compression Field Theory (CFT) was developed by Collins and Mitchell [4] by applying the "Tension Field Theory" in concrete members to calculate the inclination angle of the compression struts. The Modified Compression Field Theory (MCFT) [5] was introduced in 1986 to account for the tensile stress in cracked concrete, which was assumed to be zero in CFT. Truss models, CFT and MCFT were unable to accurately predict the concrete contribution to the shear strength of a concrete member. Thus a large number of experimental investigations have been conducted to formulate empirical expressions for predicting the concrete shear strength in a member [6]. Various shear design provisions use different approaches to estimate the shear strength of a concrete member. This has led to the development of simpler and more accurate shear design equations for PC by several researchers. Creation of a comprehensive shear database is essential to understand the complex behaviour of PC beams and to investigate the merits and demerits of individual shear strength equations included in various codes and proposed by other researchers.

2. Research Significance

In the present study, the degree of the conservativeness of various shear design code provisions and shear strength equations developed for PC members has been studied through the development of a traditional shear database for PC members with shear reinforcement. The new comprehensive traditional shear database consisting of 274 PC beams with rectangular, T, I and U-shaped sections exclusively with shear reinforcement tested under shear failure adds the latest shear tests on PC members to the previous shear databases developed by various researchers for reinforced concrete (RC) and PC members [7–10]. The specimens included in the database have failed in a traditional shear failure mode like web-shear and flexure-shear. The shear databases developed so far by various researchers on PC specimens have very few specimens with shear reinforcement that failed in either web-shear or flexure-shear failure modes. None of them compared the degree of accuracy and conservativeness of different code provisions with newly developed shear strength equations for traditional shear failure PC specimens. The ratio of experimental to analytical shear strengths of the 274 PC beams has been obtained in the present study using various shear design provisions and shear strength equations proposed by other researchers. The variation of shear strength ratios of web-shear and flexure-shear failure specimens with various parameters that govern the shear failure behaviour has been studied. Comparative analysis of the strength ratios highlights the drawbacks of the current shear design provisions and modifications required for further development of simpler shear design equations.

3. Shear Design Provisions and New Shear Strength Equations

The various shear design provisions and shear strength equations for PC members included in the present study for analysing the 274 PC