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Improvements of IS 1343-2012 Shear Design Provisions Using a New Traditional Shear Database of Prestressed Concrete Members with Stirrups

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Abstract. Various national codes of practice play a crucial role in the development of the country's infrastructure and should be developed based on principles of mechanics and experimental verification. Continuous monitoring of infrastructure and updating of relevant codes of practice at regular intervals is essential to withstand the ever-increasing demand of the country's infrastructure. In the present study, the shear design provisions of prestressed concrete (PC) in IS 1343-2012 have been reviewed. The assumptions used in the formulations of the existing shear design equations in IS 1343-2012 have been discussed. The present study reveals that the IS 1343-2012 shear design provisions, which are based on old test data, are too conservative and are unable to distinguish the two major modes of traditional shear failure, namely web-shear and flexure-shear. Modifications for the existing IS 1343-2012 shear design equations have been proposed to improve the shear strength estimation of PC members and also to distinguish between the web-shear and flexure-shear failure modes. A detailed comparison of existing IS 1343-2012 shear design provisions with the proposed modified shear strength equations has also been made with the help of a traditional shear database on PC members with stirrups.

Keywords. Shear Design; Ultimate Shear Capacity; IS 1343-2012; Shear Database; Web-Shear; Flexure-Shear; Prestressed Concrete.

1. Introduction

The usage of prestressed concrete (PC) structures has been increased enormously due to the rapid development of huge infrastructures in developing nations. The problem of shear design of PC members is still an intriguing problem to several researchers since there is no universally accepted rational theory on the shear behaviour of concrete structures. The first code provision on PC members was introduced in the Indian Standards in 1963 [1]. The second revision for IS 1343 has been published in 1980 with significant changes in the existing design guidelines. The latest IS 1343-2012 [2] shear design provisions are identical to the ones introduced in the 1980 version [3]. Tandavamoorthy and Paramesvaran [4] have investigated the inconsistency of IS 1343-1980 [3] code provisions in estimating the moment capacity of flexural members at limit state of collapse and proposed a new table to calculate the ultimate moment capacity of rectangular sections. Later, Paul and Menon [5] showed that the existing Table 11 of Appendix-B [2] was unable to satisfy the equilibrium conditions and proposed a new table for bonded pre-tensioned and post-tensioned members. Thus, significant improvements have been proposed to the provisions for evaluating the ultimate moment capacity of PC members in IS 1343. However, no such investigations have been conducted to improve the shear design provisions of IS 1343-2012 [2]. In the present study, the shear design provisions of IS 1343-2012 [2] has been investigated using a new traditional shear database of PC members with stirrups developed by Perumalla and Laskar [6].

Flexural and shear cracks in PC members develop perpendicular to the direction of principal tensile stress when the principal tensile stresses reach the tensile capacity of concrete. The classification of various crack zones in a PC beam is shown in figure 1 [7]. Shear design of PC members in IS 1343-2012 [2] code provisions is based on a sectional approach. The ultimate shear resistance (V_{uR}) of a section in a PC member consists of the concrete contribution (V_c) and the steel contribution (V_s). The value of V_c at a section of a PC member depends on whether the section is cracked

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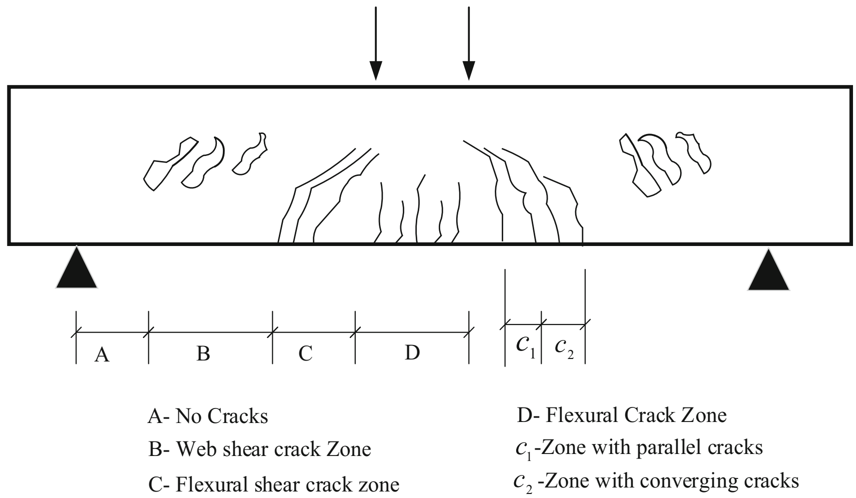

Figure 1. Description of Crack Zones in PC Member.

(i.e., section is in the zone of flexure-shear cracking) or un-cracked (i.e., section is in the zone of web-shear cracking). The concrete contribution to the ultimate shear resistance at a section of a PC member is taken as the minimum of the web-shear and the flexure-shear strengths at the section. The web-shear strength of concrete is referred to as the un-cracked strength (V_{co}) and is taken as the shear force that is carried by concrete when the principal tensile stresses in Zone B (figure 1) of a PC member are equal to the tensile strength of concrete. The flexure-shear strength of concrete is referred to as the cracked strength (V_{cr}) and is taken as the shear force that is resisted by the beam at the formation of the flexure-shear cracks in Zone C (figure 1) of a PC member. The un-cracked and cracked shear strengths of concrete in a PC member as per Section 23.4 of IS 1343-2012 [2] are shown in Eqs. (1) and (2), respectively.

$$V_{co} = 0.67bD\sqrt{f_t^2 + 0.8f_{cp}f_t} \tag{1}$$

$$V_{cr} = \left(1 - 0.55\frac{f_{pe}}{f_{pu}}\right)\varsigma_c bd + M_o\frac{V}{M} \tag{2}$$

2. Research Significance

The present study aims to evaluate the IS 1343-2012 [2] shear design provisions for PC members with the help of a newly developed database [6] of two hundred and seventy-four traditional shear failure specimens (web-shear and flexure-shear). The shear strength ratio (SSR) for each of two hundred and seventy-four shear test specimens in the database [6] has been calculated as the ratio of the experimental shear strength of a specimen to the shear strength of the corresponding specimen predicted using the specified IS 1343-2012 [2] shear strength equations. The assumptions used in the formulations of 1343-2012 [2] shear design provisions have been discussed, and the ability to predict the type of shear failure (web-shear and flexure-shear) has been studied. The drawbacks of the IS 1343-2012 [2] shear design provisions have been highlighted and the modifications that can be implemented to improve the shear strength predictions, as well as the type of shear failure, have been proposed. The SSR values for the individual specimens in the database [6] have also been calculated using the proposed modified shear strength equations.

3. IS 1343-2012 Shear Design Provisions

IS 1343-2012 [2] shear design provisions adopt the 45-degree truss analogy [8] to calculate the steel contribution. The concrete contribution is taken as the minimum of the un-cracked (V_{co}) and cracked strengths (V_{cr}) shown in Eqs. (1) and (2). The maximum shear stress values for PC members specified in table 9, Section 23.4.4 of IS 1343-2012 [2] is a function of $\sqrt{f_{ck}}$ and has an intrinsic strength reduction factor of 0.85. The derivations and assumptions of the un-cracked and cracked shear strength equations have been discussed in sections 3.1 and 3.2.

3.1 *Un-Cracked Shear Strength*

The web-shear cracking strength of a PC member can be obtained by equating the tensile strength of concrete (f_t) with the maximum principal tensile stress at the neutral axis (NA) of the member. The shear stress in the element can be expressed in terms of the shear force acting on the cross-section of the PC member under the web-shear cracking load (V_{co}). The web-shear cracking strength can thus be obtained as shown in Eq. (3).

$$V_{co} = \frac{Ib}{Q}\sqrt{f_t^2 + f_{cp}f_t} \tag{3}$$

Ib/Q is taken as 0.67bD in IS 1343-2012 [2], assuming the cross-section of the PC member is rectangular. However, Ib/Q is mostly higher than 0.67bD for a flanged section, thereby making the estimated web-shear strength in IS 1343-2012 [2] conservative. IS 1343-2012 [2] also uses 0.8 f_{cp} to incorporate the unforeseen variation in the compressive stress due to prestress at the centroidal axis (f_{cp}). The value of f_t is taken as $0.24\sqrt{f_{ck}}$ which has an intrinsic factor of safety (FOS) of 1.5 for concrete strengths. Therefore, the web-shear strength of concrete in PC members is obtained in IS 1343-2012 [2] from Eq. (3) using the assumptions and intrinsic factors of safety discussed above.

3.2 *Cracked Strength*

IS 1343-2012 [2] provides an empirical equation for estimating the flexure-shear cracking strength of PC members. The equation specified in IS 1343-2012 [2] was formulated based on the test results of Sozen [9], which were first adopted in ACI 318-63 [10]. Figure 2 shows the exact data used to calibrate the flexure-shear strength equation used in ACI 318-63 [10].

The flexure-shear strength equation, which is formulated based on the flexure-shear crack model [11] is shown in Eq. (4)

$$V_{cr\_ACI318-63} = 0.6\sqrt{f_c'(\text{psi})}b_w d + M_{cr}\frac{V}{M} \tag{4}$$

The additional term $0.6\sqrt{f_c'}b_w d$ in Eq. (4) has been added to account for the tensile strength of concrete. Eq. (4) has also

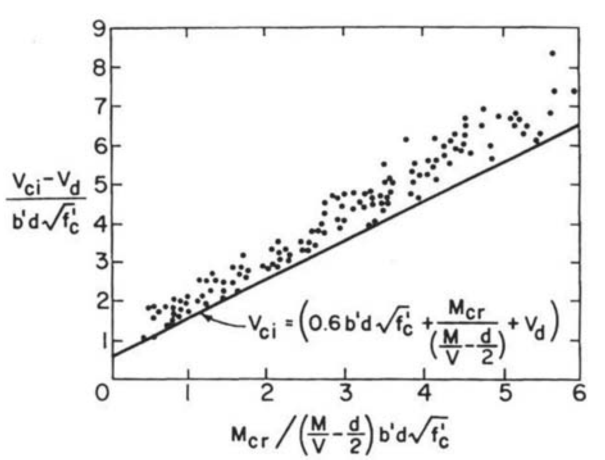

Figure 2. Experimental Data for Calibration of ACI 318-63 Flexure-Shear Strength.

been used in IS 1343-2012 [2] in SI units in terms of the concrete cube strength [11] as shown in Eq. (5).

$$V_{cr} = 0.037\sqrt{f_{ck}}bd + M_{cr}\frac{V}{M} \tag{5}$$

The value of M_{cr} is taken as the sum of moment necessary to produce zero stress in the concrete (M_0) and the moment required to produce concrete stress equal to its tensile strength $0.37\sqrt{f_{ck}}$ [11]. The flexure-shear strength equation shown in Eq. (5) has been changed to Eq. (6a) by assuming a rectangular section, with f_{ck} = 50 MPa and a/d ratio of 4 [11]. The flexure-shear equation has been further generalised for PC as well as reinforced concrete (RC) members by including the effect of the prestressing force in Eq. (5), as shown in Eq. (6b).

$$\frac{V_{cr}}{bd} = 0.26 + 0.11 + \frac{M_o V}{Mbd} \tag{6a}$$

$$\frac{V_{cr}}{bd} = \left(1 - n\frac{f_{pe}}{f_{pu}}\right)\zeta_c + \frac{M_o V}{Mbd} \tag{6b}$$

The value of n in Eq. (6b) has been calibrated using Eq. (6a) for $\frac{f_{pe}}{f_{pu}} = 0.6$. Assuming $\zeta_c = 0.55$ for 0.5 % of steel as obtained from CP 110-1972 [12] (table 5, CP 110-1972) the value of "n" in Eq. (6b) has been obtained as 0.55. Thus, Eq. (6b) can be expressed as shown in Eq. (7) which has been included in IS 1343-2012 [2] to estimate the ultimate flexure-shear strength of concrete in a PC member. Thus, the flexure-shear strength equation in IS 1343-2012 [2] has been formulated by considering a rectangular section with a/d = 4, $f_{ck} = 50$ MPa and $\zeta_c = 0.55$[11] and can, therefore, be inaccurate for other cases.

$$V_{cr} = \left(1 - 0.55\frac{f_{pe}}{f_{pu}}\right)\zeta_c bd + M_o\frac{V}{M} \tag{7}$$

3.3 *Analysis of Traditional Shear Failure Specimens*

A shear strength equation should be able to predict the type of shear failure (i.e., flexure-shear or web-shear) in addition to the prediction of the actual failure load. IS 1343-2012 [2] has two separate equations to predict the un-cracked (web-shear) strength and cracked (flexure-shear) strength of concrete in PC members. Out of two hundred and seventy-four test specimens available in the shear database developed by Perumalla and Laskar [6], the flexure-shear critical specimens and the web-shear critical specimens have been separated in the present study based on the observed failure modes reported for the individual specimens by the corresponding researchers. Thus, there are one hundred and eleven flexure-shear critical specimens and one hundred and sixty-three web-shear critical specimens in the

Table 1. Strength Predictions for Flexure-Shear and Web-Shear Critical Specimens.

Code Provision	Type of Failure	No. of Specimens V_{co}	V_{cr}	V_{max}	Total
IS 1343-2012 with V_{max}	Flexure-shear	26 (23%)	34 (31%)	51 (46%)	111
	Web-shear	55 (34%)	29 (18%)	79 (48%)	163
IS 1343-2012 without V_{max}	Flexure-shear	74 (67%)	37 (33%)	–	111
	Web-shear	134 (82%)	29 (18%)	–	163

developed database. Table 1 shows the number of flexure-shear and web-shear critical specimens whose predicted strengths are governed by each of the three shear strength criterion included in IS 1343-2012 [2], namely the un-cracked shear strength of concrete (V_{co}), the cracked shear strength of concrete (V_{cr}) and the maximum overall shear strength of PC member (V_{max}).

It can be observed in table 1 that the maximum shear strength (V_{max}) in IS 1343-2012 [2] governs the shear strength predictions for most of the flexure-shear and web-shear critical specimens. The strengths of only 31% of the flexure-shear critical specimens and 34 % of web-shear critical specimens are governed by the cracked and un-cracked shear strength contribution of concrete as per IS 1343-2012 [2] guidelines. Since, it is evident that the maximum shear strength equation governs the shear strength predictions of most of the web-shear critical and flexure-shear critical specimen as per IS 1343-2012 [2] shear design provisions, the shear strength predictions of the specimens have been re-calculated without considering the IS 1343-2012 [2] maximum shear strength (V_{max}) criteria. Table 1 also shows the number of web-shear and flexure-shear critical specimens whose predicted strengths are governed by either the un-cracked shear strength of concrete (V_{co}) or the cracked shear strength of concrete (V_{cr}) without considering the maximum shear strength (V_{max}) criteria provided in IS 1343-2012 [2]. It can be observed from table 1, that the strength of most of the flexure-shear and web-shear critical specimens are governed by the un-cracked shear strength concrete contribution of IS 1343-2012 [2] when the maximum shear strength criteria of IS 1343-2012 [2] is not considered. Thus, the un-cracked shear strength contribution of concrete in IS 1343-2012 is significantly more conservative than the cracked shear strength contribution of concrete. Hence, IS 1343-2012 [2] shear design provisions are not suitable to accurately predict and distinguish between the two types of shear failure. Thus, it is essential to modify the equations for predicting the concrete contribution to shear as well as the maximum shear strength equation in IS 1343-2012 [2] such that the concrete contribution of the majority of the specimens represent the correct failure mode of the specimens by using the modified strength equations.

4. Improvements to IS 1343-2012 Shear Design Provisions

4.1 *Un-Cracked Shear Strength*

The underlying assumptions and the formulation used for the development of the un-cracked shear strength equation concrete in IS 1343-2012 [2] have been explained in section 3.1. IS 1343-2012 [2] assumes the tensile strength of concrete to be $0.24\sqrt{f_{ck}}$ with an intrinsic FOS of 1.5. ACI 318-14 [13], on the other hand, assumes the tensile strength of concrete to be $0.33\sqrt{f_c}$ for estimating the un-cracked shear strength. Bentz [14] showed that the use of $0.33\sqrt{f_c}$ for the web-shear cracking strength calculation in ACI 318-14 [13] is in good agreement with the direct tensile strength of concrete. Hence, a total of one hundred and ninety-five split tensile strength values of concrete used in PC test specimens available in the literature have been used to investigate the accuracy of the concrete tensile strength assumed in IS 1343-2012 [2]. The details of the split tensile strength values of concrete used in the PC test specimens by various researchers are given in online Appendix-A. The variation of split tensile strength with the cube strength of concrete has been plotted in figure 3.

It can be observed from figure 3 that the split tensile strength values used in IS 1343-2012 [2] and ACI 318-14 [13] code provisions are conservative over entire range concrete compressive strengths covered in the literature. However, IS 1343-2012 [2] predicted split tensile strength values are too conservative for higher strengths of concrete normally used in PC members at present. Thus, it has been proposed to use ACI 318-14 [13] recommended $0.33\sqrt{f_c}$ as the limiting tensile strength of concrete instead of the IS 1343-2012 [2] adopted tensile strength values. The modified un-cracked shear strength equation needs to be further verified with the developed shear database [6] of two hundred and seventy-four specimens.

4.2 *Cracked Shear Strength*

The underlying assumptions and the formulation for the shear strength of cracked concrete in IS 1343-2012 [2] have been explained in section 3.2. The shear contribution of cracked concrete in a PC member as per IS 1343-2012 [2]

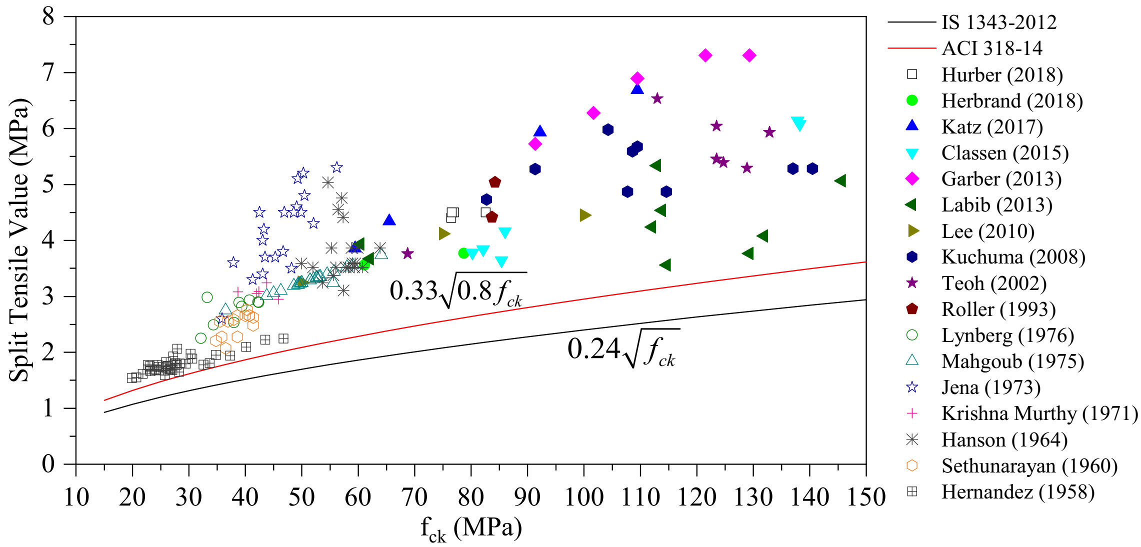

Figure 3. Variation of Split Tensile Strengths with Cube Strength of Concrete.

is shown in Equation (7). The second term on the right-hand side of Eq. (7) represents the effect of the shear span-to-depth ratio of the member on the flexure-shear strength contribution of concrete. The shear strengths of the flexure-shear critical specimens in the developed shear database by Perumalla and Laskar [6] has been used to estimate the necessary modifications required to improve the shear strength contribution of cracked concrete in IS 1343-2012 [2]. The variation of the flexure-shear strength of concrete due to the shear span-to-depth ratio has been obtained from the experimental failure load and the steel strength in the flexure-shear critical specimens. The flexure-shear strength of concrete due to the shear span-to-depth ratio of the specimens has been represented by $\frac{\left[\left\{V_{\exp}-V_{S-FOS}\right\}-\left\{\left(1-0.55\frac{f_{pe}}{f_{pu}}\right)\varsigma_c bd\right\}\right]}{M_o}$ and its variation with respect to the shear span-to-depth ratio of the one hundred and eleven flexure-shear critical specimens (represented by the V/M ratio of the specimens) has been plotted in figure 4. It can be observed that the $\frac{\left[\left\{V_{\exp}-V_{S-FOS}\right\}-\left\{\left(1-0.55\frac{f_{pe}}{f_{pu}}\right)\varsigma_c bd\right\}\right]}{M_o}$ value increases as V/M increases. A limiting line (red) which represents the minimum flexure-shear strength of 95% of the flexure-shear critical specimens has been plotted in figure 4. A modification factor of 0.8 which is equal to the slope of the limiting line, has been used for the cracked shear strength contribution of concrete due to the shear span-to-depth ratio of the specimens. The modified cracked shear strength contribution of concrete thus proposed is shown in Eq. (8). The limiting line corresponding to the existing flexure-shear strength equation (black) is also shown in figure 4. Comparison of the two limiting lines shows that only a minor but subtle change in the existing equation has been proposed in the present study to improve the flexure-shear strength predictions. The effectiveness of the proposed modification of cracked shear strength equations needs to be verified along with the proposed modification of the un-cracked shear strength contribution of concrete discussed in section 4.1.

$$V_{cr} = \left(1 - 0.55\frac{f_{pe}}{f_{pu}}\right)\varsigma_c bd + M_o\left(0.8\frac{V}{M}\right) \qquad (8)$$

Analysis of prestressed concrete members by Laskar *et al* [15] showed that the flexure-shear strength is primarily dependent on a/d compared to the other parameters such as f_{ck} and ζ_c. The simplifications used in the formulation of the flexure-shear strength equation in IS 1343-2012 have resulted in the over-estimation of flexure-shear strength predictions. Hence the existing flexure-shear strength equation of IS 1343-2012 has been considered in the present study to propose a modification factor of 0.8 to the major governing a/d (M/V) term and thereby reduce the over-estimation of the flexure shear strength due to the simplifications used in the existing equation. The proposed modification involves minimum change in the existing equation and results in improved flexure-shear strength predictions and better distinction of the type of shear failure.

4.3 *Maximum Shear Strength*

IS 1343-2012 [2] maximum shear strength equation is too conservative, as discussed in Section 3.3. Hence, the maximum shear strengths of PC members recommended by

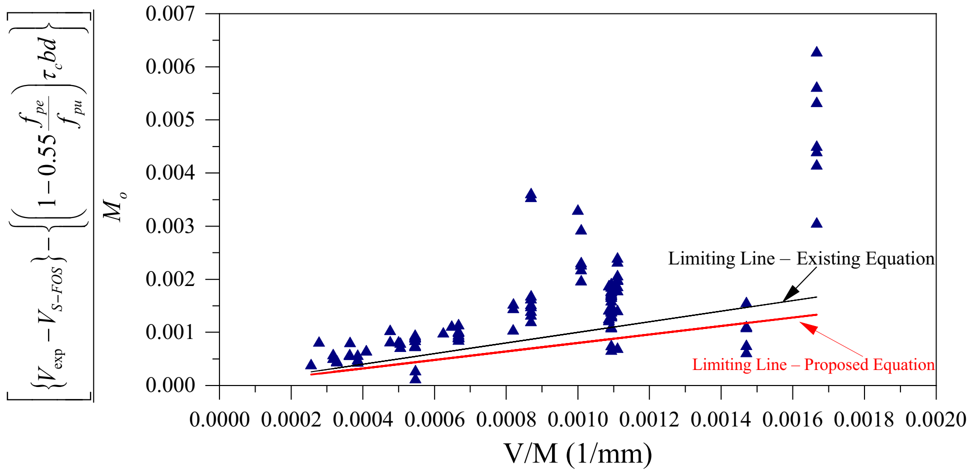

Figure 4. Variation of Cracked Shear Strength with V/M.

other researchers and code provisions have also been investigated along with the modified shear strength equations discussed in sections 4.1 and 4.2. The maximum shear strength equation in the UH Method has been developed based on the results of panel tests at the University of Houston [16]. The maximum shear strength is a function of concrete compressive strength $\sqrt{f_c}$ and principal tensile strain in concrete. The simplified form of the maximum shear strength criteria is shown in Eq. (9). The value of C has been calibrated as 1.33 by Laskar *et al* [16] to ensure the ductile failure of PC members using the shear test results of PC beams available in the literature.

$$V_{UH,\max} = C\sqrt{f_c'}b_w d \qquad (9)$$

IS 1343-2012 [2] specifies the variation of maximum shear stress for concrete compressive strengths from M30 to M55. The maximum shear stress is assumed to remain constant for concrete compressive strengths higher than M55. However, the maximum shear stress of $0.63\sqrt{f_{ck}}$ has been used in the present study for the range of concrete compressive strengths covered by the specimens in the shear database. Maximum shear stress of $0.995\sqrt{f_c}$ (MPa) was proposed by Sandra *et al* [17] based on the results of full-scale tests on AASHTO Type II PC beams. ACI 318-63 [10] used maximum shear stress of $0.83\sqrt{f_c}$. ACI 318-14 [13] code also limits the maximum steel strength to $0.66\sqrt{f_c}$ in addition to the maximum shear stress of $0.83\sqrt{f_c}$. The variation of experimental shear strength ($V_{exp}/b_w d$) of over-reinforced PC specimens, available in the shear database developed by Perumalla and Laskar [6], with the concrete compressive strength of the specimens, has been plotted in the present study as shown in figure 5.

The maximum shear strength of PC members as per IS 1343-2012 [1], ACI 318, Sandra *et al* [17] and the UH Method [16] has also been plotted in figure 5. It can be observed from figure 5 that the maximum shear strength of PC members recommended by IS 1343-2012 [2] is too conservative and is significantly lower than the shear strengths observed in over-reinforced PC specimens. Hence, the maximum shear stress criteria of IS 1343-2012 [2] mostly governs over the un-cracked and cracked shear strength estimates thereby leading to underestimation of member strengths. The same has been observed in section 3.3, where maximum shear strength criteria of IS 1343-2012 [2] governs the shear strength predictions of most of the flexure-shear critical and web-shear critical specimens. A comparative study of the actual shear strength equations in IS 1343-2012 [2] with the set of modified shear strength equations proposed in the present study (discussed in sections 4.1 and 4.2) has been performed in section 4.4 to find the most suitable estimate of the maximum shear strength of PC members for IS 1343-2012 [2] code provisions.

4.4 *Modified Shear Strength Equations*

The modifications proposed for the code specified shear strength equations has been verified with the shear test results of the web-shear and flexure-shear critical specimens available in the developed shear database [6]. Shear strength calculations of two hundred and seventy-four shear test specimens have been performed with the various maximum shear stress criterion discussed in section 4.3 (i.e., IS 1343-2012 [2], UH Method [16], ACI 318 and Sandra *et al* [17]). The calculation results have been summarised in figure 6 by showing the number of web-shear and flexure-shear critical specimens whose strengths are governed by the cracked shear strength of concrete (V_{cr}), the un-cracked shear strength of concrete (V_{co}) and the maximum shear strength of the member (V_{max}). Thus, the

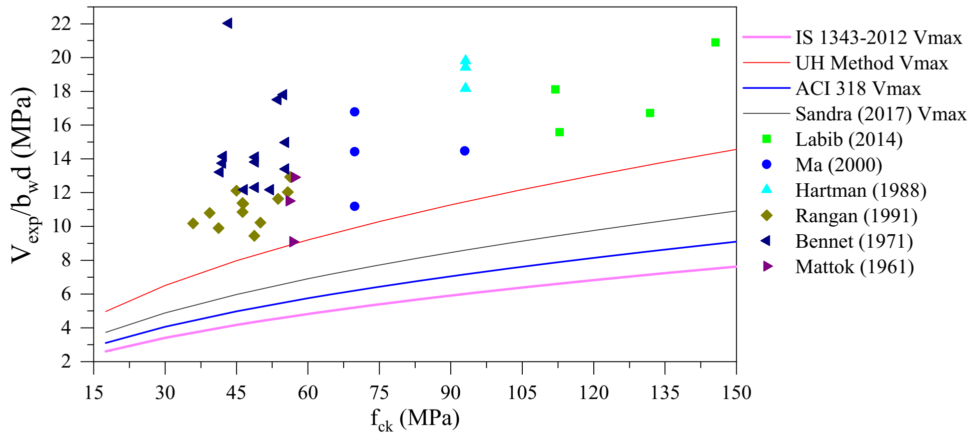

Figure 5. Variation of Maximum Shear Strength with Concrete Strengths.

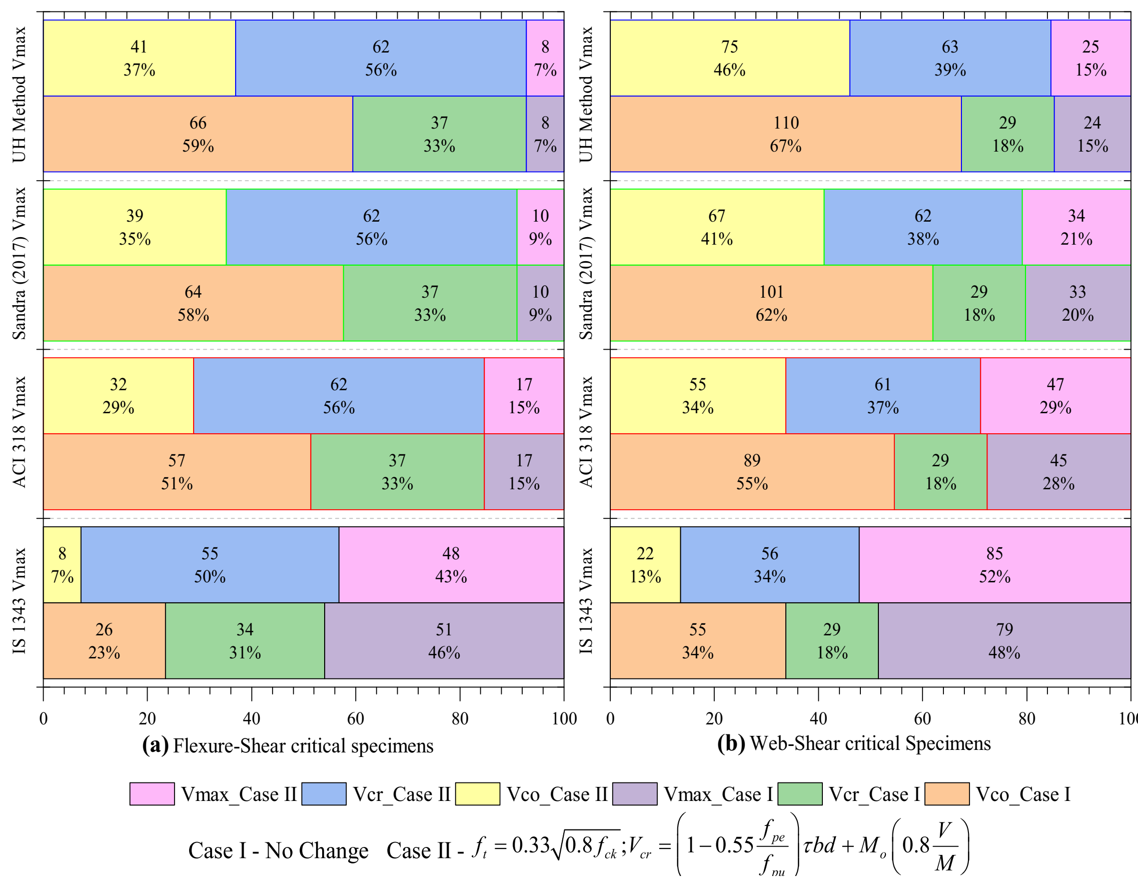

Figure 6. Governing Failure Mode Comparison of Flexure-Shear and Web-Shear Critical Specimens.

majority of the specimens should fall under the V_{co} and V_{cr} in the cases of web-shear and flexure-shear critical specimens, respectively. The effect of the various maximum shear strength criterion on the IS 1343-2012 [2] shear strength equations and the modified shear strength equations proposed in the present study are shown as Cases I and II, respectively. The summary of the governing failure mode comparison with different maximum shear strength criteria for flexure-shear and web-shear critical specimens performed in the present study is shown in figures 6a and b, respectively.

IS 1343-2012 V_{max}: It can be observed from figure 6a that the number of flexure-shear critical specimens whose strength is governed by cracked shear strength of concrete is higher with the proposed modifications in the cracked shear strength equation (Case I - 34 vs Case II - 55) along with IS 1343-2012 V_{max} criteria. However, the strength of most of the web-shear critical specimens is governed by the maximum shear strength equation of IS 1343-2012 [2] both with and without the proposed modifications in the un-cracked shear strength equations (Case I - 79 and Case II – 85), as shown in figure 6b. Hence, it is necessary to use a different maximum shear strength equation so that the un-cracked shear equation governs the strength of most of the web-shear critical specimens.

ACI 318 V_{max}: It can be observed from figure 6a that the number of flexure-shear critical specimens whose strength is governed by cracked shear strength of concrete is also higher with the proposed modifications in the cracked shear strength equation (Case I - 37 vs Case II - 62) along with the ACI 318 V_{max} criteria. However, the strength of most of the web-shear critical specimens is governed by the modified cracked shear strength contribution of concrete proposed in the present study. Hence, the proposed modifications in the IS 1343-2012 [2] equations for concrete contribution to the shear strength of PC members in combination with the maximum shear strength criteria of ACI 318 are not suitable for accurate prediction of the failure mode of the web-shear critical specimens. It can be observed in figure 6b that the increment in the maximum shear stress (from IS 1343-2012 to ACI 318 criteria) improves the prediction of the web-shear failure mode.

Sandra *et al* V_{max}: It can be observed in figure 6a that the replacement of the ACI 318 maximum shear strength criteria with the maximum shear strength criteria proposed by Sandra *et al* [17] does not affect the prediction of flexure-shear failure mode (Case I - 37 vs Case II - 62). However, an increase in the maximum shear stress improved the prediction of the un-cracked shear strength of concrete in the web-shear critical specimens using the modifications in the cracked shear strength equation proposed in the present study.

UH Method V_{max}: It can be observed from figure 6a that the number of web-shear critical specimens whose strength is governed by the UH Method maximum shear strength criteria is very low both with and without the proposed modifications in the un-cracked shear strength equations (Case I - 24 vs Case II - 25). The strengths of the maximum number of web-shear critical and flexure-shear critical specimens are also predicted using the modified equations for un-cracked and cracked shear strength of concrete respectively by increasing the maximum shear strength criteria of IS 1343-2012 [2] to $1.33\sqrt{f_c}$ as proposed in the UH Method [16].

Thus, the proposed modified shear strength equations for IS 1343-2012 [2] shear guidelines are shown in Eqs. (10) through (12).

$$V_{co} = 0.67bD\sqrt{f_t^2 + 0.8f_{cp}f_t} \tag{10a}$$

$$f_t = 0.33\sqrt{0.8 \times f_{ck}} \tag{10b}$$

$$V_{cr} = \left(1 - 0.55\frac{f_{pe}}{f_{pu}}\right)\varsigma_c bd + M_o\left(0.8\frac{V}{M}\right) \tag{11}$$

$$V_{UH,\max} = 1.33\sqrt{f_c'}b_w d \tag{12}$$

5. Comparison of SSR Values with Proposed Modified Shear Design Equations

The SSR values of all the specimens in the developed shear database [6] has been used to compare the accuracy and conservativeness of IS 1343-2012 [2] shear strength equations with the modified IS 1343-2012 [2] shear strength equations. Statistical parameters like mean, standard deviation (SD), coefficient of variation (COV) have been obtained for the SSR values obtained using the IS 1343-2012 shear strength equations (1) and (2) and the modified shear strength equations (10) through (12). The statistics of the SSR values obtained using the two sets of equations are shown in table 2.

The mean SSR values obtained using the modified shear strength equations have been reduced from 2.146 to 1.798 and COV slightly reduced from 0.351 to 0.310. It can also be observed from table 2 that the modified shear strength equations marginally over-estimated the strength of two out of the two hundred and seventy-four specimens available in the shear database resulting in SSR values less than unity (minimum SSR value of 0.965). The SSR values of both these specimens obtained using the shear strength equations specified in IS 1343-2012 [2] were more than unity only because the shear strengths of both these specimens were governed by the highly conservative IS 1343-2012 V_{max} criteria and did not result in the prediction of the correct failure mode. Thus, significant improvements in the shear strength predictions has been observed with the modified IS 1343-2012 shear strength equations.

The variation of SSR values of the specimens in the shear database with the strength of concrete (f_{ck}) and the shear reinforcement index ($\rho_y f_y$) of the specimens has been studied for the IS 1343-2012 [2] and modified shear strength equations. The variation of SSR values of flexure-shear and web-shear critical specimens with both these parameters are shown in figure 7. The statistics of the SSR values obtained using IS 1343-2012 and modified shear strength equations (within parenthesis) for the flexure-shear and web-shear critical specimens are tabulated in tables 3 and 4, respectively.

The mean SSR values of the specimens obtained using IS 1343-2012 [2] shear strength equations increased from low strength (<30 MPa) to high strength of concrete (>100 MPa) as shown in tables 3 and 4. The mean SSR values of

Table 2. Statistics of IS 1343-2012 and Modified Shear Strength Equations.

Statistical Parameters	IS 1343-2012	Modified IS 1343-2012
Mean SSR	2.146	1.798
SD SSR	0.754	0.558
COV SSR	0.351	0.310
Maximum SSR	5.736	4.221
Minimum SSR	1.077	0.965
	0	2

the web-shear critical specimens with high concrete strength is more than twice the mean SSR values of the web-shear critical specimens with low concrete strength. This is primarily because IS 1343-2012 [2] un-cracked shear strength equations assume very conservative split tensile values and are based on old test data. The mean SSR values obtained with the updated split tensile strength values in the modified IS 1343-2012 shear strength equations do not change significantly with the concrete strength for the flexure-shear critical specimens (shown in figure 7a) and are slightly increased at higher strength of concrete (>100 MPa) in the case of web-shear critical specimens. The mean SSR values obtained with the modified IS 1343-2012 shear strength equations are almost constant for high strength concrete specimens (as shown in table 3) and improve significantly when compared with the SSR values obtained using the original specified shear strength equations in IS 1343-2012 [2] (as shown in table 3).

The mean SSR values of the flexure-shear and web-shear critical specimens obtained using the modified shear strength equations decreased from lower (<1 MPa) to higher (>6 MPa) shear reinforcement index values as shown in tables 3 and 4, respectively. However, the mean SSR values obtained using the IS 1343-2012 [2] shear design equations increase as the shear reinforcement index values increase. This is primarily due to the usage conservative values of the maximum shear strength of the specimens in IS 1343-2012 [2] shear strength equations which lowers the actual shear strength predictions of specimens with higher shear reinforcement index values and thereby lowers their SSR values. The improvement in the SSR values obtained with the modified IS 1343-2012 [2] shear

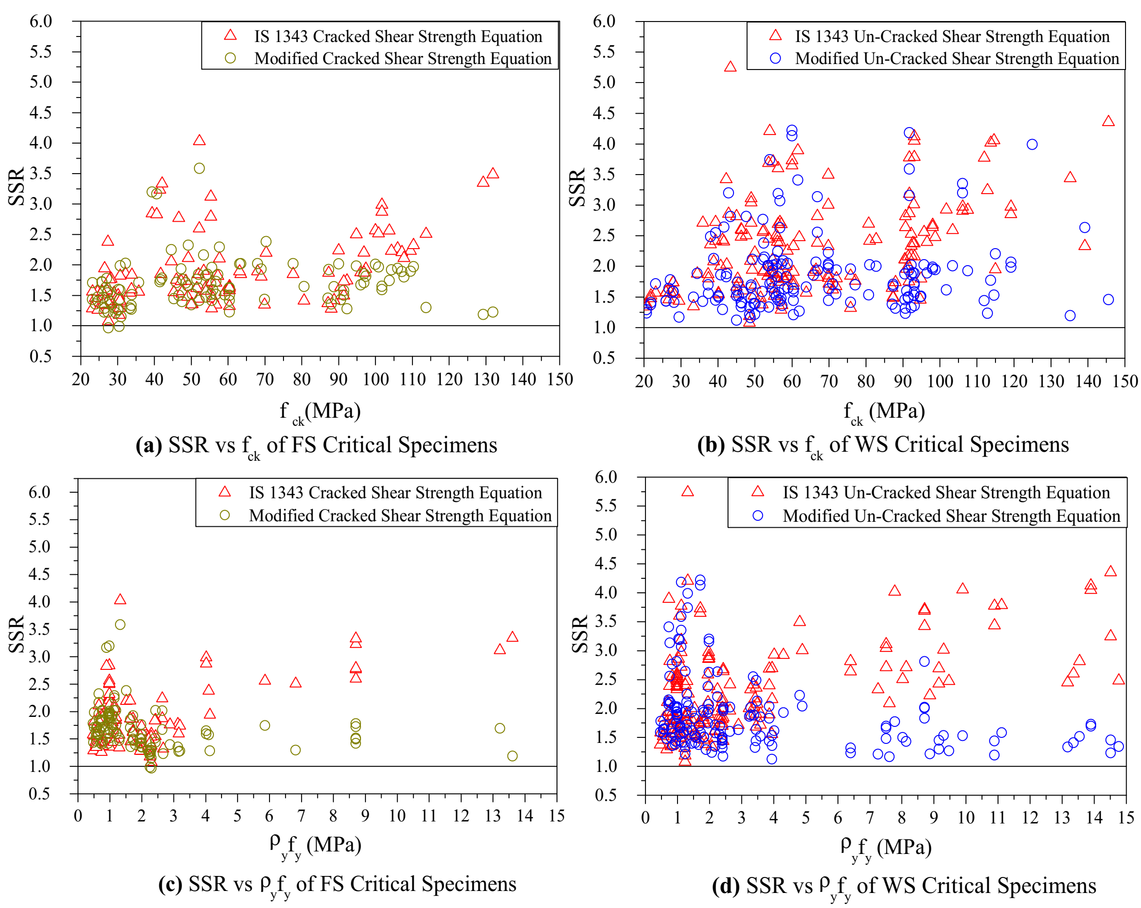

Figure 7. Variation of Shear Strength Ratio with Parametric Values.

Table 3. Statistics of IS 1343-2012 and Modified Shear Strength Equations for Flexure-Shear Critical Specimens.

	f_{ck} (MPa)				$\rho_y f_y$ (MPa)			
Statistics	<30	30–60	60–100	>100	<1	1–2	2–6	>6
Mean of SSR	1.54 (1.45)	1.86 (1.73)	1.75 (1.71)	2.59 (1.72)	1.81 (1.83)	1.73 (1.75)	1.75 (1.39)	3.02 (1.48)
SD of SSR	0.28 (0.20)	0.61 (0.49)	0.30 (0.28)	0.42 (0.28)	0.42 (0.36)	0.48 (0.43)	0.48 (0.26)	0.34 (0.21)
COV of SSR	0.18 (0.14)	0.33 (0.28)	0.17 (0.16)	0.16 (0.16)	0.23 (0.20)	0.27 (0.24)	0.27 (0.19)	0.11 (0.14)
Maximum	2.38 (1.78)	4.03 (3.59)	2.50 (2.38)	3.48 (2.01)	2.84 (3.20)	4.03 (3.59)	2.99 (2.02)	3.48 (1.78)
Minimum	1.08 (0.97)	1.18 (0.99)	1.28 (1.23)	2.11 (1.19)	1.26 (1.40)	1.28 (1.35)	1.08 (0.97)	2.51 (1.19)
SSR < 1	0 (1)	0 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (2)	0 (0)

Table 4. Statistics of IS 1343-2012 and Modified Shear Strength Equations for Web-Shear Critical Specimens.

	f_{ck} (MPa)				$\rho_y f_y$ (MPa)			
Statistics	<30	30–60	60–100	>100	<1	1–2	2–6	>6
Mean of SSR	1.53 (1.47)	2.23 (1.85)	2.37 (1.94)	3.32 (2.10)	2.02 (1.95)	2.23 (2.19)	2.10 (1.74)	3.13 (1.52)
SD of SSR	0.11 (0.18)	0.72 (0.54)	0.71 (0.70)	0.88 (0.78)	0.53 (0.46)	0.91 (0.87)	0.47 (0.36)	0.73 (0.32)
COV of SSR	0.07 (0.12)	0.32 (0.29)	0.30 (0.36)	0.27 (0.37)	0.26 (0.24)	0.41 (0.40)	0.22 (0.21)	0.23 (0.21)
Maximum	1.74 (1.78)	5.24 (3.74)	4.13 (4.22)	5.74 (3.99)	3.89 (3.41)	5.74 (4.22)	3.50 (2.63)	5.24 (2.81)
Minimum	1.34 (1.17)	1.08 (1.12)	1.32 (1.21)	1.95 (1.19)	1.29 (1.36)	1.08 (1.21)	1.34 (1.12)	2.09 (1.16)
SSR < 1	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

strength equations, as discussed above, can be observed in figure 7c and d.

The ranges of concrete strength and shear reinforcement index values of the two flexure-shear critical specimens having SSR values lower than unity (SSR < 1) due to the higher shear strengths of these specimens predicted by the modified shear strength equations, are shown in the last row of table 3. The over-estimation of shear strengths of two out of two hundred and seventy-four specimens is statistically insignificant and can therefore be ignored to achieve the significant improvements in the shear strength predictions observed with the modified shear strength equations.

6. Summary and Conclusions

Shear design provisions of IS 1343-2012 [2] which are based on old test data have been reviewed in the present study and the various assumptions used in the formulations of the web-shear and the flexure-shear strength equations have been discussed. The conclusions drawn from the present study are as follows:

- IS 1343-2012 [2] V_{max} is too conservative and lowers the estimated values of un-cracked and cracked shear strengths of PC members. Thus, the IS 1343-2012 [2] V_{max} criteria governs the predicted shear strengths of most of the web-shear and flexure-shear critical specimens available in the shear database. If the IS 1343-2012 [2] V_{max} criteria is ignored, then most of the web-shear and flexure-shear critical specimens are governed by the un-cracked shear strength equation.
- The split tensile strength of concrete used for estimating the web-shear strength of PC members in IS 1343-2012 [2] is very conservative. ACI 318-14 [13] provides a more accurate estimate of actual split tensile strength values than IS 1343-2012 [2].
- A modification factor of 0.8 for the cracked shear strength equation and the ACI 318-14 recommended split tensile strength of concrete for the un-cracked shear strength equation of IS 1343-2012 [2] have been proposed along with the maximum shear strength equation recommended by the UH method [16]. The shear strength of the maximum number of flexure-shear and web-shear critical specimens are governed by the cracked and un-cracked shear strength equations of concrete respectively with the modified IS 1343-2012 shear strength equations.
- The modified IS 1343-2012 shear strength equations result in lower mean, SD, COV of SSR values of two hundred and seventy-four PC specimens in comparison to the IS 1343-2012 shear design equations. Thus, an improvement in the shear strength predictions can be observed with the case of modified IS 1343-2012 shear strength equations.
- The updated split tensile strength values in the modified IS 1343-2012 shear strength equations result in better strength prediction of the flexure-shear critical as well as web-shear critical specimens at higher strength of concrete.

- The modified IS 1343-2012 shear strength equations with UH maximum shear strength equation improves the strength predictions of PC specimens with higher reinforcement index values.

Nomenclature

ζ_c	design shear stress as per IS 1343-2012
ρ_y	stirrup steel reinforcement ratio
a/d	shear span-to-depth ratio
b, b_w	width of the web
d	effective depth
D	total depth of the section
I	moment of inertia of the section
Q	first moment of area
M_o	moment required to produce zero stress in concrete as per IS 1343-2012
M_{cr}	cracking moment
V_{ur}	ultimate shear resistance
V_c	ultimate shear resistance of concrete
V_{co}	un-cracked concrete contribution to shear resistance as per IS 1343-2012
V_{cr}	cracked concrete contribution to shear resistance as per IS 1343-2012
$V_{cr\_ACI318-63}$	cracked concrete contribution to shear resistance as per ACI 318-63
V_{exp}	experimental shear failure load
V_{s-FOS}	ultimate shear resistance of stirrup steel as per IS 1343-2012
$V_{UH,max}$	maximum shear strength as per UH Method
V_{max}	maximum shear strength as per IS 1343-2012
f_c	compressive cylinder strength of concrete
f_{ck}	compressive cube strength of concrete
f_t	maximum principal tensile stress as per IS 1343-2012
f_{cp}	compressive stress at the centroid of the section due to prestress
f_{pe}	effective prestress
f_p	characteristic strength of prestressing steel as per IS 1343-2012
f_y	yield strength of stirrup steel

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