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Predicting shear capacity of NSC and HSC slender beams without stirrups using artificial intelligence

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Abstract. The use of high-strength concrete (HSC) has significantly increased over the last decade, especially in offshore structures, long-span bridges, and tall buildings. The behavior of such concrete is noticeably different from that of normal-strength concrete (NSC) due to its different microstructure and mode of failure. In particular, the shear capacity of structural members made of HSC is a concern and must be carefully evaluated. The shear fracture surface in HSC members is usually trans-granular (propagates across coarse aggregates) and is therefore smoother than that in NSC members, which reduces the effect of shear transfer mechanisms through aggregate interlock across cracks, thus reducing the ultimate shear strength. Current code provisions for shear design are mainly based on experimental results obtained on NSC members having compressive strength of up to 50MPa. The validity of such methods to calculate the shear strength of HSC members is still questionable. In this study, a new approach based on artificial neural networks (ANNs) was used to predict the shear capacity of NSC and HSC beams without shear reinforcement. Shear capacities predicted by the ANN model were compared to those of five other methods commonly used in shear investigations: the ACI method, the CSA simplified method, Response 2000, Eurocode-2, and Zsutty's method. A sensitivity analysis was conducted to evaluate the ability of ANNs to capture the effect of main shear design parameters (concrete compressive strength, amount of longitudinal reinforcement, beam size, and shear span to depth ratio) on the shear capacity of reinforced NSC and HSC beams. It was found that the ANN model outperformed all other considered methods, providing more accurate results of shear capacity, and better capturing the effect of basic shear design parameters. Therefore, it offers an efficient alternative to evaluate the shear capacity of NSC and HSC members without stirrups.

Keywords: artificial intelligence; analysis; aggregate interlock; concrete; high-strength; prediction; shear.

1. Introduction

High-strength concrete (HSC) emerged in response to the increasing demand for high-performance construction materials and has been employed in various challenging applications such as offshore structures (Jackobsen 1989), tall buildings (Walther 1987), highway bridges, and hazardous waste storage facilities. Current advances in concrete technology allowed using very low water/cement ratio mixtures along with ultrafine supplementary cementing materials and microfillers in concrete

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production, therefore, reshaping the internal characteristics and microstructure of concrete, and enhancing, in particular, the transition zone between aggregates and cement paste. HSC exhibits a much stronger bond between cement paste and aggregate particles and less internal micro-cracking than does NSC.

Despite the fact that concrete properties generally improve as its compressive strength increases, some of the mechanical characteristics of HSC need to be cautiously evaluated for adequate use in current design procedures and empirical equations. For instance, due to the enhancement of the aggregate-cement paste transition zone in HSC, microcracks tend to propagate through aggregates rather than around them, and the fracture surface is therefore smoother than that in NSC. This behavior has serious implications especially in the shear design of reinforced HSC beams not containing shear reinforcement. It is well known that the total shear resistance of reinforced concrete beams is supplied by two components: V_s (shear resistance provided by the shear reinforcement), and V_c (shear resistance provided by the concrete itself). The first component is well understood and can be quantified, whereas the concrete contribution to total shear capacity and the mechanisms through which such contribution is transferred still remain unresolved despite the numerous studies carried out on this subject since the start of last century.

Several shear calculation techniques for reinforced concrete have appeared in the literature since the original method proposed by Ritter (1899) at the end of the nineteenth century and the subsequent method of Mörsch (1909) during the first decade of the twentieth century. These techniques include semi-empirical, statistical, and analytical methods. Semi-empirical and statistical methods are normally based on observations from available experimental data, whereas analytical methods use more rational approaches, yet they often require extensive calculations. The ability of current shear design specifications to accurately calculate the shear capacity of reinforced concrete beams without shear reinforcement (especially large, lightly reinforced beams) is still debatable (Angelakos, *et al*. 2001). In particular, such methods have typically been developed for NSC with compressive strength of less than 50MPa, and their validity to calculate the shear strength of HSC members still needs to be proven.

Shear friction due to aggregate interlock, V_a across fracture surfaces in reinforced concrete slender beams without shear reinforcement (Fig. 1) constitutes a significant part of the total shear resisted by concrete. The aggregate interlock mechanism usually contributes about 35-50% of the total shear capacity of reinforced concrete beams without shear reinforcement (Taylor 1970). Thus, the shear behavior of such beams can be greatly affected by the cracking mechanism which is usually transgranular in HSC, leading to smoother fracture surfaces and hence reducing the contribution of the aggregate interlock mechanism to the ultimate shear strength by up to 35% compared to that in NSC (Duthinh and Carino 1996, Walraven 1995). This imposes constraints on using current shear design methods to calculate the shear strength of HSC beams.

The present study investigates the feasibility of using an alternative approach called artificial neural networks (ANNs) to predict the shear capacity of reinforced NSC and HSC slender beams ($a/d \geq 2.5$) without shear reinforcement, and to compare such predictions to results obtained from five different existing methods namely, Zsutty's method, Response 2000 (based on the modified compression field theory), the ACI (11-5) method, the CSA simplified method, and the method provided by the final draft of Eurocode-2. A sensitivity analysis was also carried out to evaluate the ability of the various methods to accurately capture the effects of basic shear design parameters on the shear capacity of NSC and HSC beams.

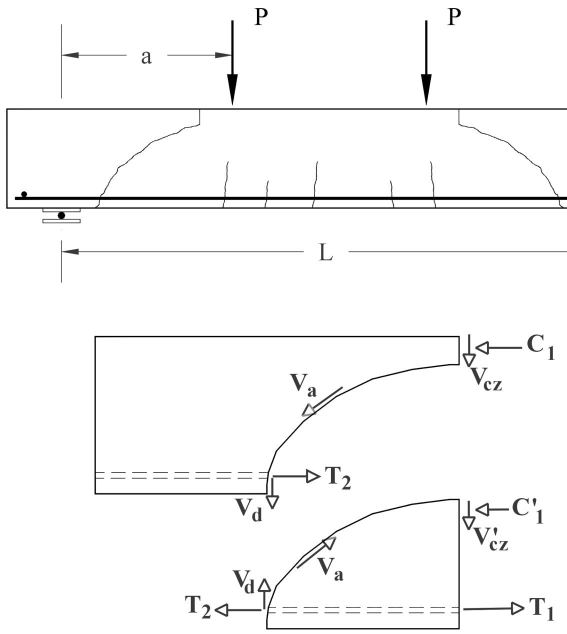


Fig. 1 Shear transfer mechanisms in reinforced concrete beam without web reinforcement

2. Shear evaluation techniques included in this study

Several shear calculation methods have been developed during the last century and they all concur that the shear strength of reinforced concrete beams without shear reinforcement depends on the compressive strength of concrete, f'_c, the ratio of longitudinal steel, ρ_l, the beam's effective depth, d, and the shear span to depth ratio, a/d. However, such methods vary considerably in evaluating the effects of the above parameters on shear strength. These methods were developed based on equilibrium trusses, exact solutions, plastic analysis, shear friction, or statistical approaches. They went through series of refinements since their initial development and are described in detail elsewhere (Duthinh, and Carino 1996). Only the shear methods that have been used in the present study are briefly discussed below.

2.1. Statistical and analytical methods

Zsutty (1968 & 1971) formulated empirical equations for predicting the shear capacity of RC beams using regression analysis of experimental data. Despite the empirical nature of these equations, they have proven to be relatively accurate in estimating the shear strength of NSC beams without stirrups. Thus, this statistical method has become widely used in the literature. The equation proposed by Zsutty to estimate the ultimate shear capacity of reinforced concrete slender beams not containing shear reinforcement is expressed as follows:

$$V_u = 2.2\left(\frac{f'_c\rho_l d}{a}\right)^{1/3} b_w d \tag{1}$$

where

- d is the effective beam's depth (mm),
- b_w is the beam's breadth (mm),
- a is the shear span (mm),
- f'_c is the compressive cylinder strength of concrete (MPa),
- ρ_l is the longitudinal reinforcement ratio, and
- V_u is the ultimate shear at failure (N).

Recently, Bentz and Collins (http://www.ecf.utoronto.ca/~bentz/r2k.htm) developed a computer program called Response 2000 (R2K), which is a versatile tool for sectional analysis of reinforced concrete members. It is an extension of the modified compression field theory MCFT (Vecchio and Collins 1986), which explicitly incorporates rigid slipping along crack surfaces into compatibility relations. The MCFT is also the foundation of the CSA A23.3-94 (1994) general method, and is considered as one of the most refined analytical methods for shear analysis of reinforced concrete members.

2.2. Design specifications

Three commonly used shear design methods: The ACI 318-99 (1999), the CSA simplified method (1994), and the final draft of Eurocode-2, EC-2 (2002) were employed in this study. The ACI 318-99 and the simplified method of CSA A23.3 94 consider the shear capacity of reinforced concrete beams without web reinforcement, V_c, as the shear value at which diagonal cracking is initiated. ACI 318 calculates V_c using one of two equations. The first one, ACI 11-3, (approximate method) directly relates the contribution of concrete to the shear resistance of a beam to the concrete compressive strength as follows:

$$V_c = \frac{1}{6}\sqrt{f'_c}b_w d, \quad \sqrt{f'_c} \le 8.3\,\text{MPa} \tag{2}$$

The second equation, ACI 11-5, takes into account the effect of longitudinal reinforcement and shear span to depth ratio and is expressed as:

$$V_c = \left(0.158\sqrt{f'_c} + 17.2\rho_l\left(\frac{Vd}{M}\right)\right)b_w d \le 0.3\sqrt{f'_c}b_w d \tag{3}$$

Where M and V are the moment and shear force, respectively at a section subjected to factored load, and $f'_c < 70\,\text{MPa}$.

V_c calculated using the simplified method of CSA A23.3, however, is expressed as follows:

$$V_c = 0.2\lambda\sqrt{f'_c}b_w d \qquad d \le 300\,\text{mm} \tag{4}$$

$$V_c = \left(\frac{260}{1000 + d}\right)\lambda\sqrt{f'_c}b_w d \not< 0.1\sqrt{f'_c}b_w d \qquad d > 300\,\text{mm} \tag{5}$$

where λ is a factor accounting for the density of concrete.

The final draft of Eurocode-2, EC-2 was adopted in April 2002 and includes several changes from its predecessor in terms of the shear design procedure. The expression provided by EC-2 to calculate the shear resistance of concrete members not requiring shear reinforcement is as follows:

$$V_{rd,c} = [0.18k(100\rho_l f_{ck})^{1/3} + 0.15\sigma_{cp}]b_w d \geq V_{rd,\min} = [0.035k^{3/2} f_{ck})^{1/2}]b_w d \quad (6)$$

where

- f_{ck} is the characteristic cylinder compressive strength $\leq$ 100 MPa,
- $k = 1 + \sqrt{\frac{200}{d}} \leq 2.0$,
- $\rho_l \leq 0.02$,
- $\sigma_{cp} = \frac{N_{Ed}}{A_c} \leq 0.2 f_{cd}$ (MPa),
- N_{Ed} is the axial force in the cross-section (N),
- A_c is the area of the concrete cross-section (mm^2), and
- V_{Rd} is the shear value (N).

3. Artificial neural networks methodology

Artificial neural networks (ANNs) are powerful computational tools inspired by the understanding and abstraction of the structure of biological neurons and the internal operation of the human brain (Haykin 1994). Multi-layer perceptrons (MLPs) are the most widely used neural networks in engineering applications due to their ability to implement non-linear transformations and supersede outliers and imprecise results (Haykin 1994). They are highly adaptive data-driven trainable systems that have the ability to learn from examples and to capture hidden behavior. They consist of an input layer containing parameters that affect certain properties represented by units in the output layer and a number of hidden layers. Processing units in a MLP network are connected to units in the subsequent layer with assigned strengths. The main objective in building a neural network-based model is to train a specific network architecture using experimental data to search for an optimum set of connection strengths (weights) between its processing units. Using the final set of weights, the trained ANN can predict accurate values of outputs for a given set of inputs within the range of the training data. Ample details on the fundamental basis of ANNs and on how to build, train, and validate a MLP network can be found in Haykin (1994), Rumelhart, Hinton, and William (1986). Although the training process of MLP networks depends on several parameters, the database used for training is considered as the most important factor that affects the network's performance and generalization.

4. Selection of database

The performance of ANNs depends, to a great extent, on the learning material provided for their training. Therefore, an adequate database must be generated to train a MLP network to predict the shear capacity of reinforced concrete beams. The training database should be large enough, accurate, comprehensive, and must contain the necessary information to assist in capturing the embedded relationships between the influential parameters of reinforced concrete beams and their corresponding shear capacity.

Experimental shear strength results for 523 reinforced concrete beams without shear reinforcement

Table 1 Statistical data for design parameters and shear capacity of beams used in database

Parameters	Training data			Testing data		
	Minimum	Maximum	Average	Minimum	Maximum	Average
d (mm)	40.60	1097.28	332.90	135.00	930.00	387.69
b_w (mm)	38.10	400.00	186.65	38.10	400.00	212.30
ρ_l (%)	0.48	5.04	2.15	0.50	5.04	2.21
f'_c (MPa)	10.50	99.00	42.55	18.00	99.00	46.57
a/d	2.40	6.05	3.31	2.41	4.49	3.15
V_u (kN)	2.69	386.10	87.83	8.38	332.10	112.78

were collected from the literature (358 beams made of NSC and 165 beams made of HSC). Only slender beams with a shear span to depth ratio ($a/d \geq 2.5$) that exhibited shear failures during testing were considered. All beams were simply supported and subjected to either three-point or four-point loading acting symmetrically with respect to the centerline of the beam. The database thus generated was further screened to eliminate outliers and beams having one or more of their design parameters isolated from the range of values of the same parameter for the rest of the beams so that the final database was made of 387 beams (263 NSC and 124 HSC). Table 1 includes the maximum, minimum, and average values of all design parameters and shear capacity at failure for beams in the final database.

5. ANN model

In this study, two feed-forward back-propagation MLP networks having the same input and output variables were developed. The first network, (2 hidden layers) was trained on experimental results of 329 beams (226 NSC and 103 HSC) and tested on 58 different beams (37 NSC and 21 HSC). The second network (one hidden layer) was trained and tested on results obtained from 124 HSC beams only (103 beams for training and 21 beams for testing). The performance of both networks in predicting the shear capacity of reinforced HSC beams without web reinforcement and their sensitivity analysis (ability to capture the effect of basic shear design parameters on shear strength) were found to be similar. Therefore, only the first model is considered herein for its robustness and ability to study the effect of basic shear design parameters on the shear strength of beams made of either NSC or HSC.

The ANN model considered (Fig. 2) consists of an input layer containing 5 variables representing the basic shear design parameters (d, b_w, a/d, ρ_l, and f'_c), an output layer with one unit representing the ultimate shear value (V_u), and two hidden layers having 10 and 5 units, respectively. Full forward connection (between units of one layer and those of the subsequent layer) was adopted and variable learning rate and momentum were used to avoid lengthy training and ensure global convergence. The transfer function used for all units in this model was a logarithm sigmoid function (Haykin 1994) with outputs varying between 0 and 1. Therefore, prior to the training process, all variables in the generated database were scaled between 0 and 1 to speed up the training process, improve the network's generalization, and most importantly make output data compatible with both the outcome of the transfer function employed and that of the network. The database was scaled using the following equation:

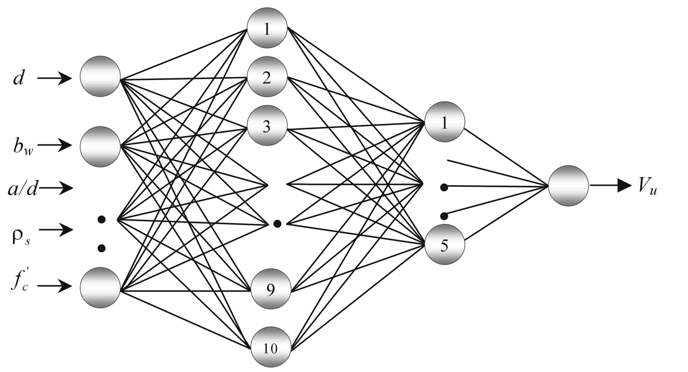


Fig. 2 Architecture of neural network model

$$x_t = \frac{(x - x_{min})}{(x_{max} - x_{min})} \tag{7}$$

Where:

- x_t is the scaled value of variable x.
- x_{min} and x_{max} are the minimum and maximum values of variable x in the database, respectively.

6. Results and discussion

The acceptance or rejection of the proposed ANN model is based not only on its ability to accurately predict the shear failure load of beams used for training, but more importantly on its ability to generalize its predictions to new beams, not familiar to the network, but having input variables from within the range of input variables of the training data. Therefore, the performance of the ANN model thus developed was evaluated based on its ability to predict the shear strength of a new set of beams (testing data) not used in the training process and randomly selected from the collected database.

The ANN model developed in this study along with the ACI equation 11-5, the CSA simplified method, Response 2000, Zsutty's method, and Eurocode-2 were employed to calculate the shear strength of all beams selected for testing. The performance of each method in calculating the shear capacity of the NSC and HSC beams was evaluated using the average absolute error (AAE) calculated using Eq. (8) and the ratio of measured to predicted shear strength (V_m/V_p).

$$AAE = \frac{|V_m - V_p|}{V_m} x100 \tag{8}$$

where V_m and V_p are the measured and calculated shear capacity, respectively.

The averages, standard deviations (STDV), and coefficients of variation (COV) of measured / calculated shear strength ratio and average absolute error (AAE) for all shear calculation methods investigated are listed in Table 2. It is shown that the ACI (11-5) and the CSA simplified method provided the least accurate shear capacity values for both reinforced NSC and HSC beams without shear reinforcement with AAE values varying between 22% and 34%. These are followed by

Table 2 Performance of shear calcualtion methods considered in this study

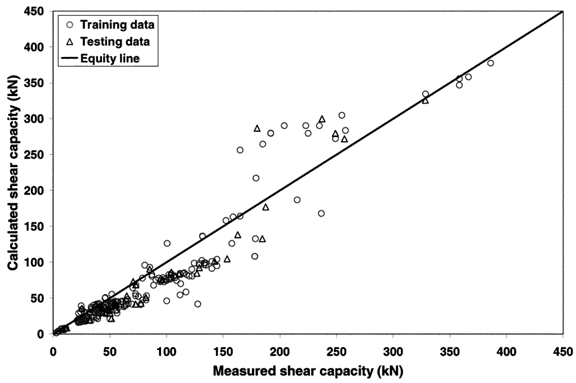
Method	High strength concrete (HSC)				Normal strength concrete (NSC)			
	AAE (%)	$V_{measured}$ / $V_{calculated}$			AAE (%)	$V_{measured}$ / $V_{calculated}$		
		Average	STDV	COV		Average	STDV	COV
ACI 11-5	34.0	1.24	0.47	38.05	24.7	1.30	0.31	23.64
CSA (simp)	28.0	1.12	0.42	37.11	21.8	1.22	0.30	24.42
EC-2	21.0	1.07	0.35	32.54	13.2	1.08	0.20	18.74
R2K	19.0	1.20	0.35	28.82	13.1	1.15	0.19	16.47
Zsutty	25.5	1.02	0.31	30.25	14.2	1.04	0.20	19.44
ANN	10.0	1.03	0.17	16.77	9.0	0.99	0.12	12.08

Zsutty's method and the Eurocode-2 with AAE values of 26% and 21% (in the case of HSC), and 14% and 13% (in the case of NSC), respectively. R2K provided relatively more accurate results with lower AAE values of 19 % and 13 % for HSC and NSC beams, respectively. The ANN model outperformed all of the above methods with an AAE of 10% in the case of HSC beams and 9 % in the case of NSC beams. Table 2 also shows that the ANN model had the lowest COV values in predicting shear strength. It is of particular interest that the AAE and COV of the shear calculation methods considered in this study in calculating the shear capacity of reinforced HSC beams are significantly higher than the corresponding ones for NSC beams, which indicates that the applicability of such methods for HSC is questionable.

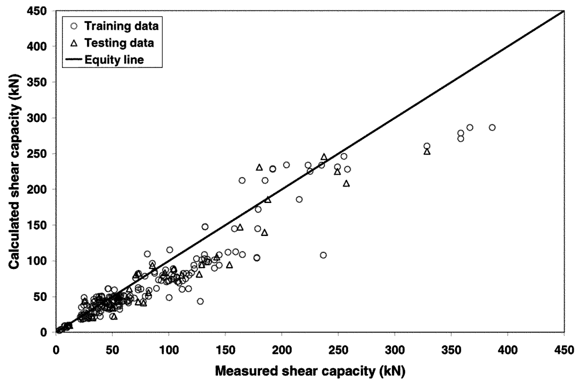
The calculated shear capacities of NSC and HSC beams by the various shear calculation methods are also plotted against the experimentally measured ones in Figs. 3 and 4, respectively. It can be observed that the data points predicted by the ANN are located either on or slightly over/under the equity line for both NSC and HSC (Figs. 3f and 4f), whereas those calculated by the other methods are scattered over a relatively wider range. For slender reinforced concrete beams without web reinforcement having shear capacity of up to 200 kN, Figs. 3(a), 4(a) 3(b), and 4(b) illustrate that the ACI (11-5) and the CSA simplified method, tended to underestimate the shear capacity of such beams for both NSC and HSC, whereas the R2K, EC-2, and Zsutty's method provided comparatively more accurate results as shown in Figs. 3(c)-3(e) and 4(c)-4(e). For beams having shear capacity larger than 200 kN (beams with either large *d* and/or having a large amount of longitudinal steel), all five methods (other than ANN) demonstrated poor estimation ability with data points scattered over a wide range away from the equity line. In most cases, especially for HSC beams, the ACI 11-5, the CSA simplified method, and Zsutty's equation in particular, tended to overestimate shear capacity as shown in Figs. 4(a), 4(b), and 4(e), respectively which can have serious implications in designing high-shear capacity beams using these methods.

6.1. Effect of compressive strength of concrete

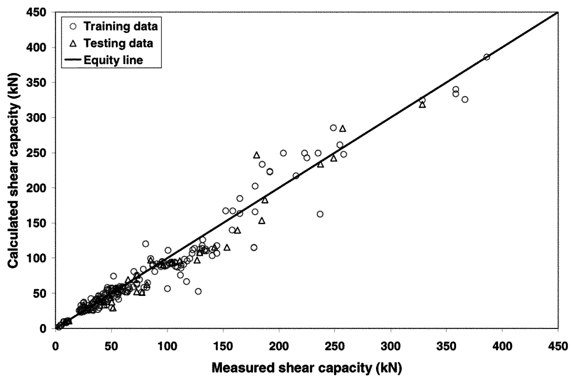
Current shear design methods account for the effect of concrete compressive strength (f'_c) in the calculation of the ultimate shear strength of reinforced concrete beams without web reinforcement. While such methods can be adequate for NSC slender beams (f'_c < 50MPa), results discussed above and some literature [e.g. Ahmad, *et al.* 1986] indicate that current design codes could be unconservative in calculating the shear capacity of HSC beams (f'_c > 50MPa). As stated earlier, about 35-50% of the ultimate shear capacity of slender concrete beams without shear reinforcement



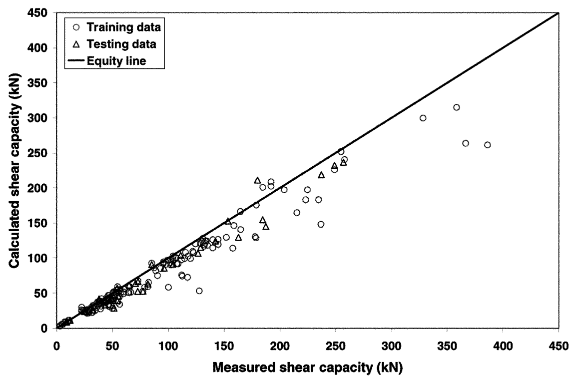
(a) – ACI 11-5



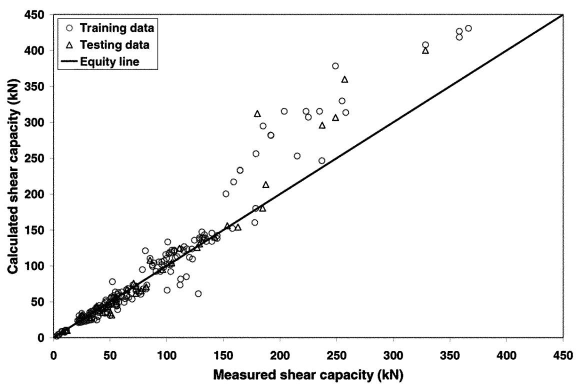
(b) – CSA



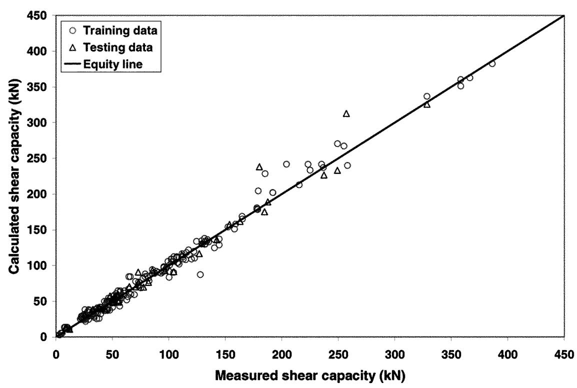
(c) - EC-2



(d) - R2K



(e) - Zsutty



(f) - ANN

Fig. 3 Measured versus calculated shear capacity values using several shear calculation methods (NSC)

is supplied by aggregate interlock along inclined cracks (Taylor 1970). Since the shear fracture surface in HSC members is usually smoother than that in NSC members (cracks propagate across aggregates), the ultimate shear strength of HSC beams is expected to be negatively affected.

To investigate the effect of compressive strength on the ultimate shear load of reinforced concrete

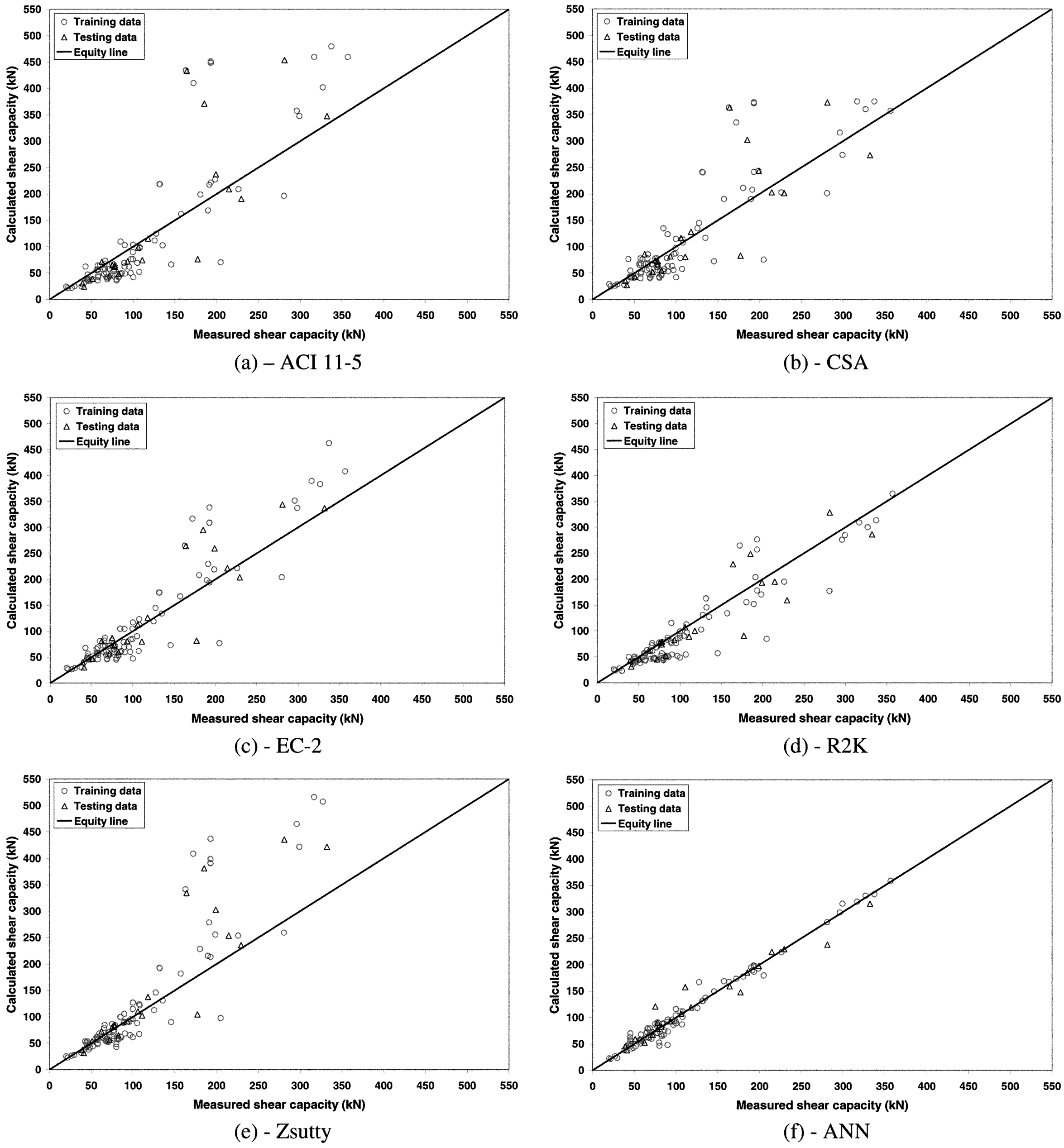


Fig. 4 Measured versus calculated shear capacity values using several shear calculation methods (HSC)

slender beams without web reinforcement, a set of ten beams was generated from the properties of a randomly selected single beam from the database. All design parameters were kept constant except f'_c, which was varied between 36 and 80MPa. Fig. 5 illustrates the effect of concrete compressive strength on the ultimate shear strength of beams as simulated by the various shear calculation methods used in this study. It is shown from the ANN analysis that the shear capacity of concrete beams

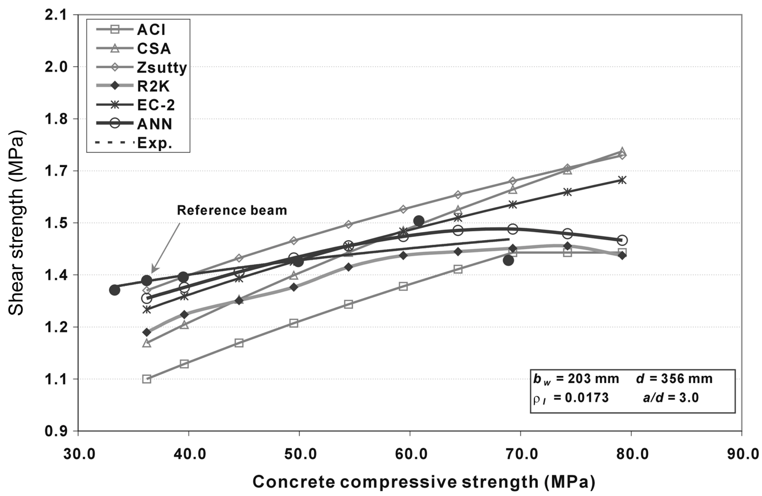


Fig. 5 Effect of f'_c on shear strength of reinforced concrete beams without web reinforcement

without web reinforcement increased with the increase of the concrete compressive strength up to 70MPa. The shear capacity, however, tended to slightly decrease with increasing f'_c beyond that value, thus capturing the effect of loss in shear friction provided by aggregate interlock due to smoother fracture surfaces in HSC. This behavior is confirmed by experimental results for beams having similar properties to those in the generated set as shown in Fig. 5, and is also supported by a previous experimental investigation in which Walraven (1995) indicated that the shear friction in HSC beams is up to 35% lower than that in NSC beams. Thorenfeldt and Drangsholt (1990) also stated that the shear strength of concrete decreases as its compressive strength increases beyond 80MPa.

Similar behavior to that of the ANN results is exhibited in results obtained using Response 2000 in which the reduction in shear carried by aggregate interlock due to smooth fracture surfaces in HSC is accounted for by introducing an additional shear design parameter representing the maximum size of aggregate, which is reduced as the concrete compressive strength increases. Conversely, EC-2, the CSA (simplified method), and Zsutty's equation tended to seriously overestimate the effect of concrete compressive strength on the shear strength of reinforced concrete beams in the high range of shear capacity. On the other hand, the limitation proposed by the ACI 11-5 on concrete compressive strength (f'_c < 70MPa) seems to be reasonable since the decrease in shear strength of reinforced concrete beams without shear reinforcement started in the region of $f'_c \approx 70\text{MPa}$. For over a 100% increase in f'_c, the ACI 11-5, the CSA (simplified method), Eurocode-2, and Zsutty's equation assumed an increase in shear strength of 43%, 48%, 30%, and 30% respectively, versus a 19% and 12% increase calculated by Response 2000, and the ANN model, respectively. All methods other than the ANN model and Response 2000 failed to accurately capture the impact of high compressive strength on the shear strength of concrete beams without web reinforcement, showing unconservative predictions for HSC beams. This is also confirmed by findings of Ahmad, *et al.* (1986) who argued that existing shear design methods (including ACI 11.5) overestimate the effect of concrete compressive strength and might be unconservative in calculating the shear strength of HSC slender beams ($a/d \geq$ 2.5) having a low flexural reinforcement ratio ($\rho_l \leq$ 2%).

6.2. Effect of tensile steel ratio

To investigate the effect of the tensile steel ratio, ρ_l on the ultimate shear capacity of reinforced concrete slender beams without web reinforcement, two sets of beams were generated using a single beam from the database. Beams in the first set have a compressive strength of 36.2MPa and share the same design parameters except the tensile steel ratio, which was varied between 1.13% and 3.50%. Beams in the second set have the same design parameters of those in the first set but have a concrete compressive strength of 70MPa. Fig. 6 shows the effect of ρ_l on the shear capacity of NSC beams (set # 1). It includes the calculated shear strength of the generated beams along with the experimental shear strength of three additional beams having similar properties. Contrary to some of the current shear design methods in which the effect of the tensile steel ratio on shear strength was ignored (e.g. the CSA simplified method and ACI 11-3), such an effect is evident in experimental results and in results of the ACI (11-5), R2K, Zsutty's equation, and the ANN model. Fig. 6 also shows that the ANN model provided more accurate predictions of experimental shear strength data.

Fig. 7 shows that the impact of the tensile steel ratio on the shear capacity of HSC beams is more pronounced than in the case of NSC beams. It is shown in Figs. 6 and 7 that increasing the tensile steel ratio from 1.13% to 3.0% increased the shear capacity of concrete beams without web reinforcement by 33% and 49% in the case of NSC and HSC, respectively. The rate of increase however, is noticeably lower for both NSC and HSC beams having tensile reinforcement ratio, $\rho_l \geq$ 2.5%. As stated earlier, the CSA simplified method does not consider the effect of longitudinal tensile reinforcement in the calculation of shear strength, whereas ACI 11-5 includes a slight effect as shown in Figs. 6 and 7. Zsutty's equation and Response 2000 however, recognize such an effect and capture the variation in shear strength of NSC and HSC beams for different tensile steel ratios in a comparable fashion to that of the ANN model. On the other hand, the Eurocode-2 reasonably accounts for the effect of $\rho_l \leq$ 0.02, but the recommended upper limit of ρ_l can lead to more conservative predictions of shear strength. The relatively higher values of shear strength predicted by Zsutty's equation in Fig. 7 are due to the fact that such a method, which was developed in the

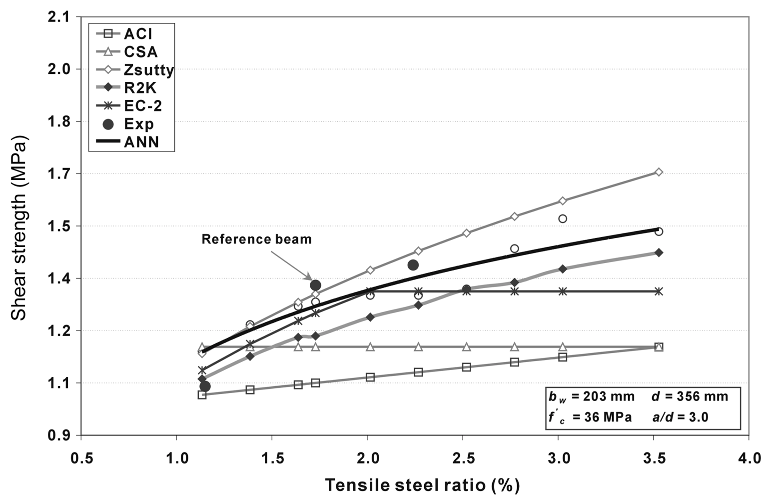


Fig. 6 Effect of ρ_l on shear strength of NSC beams without web reinforcement (f'_c = 36MPa)

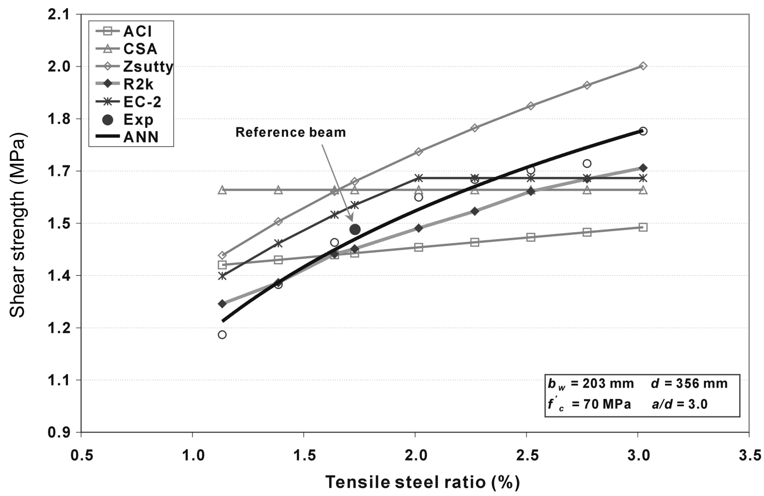


Fig. 7 Effect of ρ_l on shear strength of HSC beams without web reinforcement (f'_c = 70MPa)

late 1960's, overestimates the shear strength of beams made with concrete having high compressive strength values as discussed in the previous section.

6.3. Effect of beam's depth

A similar analysis to that used to investigate the effect of f'_c and ρ_l was carried out to study the influence of the effective beam's depth, d on the ultimate shear strength of reinforced concrete slender beams without web reinforcement. All beams used in this investigation share the same design parameters except the effective depth, which was varied between 219 and 466 mm. Fig. 8 shows the influence of the beam's effective depth, d on the shear capacity of NSC beams as calculated by the various methods considered in this study. It is apparent from this figure that the ANN prediction best correlated with experimental data, showing a significant effect of the beam's depth on the ultimate shear strength. Similar behavior was also reported in several previous experimental investigations (Kim and Park 1994) and fracture-mechanics based analysis, for instance work carried out by Bazant, *et al.* (1991 & 1984). Experimental results and results obtained by the ANN model and the Eurocode-2 in Fig. 8 illustrate that for a constant shear span to depth ratio, the ultimate shear strength decreases as the beam's effective depth increases. However, such an influence becomes less significant for beams with large depth. The CSA (simplified method) and R2K were somewhat able to capture this behavior for beams with depth larger than 300 mm. However, these methods seemed to ignore such an effect for $d < 300$ mm. Conversely, the ACI 11-5 and Zsutty's equation seemed to disregard the effect of d on the ultimate shear strength of beams with constant shear span to depth ratio regardless of the size of the beam.

The influence of the beam's effective depth, d on the ultimate shear strength of HSC beams is illustrated in Fig. 9. It can be observed that for beams with relatively small depths ($d < 300$ mm), there is no clear difference in the effect of beam's effective depth on the shear capacity of reinforced concrete beams without shear reinforcement with increasing compressive strength. However, for beams with $d \geq 300$ mm, it is shown that the effect of the beam's depth on the shear strength was less

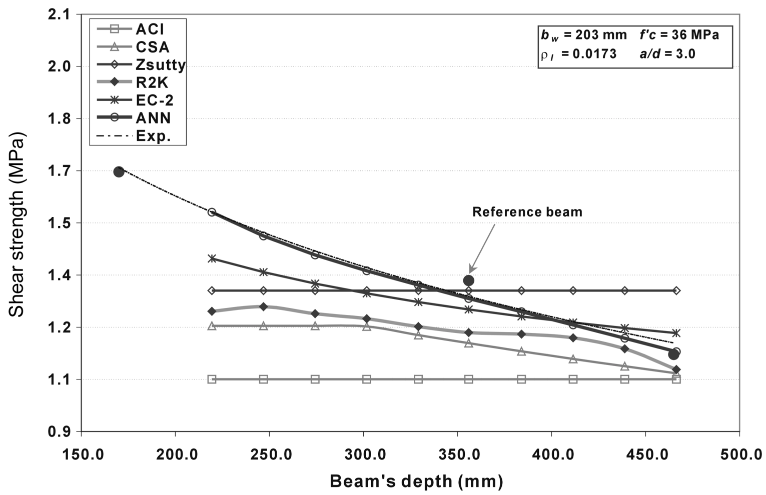


Fig. 8 Effect of d on shear strength of NSC beams without web reinforcement (f'_c = 36MPa)

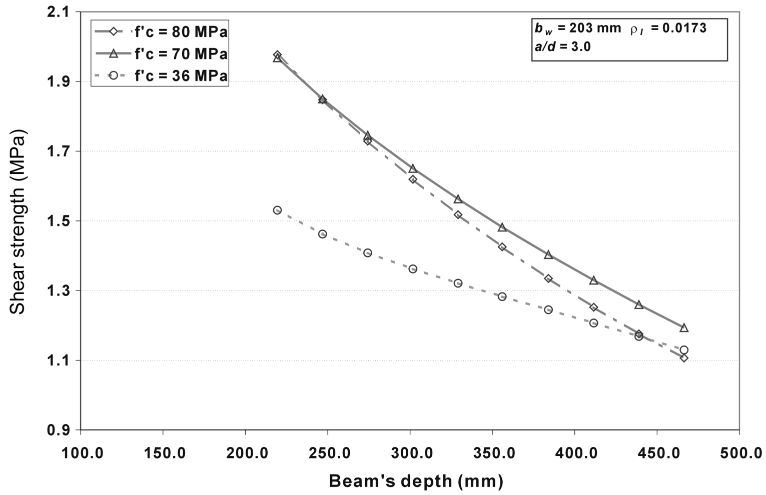


Fig. 9 Effect of d on shear strength of concrete beams without web reinforcement for different f'_c

significant at low compressive strengths. This is confirmed by findings of Fujita, *et al*. (2002) who argued that the effect of beam's size on the shear capacity differs depending on the compressive strength of concrete, and that the shear strength of NSC is proportional to the effective depth to the power of -1/4, while that of HSC is proportional to the effective depth to the power of -1/2.

6.4. Effect of shear span to depth ratio

The shear span to depth ratio (*a/d*) has been determined to have little effect on the shear strength of slender NSC beams with $a/d \geq 2.5$ and therefore, can be neglected (Rebeiz, *et. al* 2001).

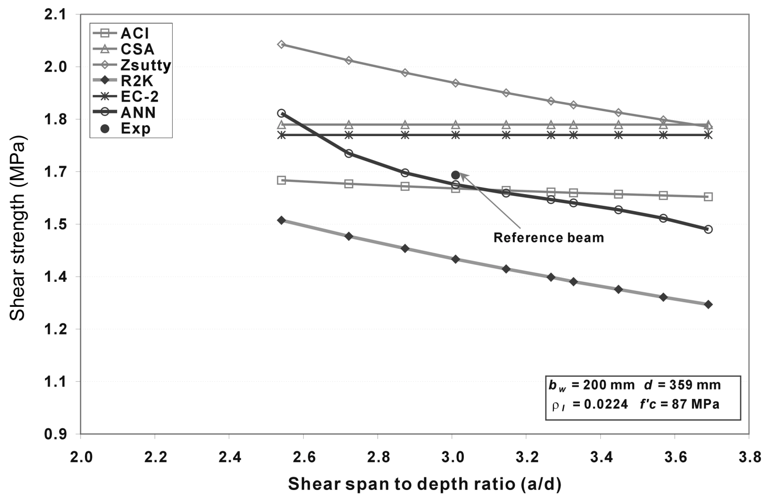


Fig. 10 Effect of *a/d* on shear strength of HSC beams without web reinforcement (f'_c = 70MPa)

However, some shear design methods such as the ACI 11.5 and Zsutty's equation consider such an effect in their proposed formulations. An investigation was carried out to evaluate the influence that *a/d* exerts on the shear strength of HSC beams. The response of all shear calculation methods considered in this study in capturing the effect of *a/d* on the shear strength of reinforced HSC slender beams not having shear reinforcement are plotted in Fig. 10. All methods show a satisfactory agreement in evaluating the effect of shear span to depth ratio for $a/d > 3.5$. However, for lower values of shear span to depth ratios, $2.5 \leq a/d \leq 3.5$, these methods differ in evaluating the magnitude of such an effect, which is minimal for ACI 11-5, does not exist for the CSA simplified method and the Eurocode-2, and is somewhat significant for the ANN model, R2K, and Zsutty's equation as shown in Fig. 10.

7. Conclusions

This study investigated the feasibility of using artificial neural networks as an alternative method for predicting the ultimate shear capacity of reinforced NSC and HSC slender beams without web reinforcement, and to compare its results to those of several existing shear design and calculation methods. Furthermore, a sensitivity analysis was carried out to evaluate the effect of basic shear design parameters on the shear strength of concrete members as simulated by various methods including the ANN model. The following conclusions can be made.

- The ANN approach can be used as an effective method to predict the shear capacity of NSC and HSC beams. This approach outperformed all other methods considered in this study and reasonably predicted the shear capacity of concrete beams regardless of their compressive strength.
- The ANN approach adequately captured the influence of compressive strength on shear capacity of reinforced concrete beams without web reinforcement. It showed that shear strength tends to decrease when concrete compressive strength increases above 70MPa. Conversely, current shear

design and calculation methods, except the R2K, tended to overestimate the shear capacity of HSC beams, and their applicability for HSC should be re-evaluated.

• This investigation showed that the amount of longitudinal tensile steel influences the ultimate shear strength of concrete beams without shear reinforcement in general, and that this influence is more pronounced for HSC beams. This observation is supported by results of the ANN model, Response 2000 and Zsutty's equation regardless of ρ_l, and by Euro-2 for $\rho_l \leq 2\%$. Conversely, the ACI 11-5 underestimates such an effect, while the CSA simplified method does not account for it

• For beams with a relatively small effective depth ($d < 300$ mm), the effective depth exerts a similar effect on the ultimate shear capacity for both NSC and HSC beams without web reinforcement. However, at high compressive strength, such an effect becomes more significant as the depth of the beam increases.

• Finally, the ANN analysis showed that similar to the case of NSC beams, the shear span to depth ratio, *a/d* slightly affects the shear strength of HSC beams, and that such an effect diminishes at higher values of *a/d*. This behavior is also observed using R2K and Zsutty's equation, whereas other methods either ignored this effect or underestimated it.

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