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Shear Strength Model Specified in ACI 318: Engineering Review

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ABSTRACT

According to many existing studies in literature, the shear design method for pre-stressed concrete (PSC) members in ACI 318 is quite complicated especially because of the presence of flexure-shear strength equation, requiring calculation of too many parameters such as design force terms and section properties. To overcome such an issue inherent in the current shear design method of PSC members, this study aims to examine the theoretical background of ACI 318 shear design method. The current ACI 318 shear design method for PSC members has not been updated much for the last decades – the present form has been used since 1971, in which the shear design strength of PSC members is taken as either of the shear capacities estimated by detailed and simple (more conservative) methods. The former known as the detailed method was implemented in 1963, while the latter was proposed by MacGregor in 1969 and then included in the main body of ACI 318 code soon after. Most of the modifications made in ACI PSC shear design provision for the last several decades were merely minor notational changes. Based on this review study, potential remedies can be identified that are able to improve the current ACI 318 model requiring high computational efforts to determine the design factors.

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1. INTRODUCTION

Shear design method specified in ACI 318 for pre-stressed concrete (PSC) members was introduced to the main body of the code in 1963. The ACI shear design procedure was derived based on empirical data from 244 tested PSC beams (ACI Committee 318, 1963). Generally, shear behavior of PSC members has great uncertainty, and many researchers agree that available theories are too complicated to be applied in practice (Oh & Kim, 2004; Villamizar, Ramirez & Aguilar, 2017). Elzanaty et al. (1986) investigated the effect of concrete strength on the shear capacity of PSC beams, and reported that the ACI code procedure is reasonably conservative for different concrete strengths. Some researchers reported unsafe trends in test-to-predicted ratio regarding the web-shear strength (V_{cw}), while opposite trends were observed due to the fact that the concrete compressive strength (f_c') increases flexure-shear strength (V_{ci}) of PSC members without stirrups. Inadequate consideration of following parameters of a/d ratio, effective prestress force and ratio of prestressing reinforcement was also recognized by existing studies. Based on several research efforts in the shear design for reinforced concrete beams (e.g., size effect by Tompos & Frosh (2002); simplified equation by Tureyen & Frosh (2004)), Wolf & Frosch (2007) introduced a unified method for shear strength of PSC beams. They firstly analyzed the applicability of Tureyen & Frosch (2002)'s model of reinforced concrete (RC) beams to PSC members. The original model was eventually modified to the unified version for calculating flexure-shear strength V_{ci} for both RC and PSC beams. The proposed equation eliminated tedious calculation of variables in V_{ci}, and V_{ci} should be calculated only in regions where an applied moment exceeds the cracking one. In other cases, the web-shear strength (V_{cw}) is being calculated according to ACI 318 design code.

Other recent studies on ACI shear design for PSC members paid attention to the tedious calculation procedure that the code demands. Portland Cement Association (Kamara & Rabbat, 2005) commented on ACI 318-05 shear design model as follows: [the subscripts of involving variables in flexure-shear strength equation were called *"confusing"* and calculation procedure of detailed method (minimum between flexure-shear and web-shear equations) were determined as *"difficult to apply without design aids"*]. As Bondy & Bondy (2016) stated that along with some uncertainties within design procedure and abnormal results from ACI 318 shear design model, there is high computational time and efforts required to complete shear strength design. The authors argued that the existence of precompression in PSC structural members should influence the shear strength V_c to make sure to exceed the analogical equation for nonprestressed beams. They developed a uniform approach for post-tensioned beams where a coefficient of 0.15 was derived through the comparison with existing code models and modified forms with a new term d_v, the distance between compression zone and centroid of nonprestressed tension reinforcement.

2. HISTORICAL DEVELOPMENT OF CURRENT ACI PSC SHEAR DESIGN MODEL

Introduction of the shear design method for PSC members in ACI 318 is traced back to 1963 (ACI Committee 318, 1963). Table 1 describes the changes made from ACI 318-63 (first appearance of PSC members) until the current version of ACI 318-14.

Table 1. Historical development of ACI shear design model for PSC members

ACI 318-63		**ACI 318-71**
$V_{ci} = 0.6b'd\sqrt{f_c'} + \frac{M_{cr}}{\frac{M}{V} - \frac{d}{2}} + V_d$ $V_{cw} = b'd\left(3.5\sqrt{f_c'} + 0.3f_{pc}\right) + V_p$	*MacGregor introduced the simple method	$V_c = 0.6\sqrt{f_c'} + 700\frac{V_u d}{M_u}$ $V_{ci} = 0.6\sqrt{f_c'} + \frac{V_d + \frac{V_i M_{cr}}{M_{max}}}{b_w d}$ $V_{cw} = \left(3.5\sqrt{f_c'} + 0.3f_{pc}\right) + \frac{V_p}{b_w d}$
ACI 318-02		**ACI 318-05**
$V_c = (0.6\sqrt{f_c'} + 700\frac{V_u d}{M_u})b_w d$ $V_{ci} = 0.6\sqrt{f_c'}b_w d + V_d + \frac{V_i M_{cr}}{M_{max}}$ $V_{cw} = \left(3.5\sqrt{f_c'} + 0.3f_{pc}\right)b_w d + V_p$	*d_p term was firstly appeared in the code *M_{cr} was modified to M_{cre}	$V_c = (0.6\sqrt{f_c'} + 700\frac{V_u d_p}{M_u})b_w d$ $V_{ci} = 0.6\sqrt{f_c'}b_w d_p + V_d + \frac{V_i M_{cre}}{M_{max}}$ $V_{cw} = \left(3.5\sqrt{f_c'} + 0.3f_{pc}\right)b_w d_p + V_p$
ACI 318-08/11		**ACI 318-14**
$V_c = \left(0.6\lambda\sqrt{f_c'} + 700\frac{V_u d_p}{M_u}\right)b_w d$ $V_{ci} = 0.6\lambda\sqrt{f_c'}b_w d_p + V_d + \frac{V_i M_{cre}}{M_{max}}$ $V_{cw} = \left(3.5\lambda\sqrt{f_c'} + 0.3f_{pc}\right)b_w d_p + V_p$	*d_p in the simple method was changed back to d	$V_c = \left(0.6\lambda\sqrt{f_c'} + 700\frac{V_u d}{M_u}\right)b_w d$ $V_{ci} = 0.6\lambda\sqrt{f_c'}b_w d_p + V_d + \frac{V_i M_{cre}}{M_{max}}$ $V_{cw} = \left(3.5\lambda\sqrt{f_c'} + 0.3f_{pc}\right)b_w d_p + V_p$

As pointed out by recent studies, the design procedure demands high computational time and efforts. To overcome such an issue inherent in the current shear design method of PSC members specified in ACI 318 code, the theoretical background of ACI 318 shear design method is considered.

The origin of the model that ACI introduced to the main body of the code was from the study by Sozen & Hawkins (1962). ACI 318-63 shear design procedure for PSC members incorporated two equations (see Table 1): web-shear strength (V_{cw}) and flexure-shear strength (V_{ci}); lesser of which determines the shear strength (V_c). However, in ACI subsequent update (ACI 318-71), the shear design procedure had one more equation, resulting in a set of three equations. The added equation had represented effective prestress force condition in the way that if it exceeds the 40% of the tensile strength of flexural reinforcement the only one V_c equation of the simple method can be applied. The modification was introduced after MacGregor & Hanson (1969)'s study on the simplification of V_{ci} equation.

In terms of analytical accuracy, ACI 318 shear design model for PSC members was turned out to be reliable. It is simply that computational time is high and significant efforts are demanded, particularly when calculating the flexure-shear strength equation

V_{ci} with so many parameters such as design forces and section properties. That is why the equation, so-called simple method, was proposed by MacGregor & Hanson (1969); to relieve the computational efforts, which was later accepted by ACI 318-71. The original two equations of V_{ci} and V_{cw} proposed by Sozen & Hawkins (1969) have been then called as detailed method. The current practice determines the shear strength by taking the maximum of the values calculated using both the simple and detailed methods, though it is okay to use either model.

The current ACI 318-14 is not too different from ACI 318-71, as the changes since 1971 are merely notation changes (see all modification steps in Table 1). In part due to its long history, PSC shear design method has remained the same.

3. CONCLUSION

Investigation of theoretical background of the code indicated that the ACI 318 shear design model for PSC members has remained unchanged for almost half of the century. Yet concerns exist in regard to the complexity of the calculation procedure. The current review study signals that more straightforward method is unquestionably needed for its better application in practice (to avoid human errors and disasters).

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