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AGGREGATE INDEX: A MEASURE FOR CALIBRATING SHEAR STRENGTH MODELS FOR DIRECT APPLICATION TO SELF-CONSOLIDATING CONCRETE BEAMS

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ABSTRACT

Existing code provisions for shear strength prediction of self-compacting concrete (SCC) beams have often fallen short of its degree of predictability in relation to experimental responses. The research study seeks to develop a model that better predicts the shear capacity of self-compacted concrete beams without shear reinforcement. In addition, the critical parameters that influence the shear strength of an SCC beam were also investigated by using varying regression techniques (Linear, Stepwise, Lasso, Ridge and Elastic Net regressions). A pooled database having a total of 179 SCC beams without shear reinforcement was compiled for the analysis. The Lasso regression was the most effective from statistical analysis having the least relative and mean squared errors. In comparison with existing codes: ACI 318-08, AASHTOLRFD Bridge Design Specification-2007, Eurocode 2 and BS8110, the Lasso model performed better with least mean percentage error (12.23%), least average safety factor (1.1012) and the least coefficient of variation (0.159). The Lasso model also showed that compressive strength, height, breadth, depth of beam, shear span to depth ratio, longitudinal reinforcement ratio, maximum aggregate size and fine to coarse aggregate ratio were all relevant parameters in shear strength prediction of SCC beams without stirrups.

Keywords: RC beams, self-compacting concrete beams, shear strength, lasso regression and error measures.

INTRODUCTION

A major performance measure in the construction of concrete structures is durability. Several site-specific constraints may warrant the improvisation and use of approaches and technologies for producing durable concrete structures. In addition, the behaviour of other non-conventional and fairly sustainable materials for concrete structures have been exploited over the past few decades ([26], [28], [30], [32-34]). One such concrete technology that originated from the lack of workers skilled in concrete consolidation ([8], [23-25], [29] and [31]), has been Self-Consolidating Concrete. The advent of self-consolidating concrete (SCC) has facilitated the placement of concrete in congested member and restricted areas without the need for vibrational energy ([1], [4], [6], [14], [16] and [17]). This has been made possible due to its composition, which has allowed its high deformability without segregation or bleeding [13]. The fresh properties of an SCC mix are seen to be advantageous than those of conventional normal concrete [7], and as such, notable and special applications of SCC include the production of precast bridge girders, lining of tunnels, and free-fall placement of concrete in columns of high rise buildings.

Nonetheless, its modified composition negatively impacts its hardened properties and consequently, its structural performance on a larger scale. The lack of information regarding its performance for various structural components has hindered its full acceptance by engineers and designers, and as noted by [7], it is imperative that SCC members meets all pre-assumptions for which structural design models of conventional normal concrete were developed.

Past research activities has identified the difficulty in predicting the shear capacity of RC beams, as a result of the epistemic uncertainties in their shear transfer mechanisms, particularly when cracks are initiated ([12] and [21]). In addition, the shear strength characterization of SCC beams is highly uncertain and quantitatively debatable. In comparison with convention normal concrete, some researchers have either reported a relatively lower ultimate shear strength ([20] and [22]), a higher ultimate shear strength [9] or insignificant difference in ultimate shear strength [5] for SCC. [2] emphasized that shear performance of SCC members highly depends on the approach employed in obtaining the SCC mix. There are thought to be three major approaches to developing an SCC mix; material-based, chemical-based and hybrid-based. Intuitively for material and hybrid-based approaches, where the proportion of coarse aggregate is reduced, there is an expect reduction in shear resistance since aggregate interlocking mechanism may be compromised [2]. This even becomes aggravated when rounder aggregates, which normally improves flowability, are used [10]. It is also generally accepted that aggregate interlocking mechanism is a major contributor to shear strength of concrete members without stirrups [21]. The mechanism entails the development of frictional forces when a concrete member is fractured, and thus provides resistance against slip. The resistance offered by the friction between the aggregates is highly dependent on the nature of the fracture surfaces. Most researches [10], [13] and [19]) have stressed that the formation of smooth cracked surfaces in SCC often accelerates its post-cracking shear failure load. Other defining metrics which may cause accelerated post-cracking failure includes the aggregate sizes of concrete matrix (relatively greater resistance to shear for larger sizes) and nature of crack opening (reduction in shear resistance as crack width/opening increases) [15]. Therefore, one may infer that for concrete specimens, which are characterized by smooth crack planes and thus accelerating the opening of cracks, are susceptible to unfavorable shear failure, particularly when the aggregate size of the concrete mix is relatively smaller. These are notable attributes of either material-based or hybrid SCC members due to the modified composition of its concrete matrix. Nevertheless, others [11] have purported that an improved interfacial transition zone for an SCC matrix, may outweigh the reduced aggregate interlocking mechanism which emanates from the presence of lower size coarse aggregate and the use of rounder aggregates.

Majority of experimental studies have attempted to independently quantify and evaluated the shear strength of SCC beams in comparison to normal vibrated concrete beams ([1], [8] and [15]). On the other hand, most of the existing shear strength predictive equations have been developed by aggregating a database of normal concrete beams ([3], [18], [27] and [21]). Nonetheless, it also becomes imperative to propose unified shear strength models for explicit applications to SCC members, particularly beams. The authors are unaware of any explicit shear strength model in literature for SCC beams without transverse reinforcements, and as such the main and primary focus of this paper is to propose one such model. The study envisions the combined effect of the reduced coarse aggregate content and size, and how they quantitatively affect the underlining shear transfer mechanisms. By employing a multivariate non-linear regression analysis, the proposed model ascertains the impact of other influential parameters on shear strength of SCC beams. Later, several metrics for assessing the performance of the proposed model are evaluated through a comparative analysis with experimental results. Calibration of shear provisions found in several design standards is then conducted, by correcting the bias in these deterministic models. Practically, many RC beams have transverse reinforcements. Even though the present study focuses on shear strength of SCC beam without transverse reinforcement, it is believed that accurate estimation of its shear strength,$V_c$is essential, since it pre-informs the designer as to whether there is the need to provide shear reinforcement or not, as stipulated by most shear design provisions.

DATA BASE

A pooled dataset of experimentally tested SCC beams reported in literature were assembled. Major parameters which typically influence the shear performance of beams were extracted for further analytic study. Several existing proposed shear strength models have employed a large database of normal concrete beams, typically above 400 test specimens ([3] and [18]). However, since SCC is a relatively new concrete technology, there is a limited number of experimental works available, and as such for this study a total of 101 beams were collected.

Influential parameters extracted from these works included compressive strength of concrete (f_c), effective depth (d), total beam height (h), longitudinal reinforcement ratio (ρ), shear-span-to-depth ratio (a/d), modular ratio (E_s/E_c) and a proxy for evaluating the effect of the reduction in coarse aggregate content and size, which is referred herein as Aggregate Index (I_a). Conceptually, Aggregate Index was defined as the product of a normalized maximum aggregate size, by the proportion of coarse aggregate present in an SCC mix, Equation. 1.

$$I_a = \frac{d_a}{12.5}\left(1 - \frac{f}{t}\right) \qquad (1)$$

where d_a is the maximum aggregate size in mm, which is normalized here by 12.5mm, a value recommended for most SCC mix. Also, f/t is the ratio of fine to total aggregate size. The proportion of coarse aggregate, $(1 - f/t)$can be viewed as a weighting function to normalized maximum aggregate of size$(d_a/12.5)$. There are several combinations of ,$(1 - f/t)$ and $(d_a/12.5)$ that will yield the same Ia. For instance, SCC mixes with a maximum aggregate size of 25mm and having a 50% of coarse aggregate, will yield an $I_a$of 1, which is also conceptually equivalent to an SCC mix made up of aggregate sizes of only 12.5mm aggregates. The effect of this parameter will be better understood when developing the shear strength model.

Considering the SCC beam members assembled, almost 50% had compressive strength lesser than 50MPa, with majority being the range of 60-70MPa as shown in Figure-1. Also, about 90% of the SCC beams had effective depth lesser than 600mm, with majority (70%) lesser than 200mm. This non-uniform distribution of influential parameter will intuitively affect the accuracy and reliability of the proposed shear strength model, and therefore this warrants the need to evaluate its performance in certain piece-wise ranges of the parameter set employed. Most of the SCC beams had longitudinal reinforcement the range of 1-2% (see Figure-1). For shear-span-to-depth ratio, almost half were approximately 2.5-3.0. The distribution of Aggregate Index (I_a) spanned 0.3-0.8, with about 33% being the range of 0.6-0.7 as shown in Figure-1.

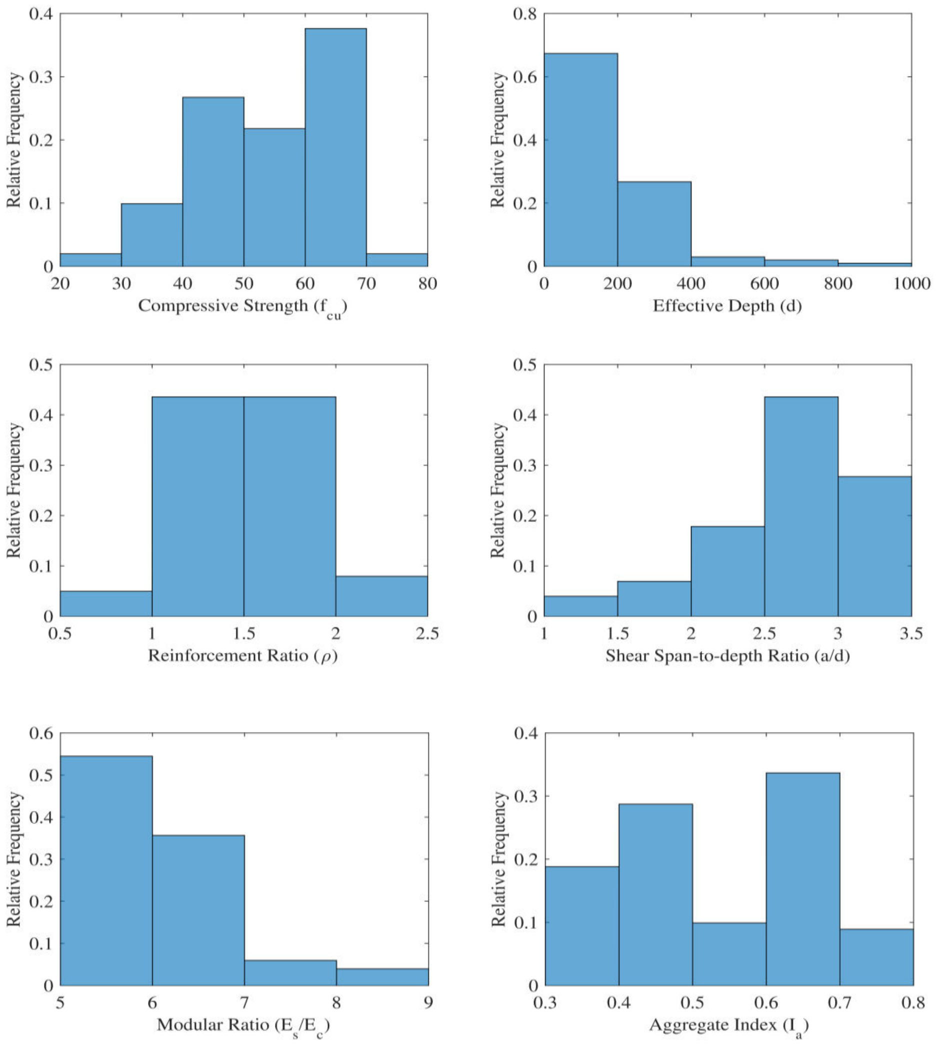

Figure-1. Distribution of parameters for SCC beams.

METHODOLOGY

A multi-variate nonlinear regression analysis is adopted in developing the proposed shear strength model. By employing seven influential parameters, a step-wise removal process was used to identify the major parameters that largely captures the variability in the response variables (shear capacity,V_c). Geometric and material properties of the beams were selected and modified (preferably normalized) in defining these parameters. The primary functional form of the proposed model is expressed in Equation 2.

$$V_C = \beta_O \left(\frac{b}{h}\right)^{\beta_1} \left(\frac{f_C}{\alpha d}\right)^{\beta_2} \left(\frac{d}{h}\right)^{\beta_3} I_a{}^{\beta_4} \left(\frac{a}{d}\right)^{\beta_5} \rho^{\beta_6} \left(\frac{E_s}{E_C}\right)^{\beta_7} \qquad (2)$$

Where$b$ is the beam's width; h is the beam's height; $f_c$is the compressive strength; is d the effective depth; $I_a$is the aggregate index; $f/t$is the fine-to-total aggregate ratio; $a/d$is the shear span-to-depth ratio; ρ is longitudinal reinforcement ratio; $E_s/E_c$is the modular ratio, andα is a normalizing constant. As seen in Equation 2, it becomes obvious that a log-transformation of all the predictor and response variables is required before conducting the multiple linear regression analysis. In identifying the key significant parameters, two statistical test metrics obtained from performing analysis of variance (ANOVA) test were utilized. These test statistics quantifies the relationship between the predictor variables and responses either individually or collectively, at a predefined significance level. The t-statistics individually assess the significance of a particular predictor variable to the response variable, whiles the F-statistics informs on the collective significance of a number of predictor variables, in accounting for the variability in the response variable. By using the notion of a p-value, a predictor variable is said to be significant when its p-value is lesser than the selected significance level. In this study, 0.05 significance level is selected in identifying significant parameters. Once the analyst obtains the final regression model, it becomes imperative to perform residual diagnostics in order to ascertain where the underlying assumptions of normality in the response variable and constant variance (homoscedacity) are satisfied.

Two predictor variables (longitudinal reinforcement (ρ) and beam width-to-depth ratio (b/h)) were found to be insignificant after performing the stepwise multivariate nonlinear regression analysis. The final functional form of the proposed parsimonious shear strength model is expressed as in Equation 3.

$$V_C = 1.96\left(\frac{f_c}{1000d}\right)^{-1.63}\left(\frac{E_s}{E_c}\right)^{-3.08}\left(\frac{a}{d}\right)^{0.29}\left(\frac{d}{h}\right)^{-5.14} I_a{}^{-0.96} \qquad (3)$$

Table-1 shows the individual model parameters (coefficients), t-statistics and obtained p-values of the log-transformed predictor variables employed in the regression analysis. Also reported are the intercept, root mean squared error, F-statistics and its corresponding p-value. Table-1 indicates that the first five predictor variables are significant since all p-values were all less than 0.05. In addition, the R-squared and adjusted R-squared were 0.91 and 0.9, and thus confirming the adequacy of the proposed shear strength model.

Table-1. Regression analysis results.

Predictor variables	Coefficient	t- statistic	p-value
$ln(f/1000d)$	-1.6305	23.963	0.000
$ln(E_s/E_c)$	-3.0849	10.51	0.000
$ln(I_a)$	-0.96095	8.0104	0.000
$ln(d/h)$	-5.1395	7.7346	0.000
$ln(a/d)$	0.28973	2.3874	0.019
$ln(b/h)$	0.21336	1.3269	0.187
$ln(\rho)$	0.10134	1.0727	0.286
Intercept = 0.67484	RMSE = 0.265	F = 181	5.97×10^{-47}

It is obvious from this analysis that the two eliminated predictor variables were of geometric quantities, and as such for SCC beams without stirrup, variables that are related to the mechanical behavior of concrete, such as compressive strength and maximum aggregate size (d_a), plays a much more dominant role in ensuring the transfer of shear stresses. This also suggests that simplified code-based shear strength model which excludes the effect of maximum aggregate size (d_a), particularly the American shear provision (ACI 318-R11), may seem inappropriate for quantifying the shear strength of SCC beams, as compared to other models.

Residual diagnostic of the multi-variate non-linear regression model was later performed in order to ascertain the aptness of the proposed model, as well as confirm whether all the necessary assumption underlining such an analysis were met. Figure-2 illustrates the scatter plot of the residuals against the major influential parameters as well as fitted values, all in logarithmic space (Figure-2 a-f). Also shown is the histogram of the residuals (Figure-3a) that suggests a nearly normal probability distribution. The normality assumption of the residual is further explored by constructing a z-score plot (Figure-3b) that includes a reference line for judging the assumption of normality. As seen, the residuals can be modelled as a normal distribution since only a few data points deviated from the reference line, hence satisfying the normality assumption of regression analysis. On the other hand, it is also expected that there exists a uniform variation of the residuals (homoscedacity assumption) with respect to the significant parameters and fitted responses. A visual inspection reveals no systematic patterns in these scatter plots, and as such the assumption of constant variance/homoscedacity is seen to be met. In conclusion the proposed shear strength model is fairly robust and satisfies the major and necessary assumption of regression analysis.

PERFORMANCE OF PROPOSED SHEAR STRENGTH MODEL

Six shear design provisions from various standards (ACI 318 R11, BS 8110-97, Eurocode 2-2004, CSA-A23.3-14, AS 3600-09 and IS 456-2000) were assembled in assessing the performance of the proposed shear strength model as against experimental observations, in a comparative analysis. The shear provisions for these design standards is tabulated in Table-2.

Metrics employed in the quantitative evaluation were the sum-of-squared error, coefficient of variation, as well as mean of the ratio of a particular model against observed shear strength for a specific test specimen. Table-3 presents these metrics, with a slight modification in the definition of the sum-of-squared error (SSE). In here, all SSE for the shear design provisions for the various standards are normalized by that of the developed shear strength model, and is later referred to as Norm SSE. This was necessary in order to quantify the extent of deviation of the shear strength estimates for the various standards as compared the proposed shear strength model.

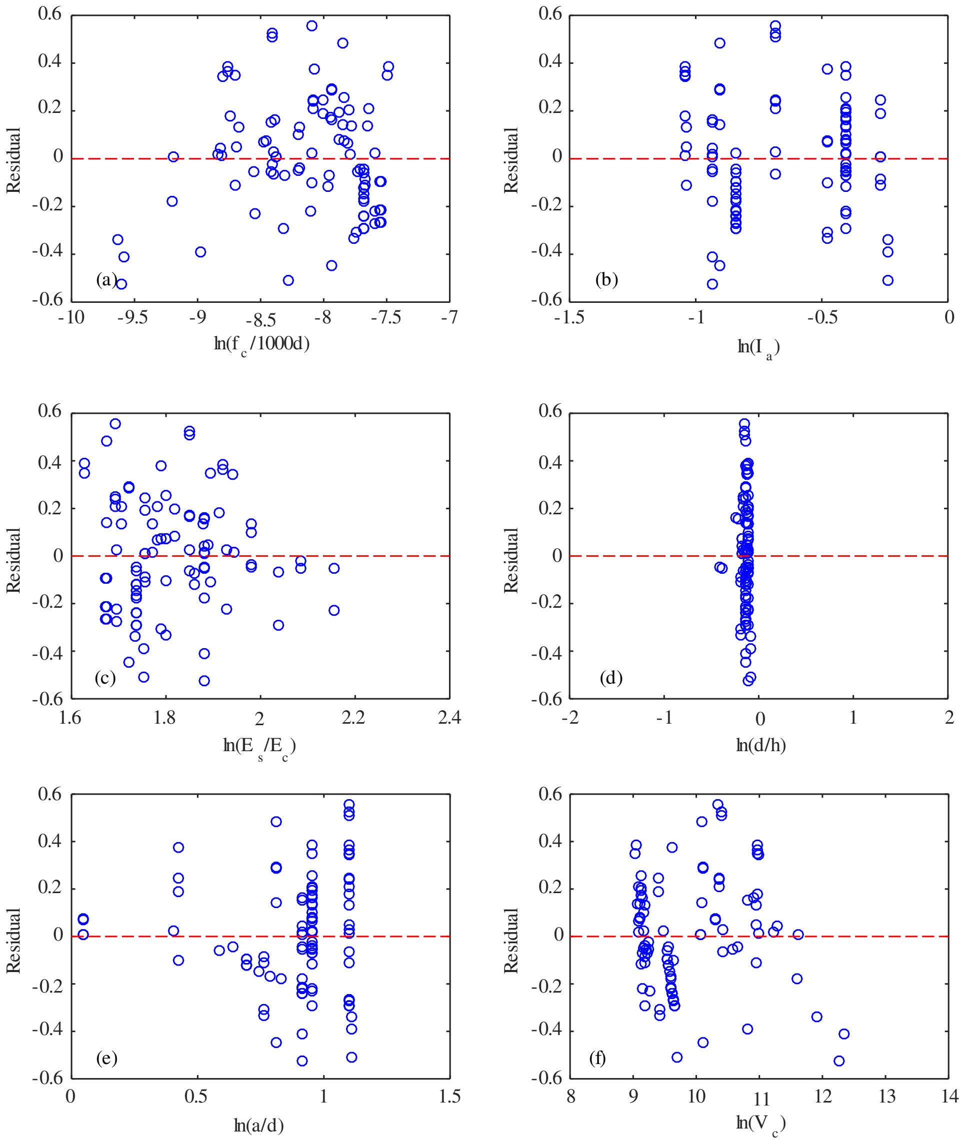

Figure-2. Diagnostic of residuals for proposed shear strength model.

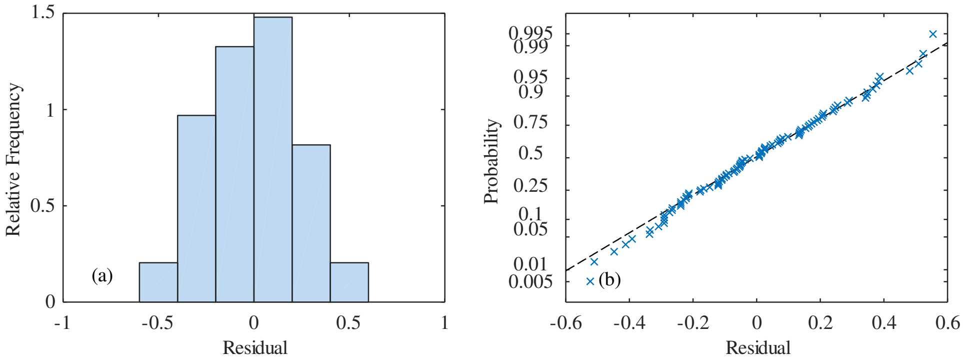

Figure-3. Probability plot of residuals.

Table-2. Base Design Shear Provisions.

Model	Mean
ACI 318 -R11	$0.167\sqrt{f_c}bd$
BS 8110-1997	$0.632\left({f_c}/{25}\right)^{1/3}\left({400}/{d}\right)^{1/4}\rho^{1/3}bd$
EU 2-2004	$0.12(\rho f_c)^{1/3}\left(1+\sqrt{{200}/{d}}\right)bd$
CSA	$0.26\sqrt{f_c}bd$
AS 3600-09	$1.1(\rho f_c)^{1/3}bd$
IS 456-2000	$0.67\sqrt{0.0576f_c+0.192{f_c}^{1.5}bd}$

Results revealed that the proposed model was generally conservative at predicting the shear strength of SCC beam, since the mean ratio was slightly less than 1. However, all design standards considered were un-conservative at predicting the shear strength of SCC beams. This finding was also corroborated by other researchers, having stressed that majority of these standards practically do not allow beam sections to go without transverse reinforcement unless the factored induced shear forces are extremely lower than the concrete shear strength. Nonetheless, due to the brittle nature associated with shear failure, it is imperative to have a lower bound value for the shear strength of reinforced concrete beams, particularly those without web reinforcement, so as to ensure conservatism. Also, one may argue that the modification in the physical composition of the concrete matrix of an SCC beam, may yield reduced shear strength values, and hence shear provisions from these standards having been formulated by assembling normal concrete beams, may be the cause of this un-conservativism.

As indicated in Table-3, British and European standards provided estimates which were fairly close to the proposed shear strength model in terms of mean ratios, coefficient of variation and normalized SSE. The other shear provisions performed poorly in terms of estimating shear strength. One physical reason for this observation may be attributed to the fact that the models for the British and European standards are similar, with same parameters ($f_c, b$and d) believed to influence shear, as well as the parameter coefficients.

Figure-4 is plotted in order to comprehensively assess the performances of the shear design provisions from the various standards, in relation to the proposed shear strength model and the experimentally observed strength. Firstly, the mean (solid line) and mean ±1 standard deviation (dashed lines) shear strength values of the proposed model for test specimens in the database are sorted in an ascending order. As expected the bounds of these values is supposed to cover almost 68% of the probability distribution of the experimentally observed strength. Later the prediction for a particular shear design provision as well as the observed strength are also arranged in ascending order and plotted as dots.

Table-3. Performance of Proposed Model with Respect to Shear Provisions of Design Codes.

Model	Mean	COV	Norm SSE
Proposed	1.013	0.2506	1.000
BS 8110-1997	1.254	0.299	1.341
EU 2-2004	1.179	0.302	1.255
ACI 318 -R11	1.380	0.318	5.470
CSA	2.153	0.318	21.361
AS 3600-09	5.179	0.321	211.256
IS 456-2000	6.686	0.326	343.575

In order to achieve an un-biased prediction, it is expected that the mean estimate of the proposed shear strength model, fairly matches the central tendencies of the experimental results. Graphically, there was an unbiased prediction for low to moderate shear strength values. Nonetheless, majority of the experimentally observed strength were successfully within the mean ±1 standard deviation of the proposed shear strength model. By contrast, all mean estimate from the shear design provisions were unbiased. ACI, CSA, AS and IS shear design provisions were un-conservative, since their plots were above the experimentally observed strength. However, with the exception of fewer cases, BS and EU models were quite conservative at representing the observed shear strength values. These observations suggest that these base shear design provisions be calibrated, by identifying parameters that are characteristic of SCC beams. In this study, the calibration procedure entailed the quantification of the parameters which were missing from the base shear provisions as documented.

CALIBRATION OF BASE SHEAR DESIGN PROVISIONS

In the following section, a calibration study of the six shear provisions of various standards is performed. It entails correcting the bias inherent in these base models, through a multivariate linear regression analysis in the logarithmic space (Equation 4).

$$lnV_0 - lnV_b = \beta_0 + \sum_{i=1}^{p}\beta_i X_i \tag{4}$$

where V_0 is the observed shear strength; V_b is the prediction from a particular shear design provision; Xi's are natural logarithms of predictors that are missing from a particular shear model, for instance the Aggregate Index; β_0 and β_i are regression coefficients. After performing this correction, the final function form of the calibrated model would typically be represented as in Equation 5.

$$V_c = e^{\beta_0} V_b \prod_{i=1}^{p} X_i^{\beta_1} \tag{5}$$

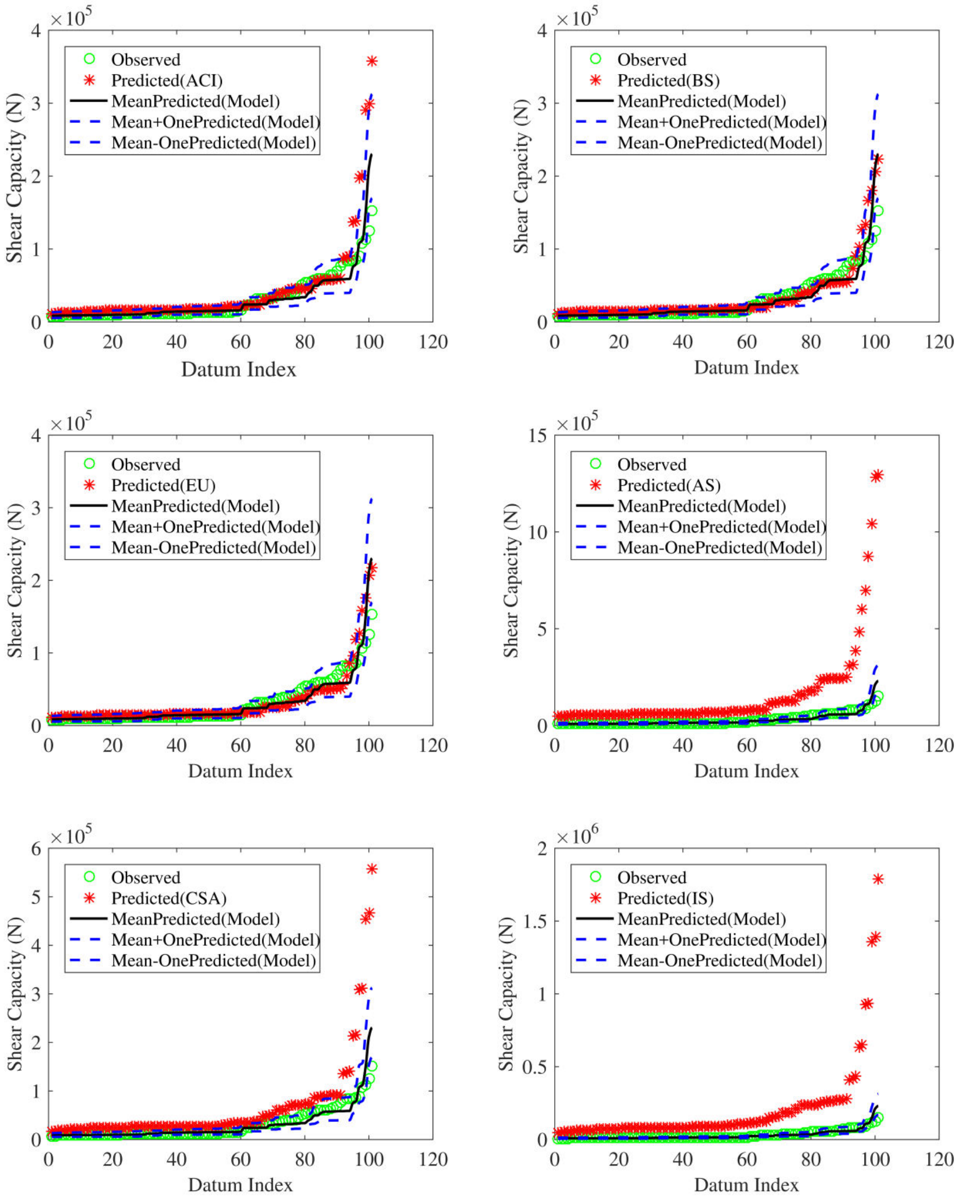

Figure-4. Performance of proposed shear strength model based on shear design provisions.

The calibration of these six models were performed, yielding mean results as tabulated in Table 4. As observed, the coefficient of I_a (β_1) was negative, which is in unison with that of the proposed shear strength model in Equation 2. This suggests a reduced shear strength when I_a increases. It is important to recognize that there are several combinations of maximum aggregate size (d_a) and proportion of coarse aggregate ($1 - f/t$) that will yield the same Aggregate Index. It is also imperative to specify some bounds on I_a that may yield valid shear strength estimates, which is given here as 0.3-0.8.

The calibration procedure resulted in significant improvement in mean estimates of the shear design provisions considered (Table-5), particularly for the Australian and Indian standards. One significant advantage of these calibrated shear models is the preservation of the design parameters for which most designers are familiar with, with the only inclusion being the Aggregate Index and modular ratio (for Indian standard). These calibrated shear models may yield similar estimates to that proposed in this study, and hence it is a matter of choice, as well as whether certain parameters are available and measurable. Nonetheless, the non-uniform distribution of Aggregate

Index (Figure-1) may intuitively affect estimated shear strength in certain ranges, and as such it is imperative to evaluate the uniform performance of these models with respect to Aggregate Index.

ASSESSING THE UNIFORM PERFORMANCE OF DEVELOPED SHEAR MODELS

Typically, there is a high risk of models performing poorly when non-uniform distribution of model parameters exists, particularly in ranges with fewer observations (Figure-1). In this study, the focus is on evaluating the uniform performance of Aggregate Index only, since it has been shown to significantly affect shear strength of SCC beams.

Table-4. Calibration Results of Shear Design Provisions.

Model	Mean
ACI 318 -R11	$0.087\sqrt{f_c}I_a^{-0.5736}bd$
BS 8110-1997	$0.341\left({}^{f_c}/_{25}\right)^{1/3}\left({}^{400}/_{d}\right)^{1/4}\rho^{1/3}I_a^{-0.6711}bd$
EU 2-2004	$0.069(\rho f_c)^{1/3}\left(1+\sqrt{{}^{200}/_{d}}\right)I_a^{-0.6722}bd$
CSA	$0.087\sqrt{f_c}I_a^{-0.5736}bd$
AS 3600-09	$0.152(\rho f_c)^{1/3}I_a^{-0.5888}bd$
IS	$0.02\sqrt{0.0576f_c + 0.192{f_c}^{1.5}}I_a^{-0.5850}(E_s/E_c)^{0.7026}bd$

Table-5. Improvement in Shear Design Provisions after Calibration.

Model	Mean (%)	COV (%)	NormSSE (%)
BS 8110-1997	16.872	10.247	25.469
EU 2-2004	11.496	9.982	10.923
ACI 318 -R11	24.430	7.342	54.835
CSA	51.558	7.342	88.435
AS 3600-09	79.822	6.470	98.652
IS	84.404	9.548	99.25

Intuitively, one would evaluate the distribution of errors for a particular shear model, in certain ranges of model parameters. This could be graphically illustrated through the use of boxplots. Three selected ranges of Aggregate Index, 0.3-0.4, 0.4-0.6 and 0.6-0.8 have been defined to represent low, medium and high Aggregate Indices respectively. By the notion of a boxplot, the scatter and bias for a given shear model relative to the observed strength can be ascertained. The 25%, 50% and 75% percentiles are enclosed in a rectangular box. The length of the vertical line of the box is used to assess the scatter of the error, whiles the location of the box relative to zero error line is used to evaluate the bias in a particular model. Similarly, the width of box has been weighted depending on the number of observations within a particular range. For instance, as seen in Figure-5, there are wider boxes for observations within the high and medium Aggregate Indices, compared to those with low I_a.

Consequently, the scatter in errors were greater for all developed models with low I_a (Figure-4). Also shown are box plots for the base shear design provisions (LB for lowI_a, MB for medium I_a, and HB for highI_a) with BS, ACI and EU base models yielding comparatively better estimates than the others standards. Moreover, the calibrated shear models resulted in significant improvement at reducing the scatter and bias in errors (LC for low I_a, MC for medium I_a and HC for high I_a), particular for the low I_a (Figure-5). One can therefore argue that such models have a fairly uniform performance with respect to Aggregate Index, successfully. However, the proposed shear strength model seems to provide the best level of uniform performance even for experimental observations with the lowI_a range. More so, there seems to be no bias for the proposed shear model at high I_a(Figure-5). In conclusion, the proposed shear strength model, as well as the calibrated ACI, EU and BS models, can be confidently used as shear predictive equations for explicit application to SCC beams.

CONCLUSIONS

The study developed a shear strength model for SCC concrete beams without transverse reinforcement by employing a multi-variate non-linear regression analysis on an extensive database of test specimens. Major influential parameters which affect shear strength were identified, and a new parameter referred in here as Aggregate Index was used to quantify the unconventional physical composition of an SCC concrete matrix. Later, six existing shear design provisions from various standards were assembled, and comparisons drawn between their estimates and that of the proposed shear model, relative the experimentally observed shear strength.

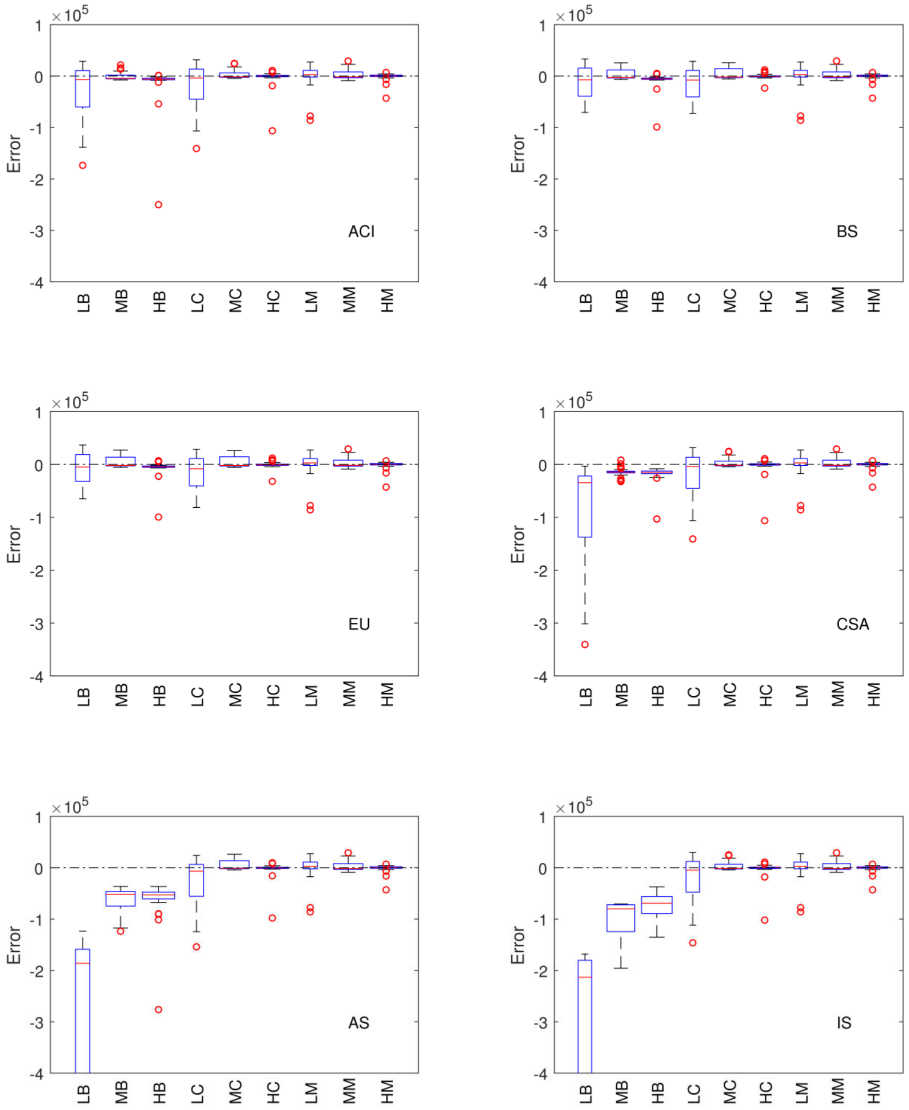

Figure-5. Boxplots for evaluating the uniform performance of calibrated models with respect of Aggregate Index.

These base shear design provisions showed significant scatter and bias at predicting the observed shear strength, and as such a calibration procedure was developed. The procedure corrected the bias in these deterministic shear models, by performing a univariate linear regression analysis on the log-transformed errors, with Aggregate Index as the prime predictor variable.

This resulted in significant improvement in mean estimates of the shear design provisions considered, particularly for the Australian and Indian standards. One significance advantage of these calibrated shear models is the preservation of the design parameters to which most designers are familiar with, with the only inclusion being the Aggregate Index and/or modular ratio. Models are highly susceptible to performing poorly when a non-uniform distribution of parameters are employed. Therefore, the uniform performance of the developed models with respect to Aggregate Index was conducted, which revealed that calibrated ACI, EU and BS models, as well as the developed shear strength models, can be confidently used as shear predictive equations for explicit application to SCC beams.

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