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Research Article

Review of BS 8110, EC2, and the Improved EC2 shear resistance models for stirrup in reinforced concrete beams

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Abstract

The majority of beams used in construction have shear reinforcement provision. However, there exists a disparity in the results of the shear capacity guaranteed by the available shear design provisions. This is so because of the complex nature of the reinforced concrete shear mechanism. This study compares the BS 8110, EC2, and the Improved EC2 shear resistance models to ascertain the differences in their predictive ability when compared to experimental results. The EC2 is the most conservative at low level of shear reinforcement, i.e., shear reinforcement $\rho_w f_{ywm} \leq 1.3\ MPa$, and at $\rho_w f_{ywm} \leq 2\ MPa$ for mean value and design value predictions respectively. From the parametric trendline chart, the Improved EC2 predicts a higher shear capacity for lightly reinforced concrete beams than the EC2 shear model. A demerit point of 76 and 187 obtained respectively for the mean and design shear capacities of the BS 8110 shows that it is the most reliable of the three models in predicting the shear strength of stirrup-reinforced concrete beams.

1. Introduction

Shear failure is an undesirable mode of failure in reinforced concrete and usually occurs with a devastating consequence [1-2]. It is therefore a structural requirement that whenever the value of design shear stress exceeds the permissible shear stress of concrete, shear reinforcement must be provided [3-4]. Owing to the complexities involved in shear transfer mechanisms and their contributing variableness, a general shear theory is evasive [5-9]. The available analytical models regarding shear strength provide results that are often different from experimental results [10-12]. Shear reinforcements, also called stirrups, are employed to modify the shear resistance of reinforced concrete beams, thus transiting from brittle to a more ductile mode of failure [13-15].

Shear reinforcement comes into play after the formation of cracks [4, 16] and has been identified to perform three primary functions, which are, to restrict the growth of diagonal cracks, improve shear resistance through aggregate interlock, and also to increase the dowel capacity of longitudinal reinforcement [17]. While accurate assessment of the shear capacity of reinforced concrete is critically important for public safety, the traditional techniques available for this task are open to dispute [18]. None of the rational models proposed to date completely satisfies the three fundamental requirements of force equilibrium, strain compatibility, and material laws simultaneously [19].

This paper compares the predictive capabilities of the Improved EC2, BS 8110-1, and the EC2 shear method at their respective mean and design values, and with the experimental observations through the use of trendlines, total demerit points, statistical and parametric analysis. Experimental observations are from a database of 160 test results compiled by [20] on slender beams with stirrup failure. The database consists of simply supported

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rectangular and flanged beams subjected to point loads that failed by diagonal tension and shear compression, and with a shear span to depth ratio (a/d) greater than 2.4. Details of the range of parameters captured in the experimental observations are summarized in Table 1.

Table 1. Range of parameters from 160 experimental observations presented by Olalusi [20]

Parameters	Minimum Value	Maximum Value
$b_w\ (mm)$	75	457
$d\ (mm)$	161	1369
$f_{cm}\ (MPa)$	13.40	125.30
$\rho_l\ (\%)$	0.14	5.20
$\rho_w\ f_{ywm}\ (MPa)$	0.28	9.80
a/d	2.40	7.10
$V_{exp}\ (KN)$	81	1330

2. Shear Capacity for Reinforced Concrete Beams

There are different design procedures for calculating the shear capacity of reinforced concrete beams with stirrups [21-22]. Some prescribed shear capacity as the sum of both concrete and stirrup contributions, while others are based solely on stirrup contributions. Several models have been developed for shear in RC members as a result of its intricate nature [7, 23]. Pertinent models upon which current design standards are based are the 45-degree Truss Model [24], the Variable Angle Truss Model (VSIM) [25], and the Modified Compression Field Theory (MCFT) [26, 27]. Although BS 8110-1 has been retracted in the UK and replaced by EC2, it is still used in Nigeria as a guide for the design of reinforced concrete [28].

The EC2, which is based on the variable strut inclination method, has been identified to suffer drawbacks when predicting the shear capacity of lightly reinforced concrete beams due to neglect of the concrete contribution which otherwise is considered significant at low a level of shear reinforcement [29-33]. This has prompted Domenico and Ricciardi [34] to develop a shear strength model considered as an upgrade to the EC2 truss model with two inclinations of the compression strut, i.e., the lower inclination θ_1 and upper inclination θ_2 to ameliorate the limitations identified in the EC2 model.

2. 1. BS 8110 Shear Design Provision

The BS 8110 adopts an empirical model for its concrete contribution while the steel contribution is based on the 45° truss model. The concrete contribution v_c and that of the stirrups v_s adds up as being the nominal shear stress v_n [MPa] of the reinforced concrete beam as obtainable from Eqs. (1)-(2):

$$v_n = v_c + v_s [\text{MPa}] \tag{1}$$

$$v_n = \frac{0.75}{\gamma_c}\left(\frac{f_{cu}}{25}\right)^{1/3}\left(\frac{100A_s}{b_w d}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4} b_w d + \frac{A_{sw} f_{yk} d}{\gamma_{ms} s} \quad [\text{MPa}] \tag{2}$$

where γ_c is the partial material safety factor for concrete ($\gamma_c = 1.25$); γ_s is the partial material safety factor for steel (γ_s=1.05); $100A_s/b_w d$ is the reinforcement ratio; $f_{yk}$is the yield strength of shear reinforcement; A_{sw} is the area of shear reinforcement; stirrup spacing $s \leq 0.75$; f_{cu} is the characteristic concrete cube strength expressed as $f_{cu} = 0.8 f_c$, where f_c is the cylindrical concrete strength.

2.2 EN 1992 Eurocode 2: 2004 Shear Design Provision

Unlike the BS 8110, the EC2 computes its shear capacity by adopting variable strut inclination θ while neglecting the concrete contribution. The Variable Strut Inclination Method (VSIM) upon which the EC2 is based allows the concrete compressive angle θ to be varied between 21.8 and 45 degrees in a truss model according to derivations from plasticity theory [35 -37] The ultimate shear capacity of the shear reinforcement $V_{Rd,s}$, the web-crushing shear capacity $V_{Rd,max}$, and the strut angle θ can be determined by Eqs. (3)-(5):

$$V_{Rd,s} = \frac{A_{sw}}{s} z \frac{f_{ywk}}{\gamma_s 1.15} \cot\theta \qquad \text{[KN]} \tag{3}$$

$$V_{Rd,\max} = \frac{\left(\frac{f_{ck}}{\gamma_c}\right) b_w z v_1 \alpha_{cw}}{(\cot\theta + \tan\theta)} \qquad \text{[KN]} \tag{4}$$

$$\theta = \sin^{-1}\sqrt{\frac{A_{sw}\left(\frac{f_{ywk}}{\gamma_s}\right)}{\alpha_{cw} b_w s v_1 \left(\frac{f_{ck}}{\gamma_c}\right)}} \qquad [\text{degrees } ^0] \tag{5}$$

where, A_{sw} is the cross-sectional area of the shear reinforcement, s is the stirrup spacing; f_{ck} and f_{ywk} are the characteristic values of the concrete compressive stenght respectively; internal lever arm is taken as $z = 0.9d$; v_1 may be taken to be $0.6\left(1 - \frac{f_{ck}}{250}\right)$; γ_c and γ_s are the partial material safety factor for concrete and steel; EC2 recommends the value of $\gamma_c = 1.5$ and$\gamma_s = 1.15$. The minimum shear reinforcement is as given in Eq. (6):

$$\rho_{w,\min} = 0.08\frac{\sqrt{f_{ck}}}{f_{ywk}} \qquad \text{[MPa]} \tag{6}$$

2.3 Improved Eurocode 2 Truss Model with Variable Inclination Struts

Domenico and Ricciardi [34] present a shear strength model which can be considered as an upgrade to the EC2 shear stress model. Though the underlying theoretical framework for the two models is similar, the Improved EC2 adopts two (rather than one) representative strut inclinations called θ_1 (lower inclination) and θ_2 (upper inclination), to capture the differences in the shear state along the web height of the beam as show in Fig. 1.

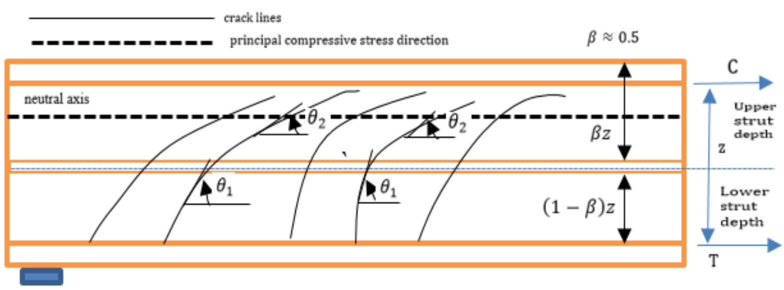

Fig 1. A rectangular beam showing the inclination angles Θ1 and Θ2 and transition depth z

By adopting a transition depth, $\beta = 1/2$, the closed-form expressions presented in Table 2 are easily adaptable for shear strength calculations for practical design and verification purposes and with less computational effort. For the Improved EC2 analysis, the efficiency factor $v_1 = 0.6(1 - f_{cm}/250)$, the mechanical ratio of the transverse reinforcement $w_w = \rho_w(f_{ywd}/f_{ywd})$, and the normalization parameters, $r = b_w z v_1 f_{cd}$ [in (N) units) are first computed. The calculated value of w_w is then checked against the limitations specified in Table 2. v_{Rd} is thus calculated based on the design region identified with the value of w_w. The shear strength of the beam, V_{Rd} [in (KN) units], is therefore obtained by multiplying the dimensionless strength of v_{Rd} computed with the normalization parameter r, $V_{Rd} = v_{Rd} r$

Table 2**.** Improved EC2 design regions and compression struts inclination by Domenico and Ricciardi [34]

Design region	ω_ω limitations	$cot\theta_1$	$cot\theta_2$	v_{Rd}
1	$0 \leq \omega_\omega \leq \omega_{\omega 1}$	$(cot\theta_1)_{max} = 2.5$	$(cot\theta_2)_{max} = 5$	$3.75\omega_\omega$
2	$\omega_{\omega 1} \leq \omega_\omega \leq \omega_{\omega 2}$	$\frac{5 + \sqrt{25 + 104\omega_\omega - 270}}{52\omega_\omega}$	$(cot\theta_2)_{max} = 5$	$\frac{5 + 260\omega_\omega + \sqrt{25 + 104\omega_\omega - 270\omega_\omega^2}}{104}$
3	$\omega_{\omega 2} \leq \omega_\omega \leq \omega_{\omega 3}$	$cot\theta_1{}^{opt} = \frac{\eta(\omega_\omega)}{2\sqrt{2\omega_\omega}}$	$cot\theta_2{}^{opt} = \frac{4\omega_\omega\sqrt{1+8\omega_\omega} + \sqrt{2\eta(\omega_\omega)}}{2\sqrt{2\omega_\omega}}$	$v_{Rd}{}^{opt} = \frac{\sqrt{2\eta(\omega_\omega)(1 + 8\omega_\omega - k(\omega_\omega) + 16\omega_\omega{}^2\sqrt{1+8\omega}}}{8(1 + 4\omega_\omega - k(\omega_\omega))}$
4	$\omega_{\omega 3} \leq \omega_\omega \leq \omega_{\omega,max}$	$cot\tilde{\theta}^{EC2} = \sqrt{\frac{1-\omega_\omega}{\omega_\omega}}$	$cot\tilde{\theta}^{EC2} = \sqrt{\frac{1-\omega_\omega}{\omega_\omega}}$	$v_{Rd}{}^{EC2} = \sqrt{\omega_\omega(1-\omega_\omega)}$
5	$\omega_{\omega,max} \leq \omega_\omega$	$cot\tilde{\theta}^{EC2} = 1$	$cot\tilde{\theta}^{EC2} = 1$	$v_{Rd}{}^{EC2}$

$where$: $\omega_{\omega 1} = 0.0716$; $\omega_{\omega 2} = 0.1136$; $\omega_{\omega 3} = 0.25$; $\omega_{\omega,max} = 0.5$;

$k(\omega_\omega) = \sqrt{1 + 8\omega_\omega - 16\omega_\omega{}^2 - 128\omega_\omega{}^3}$; $\eta(\omega_\omega) = \sqrt{1 + 4\omega_\omega - 8\omega_\omega{}^2 - k(\omega_\omega)}$

2.3 Design and Mean Shear Capacity

Design values are obtained by incorporating the characteristics material strength (f_{ck} and f_{ywk}) and the partial safety factor of concrete (γ_c) and steel (γ_s) into the expressions of the shear resistance model equations thus introducing a conservative bias into the design model [30]. The best estimate model/mean value predictions are obtained by neglecting all safety bias when calculating the shear resistance. For the mean value prediction, the characteristics material strengths f_{ck} and f_{ywk} are expressed at their mean values f_{cm} and f_{ywm} and partial safety factors γ_c and γ_s are equated to unity. The mean concrete strength as recommended by EN 1992-1-1 and the steel yield strength as recommended by Holicky [38] are given by Eqs. (7)-(8):

$$f_{cm} = f_{ck} + 8 \quad [\text{MPa}] \tag{7}$$

$$f_{ywm} = f_{ywk} + 2\sigma_{fyw} \quad [\text{MPa}] \tag{8}$$

where, $\sigma_{fyw} = 0.1 f_{fywm}$ and $2\sigma_{fyw}$ is the standard deviation of steel yield strength stipulated by practice standard in Europe.

3. Results and Discussions

3.1 Comparison of the Trendline of Normalized Experimental Observations to Design Value Predictions of the Improved EC2 Model and the Codified EC2 and BS 8110 Standards

The trend line of the normalized experimental shear stress observations was compared to that of the EC2, BS 8110, and the Improved EC2 design shear stress capacity predictions (V/bd) as shown in Figure 2 at varied amount of shear reinforcement $(\rho_w f_{ywm})$. Judging from the plot, the BS 8110 trendline depicts a consistent relative increase of shear stress over the parametric range of shear reinforcement $(\rho_w f_{ywm})$ under consideration; while the trend line pattern of both the Improved EC2 and EC2 does not depict similar consistent level of appreciable increase over the entire parametric range of $(\rho_w f_{ywm})$ increases. At a range of $\rho_w f_{ywm} \leq 2$, EC2 has the most conservative trendline of all the models considered. At $\rho_w f_{ywm} > 0.3$, the Improved EC2 has the least conservative trendline which shows an approximate closeness to the experimental observations. Based on the premise that the Improved EC2 is based on the same theoretical principles as EC2 capacity predictions, the trendlines for these models possess similar curvilinear pattern.

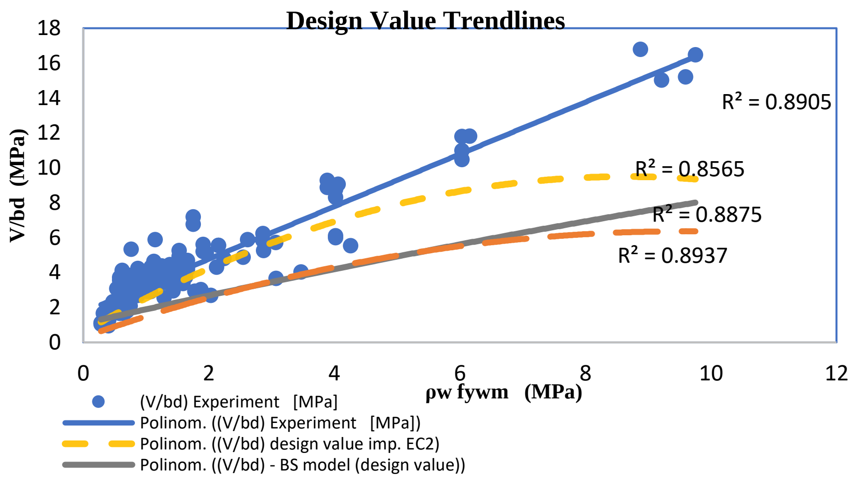

Fig. 2 Experimental and Predicted Design Value Shear Strength by Improved EC2, EC2 and BS 8110

3.2 Comparison of the trendline of normalized experimental observations to the mean value predictions of the Improved EC2 model and the codified EC2 and BS 8110 standards

The trend line of the normalized experimental shear stress observations was compared to that of the EC2, BS 8110 and the Improved EC2 mean value prediction (V/bd) as shown in Figure 3. The mean shear capacity predictions of EC2 below shear reinforcement range of 1.2 Mpa i.e $\rho_w f_{ywm} \leq 1.2\ Mpa$, is the most conservative. Above this, its trendline maintains a curvilinear pattern which though conservative, approximates the trendline of the experimental observations at $\rho_w f_{ywm} \leq 6\ Mpa$. The trendline of the improved EC2 mean predictions becomes unconservative at a parametric range of $1.1 \geq \rho_w f_{ywm} \leq 5.5\ Mpa$. The Improved EC2 thus over-predicts the shear capacity at the stated parametric range. The BS 8110 code mean predictions maintain a conservative trendline over the entire range of $\rho_w f_{ywm}$ observed.

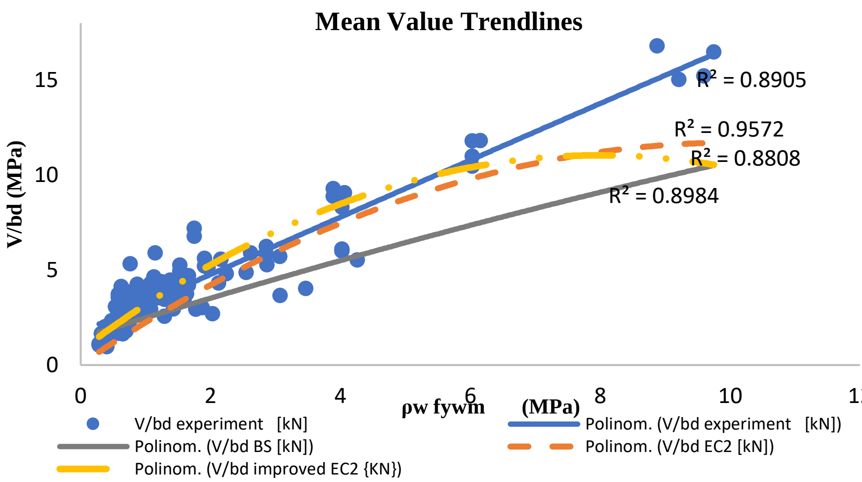

Fig. 3 Experimental and Predicted Design Value Shear Strength by Improved EC2, EC2 and BS 8110

3.3 Comparison of the Design value shear strength predictions and the mean value shear strength predictions

The design value shear strength predictions as captured in Figure 2 depicts a general conservative trendlines with the Improved EC2 as its least conservative model prediction at a range of $\rho_w f_{ywm} \geq 0.3\ Mpa$. The mean value predictions in Figure 3 depict a less conservative trendline for all the models considered with the Improved EC2 being unconservative at a parametric range of $1.1 \geq \rho_w f_{ywm} \leq 5.5 MPa$ when compared to the experimental trendline.

3.4 Total Demerit Point Analysis

Demerit point analysis introduced by Collins [39] for the performance assessment of shear strength methods assigns demerit points, within a specified range, to the ratio of experimental observations and predicted shear strength method under consideration $V_{\exp}/V_{pred}$ as given in Table 3.

Table 3. Demerit Points Classification [39]

S/N	Classification	$\left(\frac{V_{exp}}{V_{pred}}\right)$ Range	DP
1	Extremely dangerous	<0.5	10
2	Dangerous	0.50-0.65	5
3	Low safety	0.65-0.85	2
4	Appropriate safety	0.85-1.30	0
5	Conservative	1.3-2.00	1
6	Extremely conservative	>2.0	2

The corresponding values are then summed as the Total Demerit Point (TDP). The TDP shows the overall performance of each shear strength method as shown in Fig 4. A smaller value of the TDP indicates the shear strength evaluation method to be more reliable in predicting the shear strength of reinforced concrete beams under this condition. More so, Improved EC2 maintains a low variability between its design and mean shear strength.

From Table 4, it can be observed that EC2 largely underpredicts shear capacity with the highest distribution of experimental to estimated shear capacity ($V_{\exp}/V_{pred}$) in the extremely conservative class both for its mean and design value predictions which is due to the conservation provided by the strut angle(θ).

Table 4. Demerit Points Classification [39]

Range	Classification	DP	BS 8110 Mean Value Points	BS 8110 Design Value Points	EC2 Mean Value Points	EC2 Design Value Points	Improved EC2 Mean Value Points	Improved EC2 Design Value Points
<0.5	Extremely dangerous	10	0	0	0	0	10	0
0.5-0.65	Dangerous	5	0	0	5	0	35	5
0.65-0.85	low safety	2	4	0	10	0	52	20
0.85-1.30	Appropriate safety	0	0	0	0	0	0	0
1.30-2.00	Conservative	1	66	99	78	40	35	76
>2.0	Extremely conservative	2	6	88	64	228	2	24
Total Demerit Points (TDP)			76	187	157	268	134	125

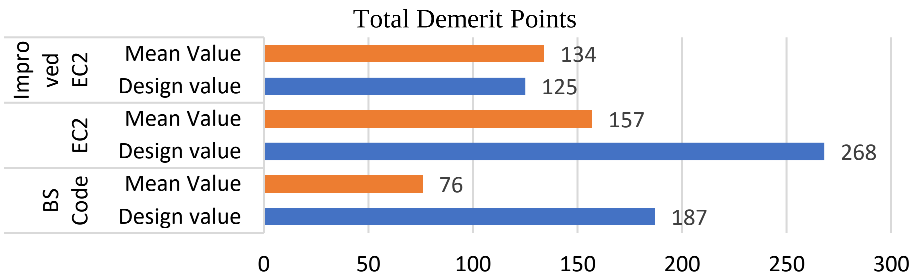

Fig. 4 Demerit point analysis

3.5 Statistical Properties

From Table 5, the sample mean of the improved EC2 has the lowest value at 1.10 and 1.30 respectively for both mean and design value predictions, followed be the BS 8110 at 1.34 and 1.77, then the EC2 at 1.58 and 2.34. The Improved EC2 thus performs best as the least conservative design method and with the lowest variability at 0.30 and 0.37 standard deviation for its best estimate and design value predictions respectively.

Table 5. Statistical Properties of BS 8110, EC2 and Imp. EC2

		Mean (μ)	Standard Deviation (σ)
BS 8110	Mean Value	1.3	0.32
	Design Value	1.77	0.43
EC2	Mean Value	1.5	0.47
	Design Value	2.34	0.65
Imp. EC2	Mean Value	1.10	0.30
	Design Value	1.36	0.37

3.5 Parametric Variation

In a bid to further examine the influence of shear reinforcement, beam size and concrete strength as its concerns the models under consideration, parametric analysis was conducted across practical ranges of the aforementioned parameters. A lot of the mean, and the design shear value of a given test section will be varied across the percentage shear reinforcement $\rho_w f_{ywm}$ as depicted in Figs. (5) to (8).

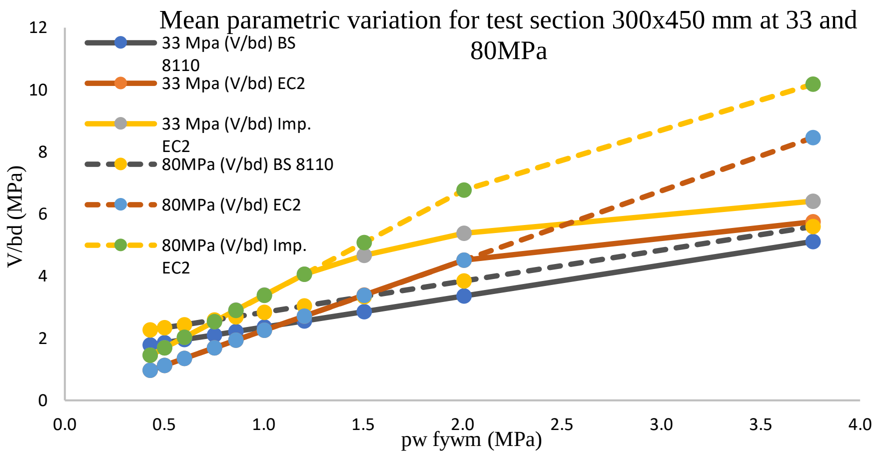

Fig. 5 Mean value parametric variation:300x450mm at $fcm = 33\ and\ 80MPa$

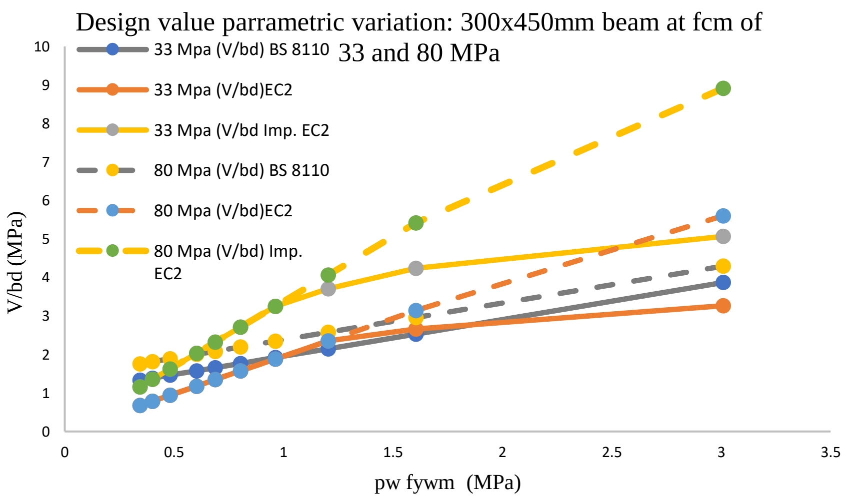

Fig. 6 Design value parametric variation:300x450mm at $fcm = 33\ and\ 80MPa$

The test beam for the parametric analysis in Figure 4 and 5 had the following section properties: $b_w = 300mm$, $d = 450mm$, $f_{ywm} = 460MPa$, $a/d = 2.5$, $\rho_l = 3.5\%$, $f_{cm} = 33\ and\ 80MPa$ respectively. The test beam for Figure 6 and 7 had the following properties: $b_w = 600mm$, $d = 900mm$, $f_{ywm} = 460MPa$, $a/d = 2.5$, $\rho_l = 3.5\%$, $f_{cm} = 33\ and\ 80MPa$ respectively. Observations from the mean value plot in Figure 4 shows that the trendlines of the EC2 and the Improved EC2 model were not affected by the concrete strength (33 and 80MPa) at $\rho_w f_{ywm} \leq 2MPa$ and $\rho_w f_{ywm} \leq 1.2MPa$ respectively above which noticeable variation is observed as the amount of shear reinforcement increases. For the design plot in Figure 5, the EC2 and the Improved EC2 remained unaffected by the varied concrete strength at a low shear reinforcement $\rho_w f_{ywm} \leq 1.2MPa$ and $\rho_w f_{ywm} \leq 0.9MPa$

respectively. The BS 8110 maintains an appreciable increase over the entire range of shear reinforcement both for the mean and design value plots at f_{cm} of 33 and 80 MPa without sudden slope change.

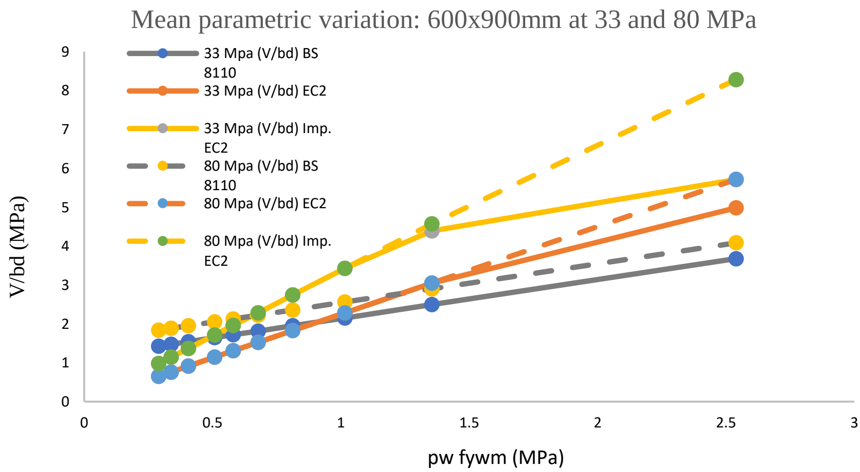

Fig. 7 Mean value parametric variation: 600x900mm at $fcm = 33\ and\ 80MPa$

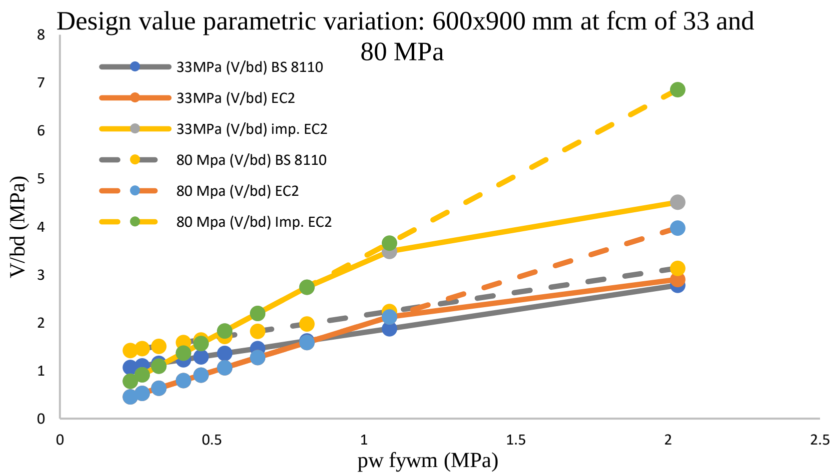

Fig. 8 Design value parametric variation: 600x900mm at fcm=33 and 80MPa

Observations from the mean value plot in Figure 6 shows that at $\rho_w f_{ywm} \leq 0.3MPa$ and $\rho_w f_{ywm} \leq 1MPa$ the trendlines is unaffected by the variations in concrete strength at 33 and 80 MPa respectively. For the design plot in Figure 7, the trendlines for the EC2 at $\rho_w f_{ywm} \leq 1.1MPa$ and the Improved EC2 at $\rho_w f_{ywm} \leq 0.8MPa$ remained unaffected by the changes in the concrete shear strength (33 and 80 MPa), and above these shear reinforcement values, concrete strength had a tolerable influence on their respective trendlines as the amount of shear reinforcement increases.

5. Conclusions

This study compares the Improved Eurocode 2 truss model having two variable inclination compression struts with Eurocode 2 and BS 8110 shear capacity prediction methods for reinforced concrete beams with stirrups. From the trendline analysis conducted in this study, the design value trendline for Improved EC2 is the least conservative which best approximates the experimental observation. The mean value prediction for the Improved EC2 between the ranges of $1.1 \geq \rho_w f_{ywm} \leq 5.5\ MPa$ is largely unconservative with shear capacity predictions exceeding experimental observations.

From the Total demerit point analysis, the Improved EC2 has the least variability between its mean and design value at 134 and 125 respectively. Though the BS 8110 gave the least mean value demerit point of 76, its design value demerit point of 187 is higher than that obtained for the Improved EC2 at 125. From the statistical analysis, the Improved EC2 had the lowest sample mean both for its design and mean value predictions when compared to the EC2 and BS 8110 shear strength methods. Also, it has the least variability of 0.30 and 0.37 standard deviation for its mean and design value predictions respectively.

From the parametric analysis, the trendlines of BS 8110 maintain an appreciable increase over the entire range of shear reinforcement both for the mean and design value plots of the two test beams under consideration without a sudden slope change. The trendline of the EC2 and the Improved EC2 follow almost the same pattern. This further confirms the underlying assumption that the two models were based on the same theoretical framework. The Improved EC2 predicts higher shear stresses than the EC2 model over the parametric range of the shear reinforcement considered on the plots. The Improved EC2 might lead to considerable savings in the amount of shear reinforcement consumed in construction works, especially for lightly reinforced concrete where the EC2 shows weakness.

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