M5' Algorithm for Shear Strength Prediction of HSC Slender Beams without Web Reinforcement

Ali Kaveh, Seyyed Mahmoud Hamze-Ziabari, and Taha Bakhshpoori

***Abstract*—Accurate prediction of the shear behavior of Reinforced Concrete (RC) beams unlike to its flexural behavior which can generally be well predicted is a challenging problem due to the complexity of the shear transfer mechanism. This issue can be more critical for High-Strength Concrete (HSC) beams compared with the beams with normal strength concrete. The present study adopts an efficient rule based data mining approach: M5' algorithm to potential development of a new formulation for predicting the shear strength of HSC slender RC beams without stirrup. A comprehensive database containing several effective parameters that consider geometrical and mechanical properties of concrete, aggregate and reinforcement are involved in prediction of the shear strength. Comparison between developed model and the most common design codes demonstrates the superiority of the developed model in term of accuracy. Furthermore, the safety analysis based on Demerit Points Classification scale also confirms the reliability of the proposed formulation.**

***Index Terms*—High strength concrete, M5' algorithm, prediction shear strength, slender beams.**

I. Introduction

The high-strength concrete (HSC) has been emerged as an increasingly used efficient structural material in buildings and civil/structural infrastructures due to its physical and mechanical characteristics, structural efficiencies, and economic and aesthetic advantages. HSC can be defined as a concrete to have strength significantly beyond what is used in normal strength concrete (NSC). Different codes and researchers specify different limits for compressive strength of concrete for demarcation between NSC and HSC [1]. However, the definition by ACI 363R-10 [2] which considers the value of 40 MPa as the demarcation limit is followed here.

Shear carrying capacity of reinforced concrete members has been investigated experimentally and analytically by several researchers. It has been found that the shear failure mechanism in concrete members under bending which are reinforced longitudinally but have no transverse reinforcement, varies significantly and size of member and shear span to-depth ratio are two main parameters which influence the shear failure. Beams are divided to deep beams (<2.5) and slender beams (>2.5) on the basis of the shear span-to-depth ratio. Accurate prediction of the shear behavior of reinforced concrete (RC) beams unlike to their flexural behavior which can generally be well predicted, is a challenging problem due to the complexity of the shear transfer mechanism.

Based on the available literature [4]-[8] differences are obvious between NSC and HSC beams without web reinforcing. Shear strength prediction of HSC slender beams without web reinforcement is thus still contentious. Elsanadedy et al. [1] very recently applied regression models and neural networks for predicting the shear strength of HSC slender RC beams without stirrups. The main objective of this study is the prediction of shear carrying capacity of slender high strength concrete beams without transverse reinforcement. The M5' as one of the model trees algorithms is used for developing predictive and simple formulas for estimation of the maximum pull out force. Unlike most of the SC algorithms such as ANN and ANFIS, the M5' algorithm can present transparent formulas that are physically sound and interpretable. A comprehensive existing database including 250 experimental tests [1] from multiple sources in literature is employed here. Various influential parameters that affect the shear strength such as the longitudinal steel ratio, the shear span-to-depth ratio, compressive strength of concrete, the size of the beam specimens, and the size of coarse aggregate are considered. The accuracy and safety of predictions of the derived M5' model are compared to those of the existing shear strength relationships of the most common design codes. The comparison results showed that the proposed model is more accurate and reliable than other design codes. Furthermore, the robustness of the proposed models is confirmed through sensitivity and parametric analyses.

Remaining of the paper is organized as follows: the following section presents some limitations of current design codes. The M5' algorithm is outlined at the third section. After presenting the used database the fourth section develops the predictive models by using M5' algorithms. Penult section discusses the results based on the developed model and also makes a safety analyses to evaluate the reliability and uncertainty of the model. The last section summarizes the findings of this study.

II. Limitations and Design Codes

In the present study, the predictive capability of the most common design codes in prediction of shear strength of the HSC slender beams including ACI 318-11 [9], CSA A23.3-04 [10], fib Model Code [11], Eurocode-2 [12], CEB-FIP Model

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[13], AS 3600-2009 [14], JSCE Guidelines [15], and Cladera and Mari [16] are investigated. Table I summarizes the main design parameters included in the mentioned codes and also the statistical error parameters related to each code. 250 recorded cases for HSC beams existing in different sources in literature are used to evaluate the performances of these design codes. The average (μ), standard deviation (σ) and coefficient of variation (COV) of discrepancy ratio between predicted and measured values of the shear strength are presented in Table I. It is clear from this table that the performances of these equations for slender beams made of HSC are remarkably limited. This can be attributed to this fact that all the design equations consider a limitation value of 65 MPa for compressive strength of the concrete (f'_c) except CEB-FIP model.

In addition, some influential parameters such as the nominal maximum size of the coarse aggregate is not included in most of the design codes (except A23.3-04 [10] and level II approximation of the fib Model [11]). The dependency of the shear strength of the HSC beams to this parameter is investigated and confirmed by Muttoni [17]. On the other hand, the contribution of different predictive parameters such as compressive strength of concrete and longitudinal steel ratio is incorporated in a different way. For example, the contribution of f'_c in prediction of the shear strength is proportional to $f'^{1/3}_c$ in Eurocode-2, CEB-FIP Model, AS 3600, and JSCE while the other codes (ACI 318-11, CSA A23.3-04, fib model) consider this contribution as $f'^{1/2}_c$. This proportion was also reported as $f'^{0.2}_c$ by Cladera and Mari [15].

In general, it can be concluded from these observations that new predictive equations should be presented to take full advantage of the positive features of the RC beams made of the HSC. Furthermore, the predictive equation must consider all effective parameters in prediction of the shear strength.

TABLE I: DETAILS OF EXISTING DESIGNS EQUATIONS AND THEIR PERFORMANCES IN PREDICTING SHEAR STRENGTH OF SLENDER HSC BEAMS

Equations or models	Design parameters								Statistical parameters on $V_{measured}/V_{predicted}$		
	b	d	A	a_g	f'_c		ρ (%)		M	σ	COV
						Limitation		Limitation			
ACI 318-11	O	O	-	-	O	≤65 MPa	O	-	1.28	0.48	0.23
CSA A23.3-04	O	O	-	O	O	≤64 MPa	-	-	1.62	0.61	0.38
fib Model Code	O	O	-	O	O	≤64 MPa	-	-	1.59	0.60	0.36
Eurocode-2	O	O	-	-	O	≤90 MPa	O	≤0.02	1.09	0.35	0.12
CEB-FIP Model	O	O	O	-	O	-	O	-	1.24	0.29	0.08
AS 3600-2009	O	O	O	-	O	≤64 MPa	O	-	1.12	0.28	0.08
JSCE Guidelines	O	O	-	-	O	≤47 MPa	O	≤0.03	1.35	0.38	0.14
Cladera and Mari	O	O	-	-	O	≤60 MPa	O	≤$g(f'_c)$	1.27	0.31	0.10
M5′ (proposed)	O	O	O	O	O	-	O	-	1.01	0.16	0.03

III. M5' ALGORITHM

The important advantages of model trees (MTs) to other soft computational approaches can be considered as being more accurate than regression trees, more transparent and understandable than Artificial Neural Networks (ANN), easy to train, and robust when dealing with missing data [19]. Among the soft computing algorithms, M5' Model Tree is one of the newly developed algorithms that has not been widely applied in structural engineering. Very recently Kaveh et al. [18] utilized this algorithm for prediction of the principal ground-motion parameters in which the efficiency of M5' is demonstrated against many other algorithms. In the following M5' algorithm is outlined [18].

M5 model was developed by Quinlan [20] in 1992 and improved later in 1997 as a system called M5' by Wang and Witten [21]. M5 model trees are more accurate and understandable than regression trees and ANNs. It can handle large number of attributes and high dimensions [22].

The algorithm consists of three main steps: building tree, pruning the tree and smoothing. By using the splitting criterion, the basic tree is formed. This splitting criterion is defined as the standard deviation of the class values that reach a node as a measure of the error at the node, and calculates the expected reduction in error as a result of testing each attribute at the node. Then, the attribute that maximizes the expected error reduction is selected. The standard deviation reduction (SDR) for M5 is calculated using the following formula:

$$SDR = sd\left(T\right) - \sum_i \frac{|T_i|}{|T|} \times sd\left(T_i\right) \tag{1}$$

where T is the set of example that reach the node, T_i is resulted set from splitting the node according to the selected attribute and sd is the standard variation [21]. The splitting process ceases when the class values of all the instances that reach a node vary by less than 5% of the standard deviation of the original instance set, or when only a few instances remain.

An over-fitting problem can occur during the MT construction based on the training data. In order to reduce this problem, a method is termed "pruning" has been used. The pruning procedure uses an estimate of the expected error that will be experienced at each node for the test data. First, the absolute difference between the predicted value and the actual output value is averaged for each of the training examples that reach the node. Since the trees have been built expressly for this dataset, this average will underestimate the expected error for new cases. To compensate for this, the output value is multiplied by the factor $(n+v)/(n-v)$, where n is the number of training examples that reach the node and v is the number of attributes in the model that represents the output value at that node. Therefore, this multiplication is performed to avoid underestimating the error for new data, rather than the data against which it is trained. If the estimated error is lower at the parent, the leaf node can be dropped [19].

Smoothing process is considered to reduce and solve the problem of sharp discontinuousness at leaves of the pruned tree. The smoothing process, as described by Quinlan [20], uses the leaf model to compute the predicted value. The value is then filtered along the path back to the root, smoothing it at each node by combining it with the value predicted by the linear model for that node. This involves the calculation as follows:

$$P' = \frac{np + kq}{n + k} \tag{2}$$

where P' is prediction which exceed to higher node, P is prediction pass to current node from the below, q is the predicted value by model at the node, n is number of training instances reach to previous node, and k is Wang & Witten constant [21].

IV. Model Development

A. Model Inputs

Based on the previous experimental studies and the existing design codes, six independent variables including the beam width (b), the effective depth (d), the shear span-to-depth ratio (a/d), the compressive strength of concrete (f'_c), the aggregate size-to-depth ratio (a_g/d), and the longitudinal steel ratio (ρ) were considered as predictive variables. The single model output is concrete shear capacity, v_u.

B. Database Used

To investigate shear strength of the HSC slender beams and develop new prediction formulas, a very recently collected comprehensive data set by Elsanadedy et al. [1] from 33 experimental studies performed between 1957 and 2013 is used. Detail of data set used can be found in [1]. The entire dataset includes 250 recorded experimental data samples for different ranges of f'_c between 42.5 MPa to 183 MPa. The data set is randomly divided into two independent parts (i) training (200) (ii) testing (50). The M5' algorithm is trained using the training dataset and then evaluated with testing dataset. The range of input and output variables for training and testing datasets is presented in Table II. It should be noted that slender beams with $a/d \geq 2.5$ in which the failure mode was shear, are selected. The specimens in mentioned experiment studies are monotonically loaded by either one or two concentrated loads.

TABLE II: Ranges of Input and Output Parameters for Training and Testing Sets

Variable	Subset	Min	Max	Mean	STD
d (mm)	Training	133	925	284.88	158.94
	Testing	135	718	255.98	96.99
a/d	Training	2.46	6.1	3.59	0.86
	Testing	2.47	6.1	3.66	0.89
a_g/d	Training	0.01	0.17	0.06	0.02
	Testing	0.02	0.17	0.06	0.02
f'_c (MPa)	Training	42.5	183	65.40	21.44
	Testing	45.3	155	64.56	20.75
ρ (%)	Training	0.33	6.64	2.17	1.31
	Testing	0.33	6.64	2.29	1.26
V(kN)	Training	0.48	4.08	1.72	0.78
	Testing	0.57	3.85	1.8	0.70

C. Developed M5' Model

M5' model can be used to generate simple and meaningful rules that can be easily applied in shear capacity calculations. However, it could just propose a linear relation between the input and the output parameters. In order to overcome this limitation, model was developed by log (inputs) and log (output). Then, the final developed model can be written as:

$$v_u\,(MPa) = A'b^{B'}d^{C'}\left(\frac{a_g}{d}\right)^{D'}\left(\frac{a}{d}\right)^{E'} f_c'^{F'}\rho^{H'} \quad or \qquad (3)$$
$$V\,(\mathrm{kN}) = A'b^{B'}d^{C'}\left(\frac{a_g}{d}\right)^{D'}\left(\frac{a}{d}\right)^{E'} f_c'^{F'}\rho^{H'}$$

where A', B', … , and H' are constant values.

The developed rules and model tree were as follows:

$$\mathbf{LM_1} \quad v = 69.02 b^{-0.37} d^{-0.36}\left(\frac{a}{d}\right)^{-0.75}\left(\frac{a_g}{d}\right)^{0.042} f_c'^{0.23}\rho^{0.37} \qquad (4)$$

$$\mathbf{LM_2} \quad v = 3.9515 b^{-0.071}\left(\frac{a}{d}\right)^{-0.57}\left(\frac{a_g}{d}\right)^{0.048} f_c'^{0.049}\rho^{0.412} \qquad (5)$$

$$\mathbf{LM_3} \quad v = 1.796 b^{-0.079}\left(\frac{a}{d}\right)^{-0.405}\left(\frac{a_g}{d}\right)^{0.20} f_c'^{0.264}\rho^{0.337} \qquad (6)$$

In Fig. 1, the classification of data set by using M5' model tree for predicting shear strength of HSC slender beams are shown.

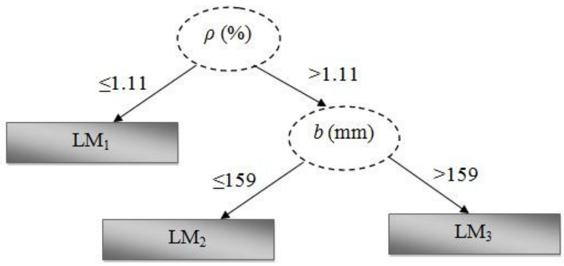


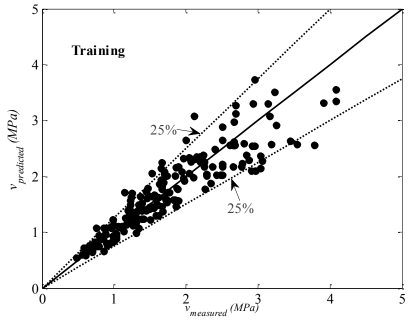
Fig. 1 Classification of dataset based on M5' algorithm.

Finally, the following statistical error parameters were used to evaluate the performance of the developed M5' algorithm for predicting shear capacity: mean absolute error (MAE), root mean square error (RMSE), scattering index (SI) and correlation coefficient (R). The readers are encouraged to the specialized literature for the mathematical statement of these parameters. The correlation coefficient R is a measure of the relative correlation between the predicted and measured values. The R values ranged between -1 and 1. If the R value is close to 1, it indicates that there is direct linear relationship between measured and predicted values. However, R sometimes may not necessarily indicate better model performance, particularly when data range is very wide and the data points distributed about their mean. Therefore, the coefficient of determination R^2, can be used as an unbiased estimate and can be a better measure for evaluating model performance. The MAE and RMSE measure the difference between predicted and measured values and values near to zero indicate close match.

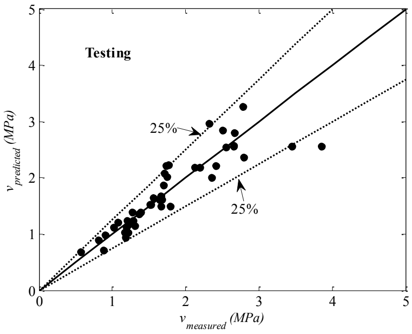
V. Results and Discussions

A. Performance Analysis

Performance of the M5′ algorithm for training and testing datasets shown in Fig. 2 demonstrates that there is a little scattering around the optimal line between measured and predicted values by M5′ algorithm for both datasets.



(a)



(b)

Fig. 2. Graphical performance of developed M5′ algorithm for (a) training (b) testing datasets.

The statistical error parameters related to training, testing and the whole dataset are presented in Table III. The results indicate that the proposed model performs well in both training and testing datasets.

TABLE III: THE PERFORMANCE OF DEVELOPED M5′ ALGORITHM

Subset	*MAE*	*RMSE*	*R*	R^2
Training	0.22	0.31	0.91	0.83
Testing	0.25	0.40	0.83	0.67
Total	0.23	0.33	0.90	0.80

Table IV tabulates statistical error parameters of the M5′ and the other shear design equations. As shown, all the error measures of the proposed model show improvement. The performances of the Eurocode2, CEB-FIP, and AS3600 are more reasonable than other design codes. However, the proposed model remarkably outperforms the others. In this respect, the *RMSE* and R^2 values of M5′ model shows improvement respectively by 37.8% and 60% compared to the AS 3600 model as the most precise model among the design equations.

TABLE IV: COMPARISON OF THE M5′ MODEL AND OTHER AVAILABLE METHODS

Model	*MAE*	*RMSE*	*R*	R^2
ACI31811	0.5891	0.7939	0.6676	-0.0787
CSAA23304	0.6976	0.9358	0.5289	-0.4988
Fib	0.6895	0.9254	0.5252	-0.4656
Eurocode2	0.4341	0.6161	0.7311	0.3503
CEB-FIP	0.4273	0.6059	0.8498	0.3718
AS36002009	0.3758	0.5402	0.8241	0.5005
JSCE	0.5430	0.7525	0.8188	0.0307
Cladera and Mari	0.4540	0.6399	0.8104	0.2992
M5′ (proposed)	0.23	0.33	0.90	0.80

The histogram of log (measured/predicted) of shear capacity for M5′ model and the three best design equations are shown in Fig. 3. The normal distribution is also fitted to logarithm of discrepancy ratio between measured and predicted shear strength.

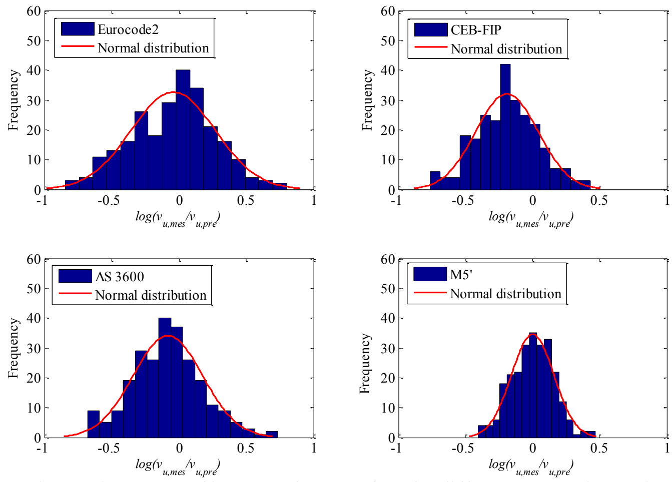


Fig. 3. Histograms of log ($v_{u,mes}$/$v_{u,pre}$) values for different approaches and their fitted normal distribution functions.

It can be seen that the values of log (Measured/Predicted) for the M5′ model are close to zero. Furthermore, the distribution of log (measured/predicted) values is nearly symmetrical and approximately concentrates in zero value. The distribution of Eurocode 2 model prediction is wider than other models. This indicates that the uncertainty of this model is high. Furthermore, the most of CEB-FIP and AS 3600 model predictions overestimate shear capacity. The log (Measured/Predicted) values of AS 3600 model are closer to zero than other design equations. However, the M5′ has remarkably better performance than other design equations in this aspect and also has narrower normal distribution (less uncertainty).

As stated in previous sections, some design codes did not consider some important parameters such as a_g/d in their models or consider different contributions for some parameters such as f'_c and ρ. The model errors should be independent of the input parameters or less sensitive to them, otherwise it can be interpreted those input parameters did not correctly incorporated in that model or should be added to the model if it has not been considered. The variations of discrepancy ratio between measure and predicted shear strength by Eurocode 2, CEB-FIP, AS 3600, and M5′ models with a/d, a_g/d, f'_c, and ρ are shown for testing dataset in Fig 4. The lines in this figure represent the best linear regression between the values of $v_{measured}/v_{predicted}$ and input variables.

The errors of design codes are remarkably sensitive to variations of a/d and ρ parameters. It may be interpreted that these parameters have not been considered correctly in the mentioned models. This sensitivity is less for f'_c and a_g/d. In general, the errors of developed M5′ model are completely insensitive to variation of effective parameters.

B. Safety Analysis

Most design codes consider a marginal accuracy in trading of safety, therefore, the proposed model should also remain in a sufficient level of safety. To evaluate the safety of the proposed model and existing design codes, a new scale introduced by Collins [23] is employed. This scale is known as Demerit Points Classification (DPC), which consider the safety, accuracy and scattering of the design codes as a function of the ratio between the ultimate resistances in experimental tests and the estimated theoretically shear capacity. In the present study, this ratio has been shown as DR parameter. The safety classification based on the Collins scale is presented in Table V.

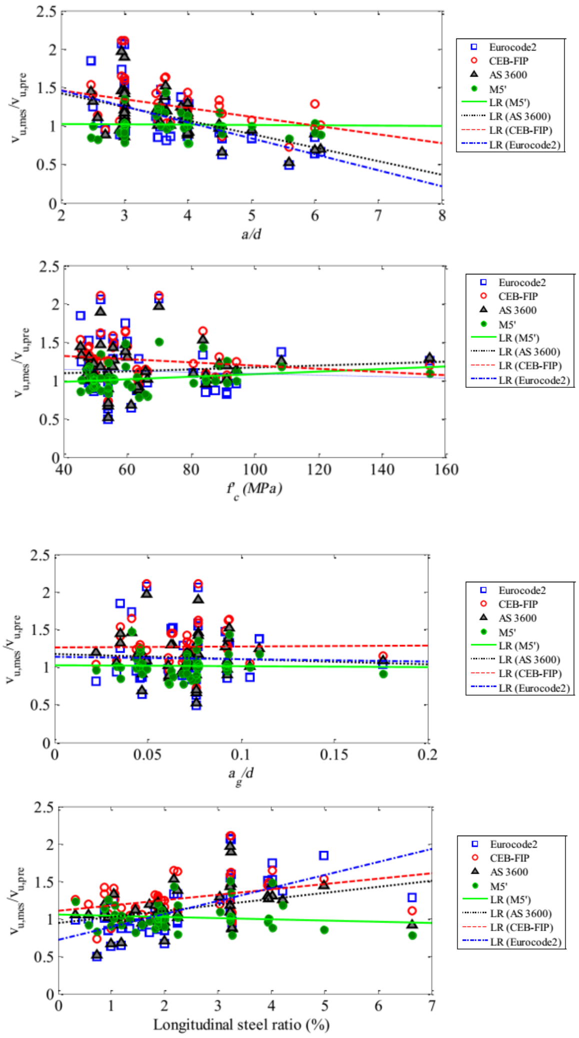


Fig. 4. Variation of discrepancy ratio (DR) between measured and predicted shear strength as a function of *a/d*, a_g/d, f'_c, and *ρ*.

TABLE V: CLASSIFICATION BY DEMERIT POINTS

$v_{u,exp}/v_{u,predicted}$	Classification	Demerit points
<0.50	Extremely dangerous	10
[0.50-0.85)	Dangerous	5
[0.85-1.15)	Appropriate and safe	0
[1.15-2.00)	Conservative	1
≥2.00	Extremely conservative	2

To quantitative evaluation of the safety of the proposed model and the existing design codes, first a demerit point is attributed to each prediction of these equations for total 250 data points based on Table VI. Then, the total values of demerit of each formula are calculated by the sum of the products of the number of specimens in each interval and their corresponding demerit penalty. The lower the value of total sum indicates that the considered formula is safer. The results of developed models and existing equations are presented in Table VI. As shown, the CEB-FIP model is the safest design codes and has the lowest demerit penalty. However, nearly 60 percent of its predictions are categorized in conservative and extremely conservative classes. It should be noted that the M5′ algorithm has the lowest demerit penalty and are safer than other design codes. Approximately, 65 percent of the predictions of M5′ algorithm are classified in the safe and appropriate region based on Collins scale.

TABLE VI: CLASSIFICATION OF DEVELOPED AND DESIGN EQUATIONS ACCORDING TO THE CRITERIA OF COLLINS

Model	DR<0.5	0.5≤DR<0.85	0.85≤DR<1.15	1.15≤DR<2	DR>2	Demerit points
M5′	- -	34 34×5	166 166×0	50 50×1	- -	220
ACI 318-11	6 6×10	38 38×5	64 64×0	121 121×1	21 21×2	413
CSA A23.3-04	- -	12 12×5	40 40×0	141 141×1	57 57×2	315
fib Model Code	- -	14 14×5	45 45×0	138 138×1	53 53×2	314
Eurocode-2	2 2×10	63 63×5	99 99×0	80 80×1	6 6×2	427
CEB-FIP Model	- -	15 15×5	87 87×0	142 142×1	6 6×2	229
AS 3600-2009	1 1×10	40 40×5	108 108×0	101 101×1	- -	311
JSCE	- -	14 14×5	65 65×0	154 154×1	17 17×2	258
Cladera and Mari	- -	16 16×5	76 76×0	149 149×1	9 9×2	247

VI. CONCLUSION

In the present study, new formulation for prediction of shear strength of the HSC slender RC beams without web reinforcement using a rule based method namely M5' algorithm is proposed. A comprehensive database of 250 available experimental data samples containing several effective parameters that consider geometrical and mechanical properties of concrete, aggregate and reinforcement are is employed to develop the model.

Comparison between the developed model and the most common design codes are performed to evaluate the accuracy of the proposed model. The *RMSE* and R^2 values of M5′ model shows improvement respectively by 37.8% and 60% compared to the AS 3600 model as the most precise model among the several design equations. Furthermore, the safety analysis based on Demerit Points Classification scale also considered to evaluate the safety of proposed formulation. Results indicate the proposed model safer than the CEB-FIP model which is determined as the safest design code among others.

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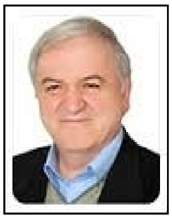

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