

Shear Predictions of Eurocode EC2

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Abstract The shear strength of reinforced concrete members is a function of shear capacity of concrete (V_c), which in turn depends on influencing parameters including concrete compressive strength (f'_c), ratio of tension reinforcement (ρ), shear span to depth ratio (a/d), size effect or depth factor (ξ), size of the aggregate in relation to the minimum size of the member (aggregate interlock aspects). Over the last several decades, researchers have tested reinforced concrete beams (without web reinforcement) over a range of variables limited by the breadth and depth of their experimental investigations and on the basis of their experimental results, have proposed empirical equations for predicting the shear capacity of normal and high strength-high performance concrete in reinforced concrete beams. In this paper a relational database using ACCESS software is developed and is populated with experimental results of 2145 shear critical reinforced concrete beams without web reinforcement using both normal as well as high strength –high performance concrete. An evaluation was also conducted to assess the predictive accuracy of shear design equation of Euro Code EC2. The results indicate for beams of normal as well as high strength concrete, the Euro Code EC2 design equation is adequate to accurately predict the shear capacity of reinforced concrete beams over the range of variables considered in this study.

Keywords: database, shear strength, concrete compressive strength, shear span to depth ratio

1. Introduction

Several definitions have been proposed for High Performance Concrete (HPC) including the definition defined by the Strategic Highway Research Program (SHRP), the American Concrete Institute (ACI), and the Federal Highway Administration (FHWA).

ACI definition of HPC is "concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing, and curing practices" [1]. These requirements may involve enhancements of placement and compaction without segregation, long-term mechanical properties, early-age strength, volume stability, or service life in severe environments. HPC is often high-strength concrete, but high-strength concrete may not necessarily be high-performance.

The definition used by SHRP [2] to defined the HPC is "any concrete which satisfies certain criteria proposed to overcome limitations of conventional concretes." SHRP's design proportions criteria include a maximum water/cementitious material ratio of 0.35, and their performance criteria include a minimum relative dynamic modulus of elasticity (durability factor) of 80% and a minimum strength meeting one of the criteria give in Table 1.

In most of the cases, attribute of concrete compressive strength and the associated stiffness (modulus of elasticity) of concrete are the primary design parameters used by the

designers and relatively less attention is given to the durability associated attributes of concrete.

Table 1. SHRP High-Performance Concrete Strength Criteria

HPC Strength Rating	Strength (psi)	Age (hours)
Very Early Strength (VES)	3000	4
High Early Strength (HES)	5000	24
Very High Strength (VHS)	10000	28

In this paper, HPC is considered to be high strength concrete as concrete strength is the principal driver for other enhanced attributes of concrete in structural applications and concrete strength is also influenced by water-cement ratio which in turns influences durability and workability of concrete.

Extensive research has been carried out over last several decades to study the shear strength of reinforced concrete, however there is no consensus among the researchers regarding the relational theory for shear failure as in case for flexural behavior of reinforced concrete. Over the years, researchers have selected different influencing parameters in their experimental program and on the basis of the variables considered in their experimental program, have proposed empirical equations for predicting the ultimate shear capacity of reinforced concrete beams without web reinforcement made with normal as well as high strength concrete [3,4,5,6,7]. The Euro Code EC2 also provides empirical equation to predict the shear capacity of reinforced concrete beams. In addition researchers have postulated semi-rational and rational theories including the compressive force path, softened truss model and the modified compression field

theory to predict the shear behavior of reinforced concrete members [8-15].

In this study a relational database is developed and populated with test data of shear critical reinforced concrete beams without web reinforcement made with normal as well as high strength concrete. The database is populated with the experimental results of 157 shear critical reinforced concrete beams (without web reinforcement) made with high strength concrete that were tested between 2002 and 2009 [16-21]. The database is further populated with experimental results of 439 reinforced concrete beams (without web reinforcement), tested prior to 2002, contained in the Database of Karl-Heinz Reineck et al [22] and 1849 reinforced concrete beams (without web reinforcement), tested prior to 2002, contained in the database of Michael P. Collins et al [23]. Thus the shear database contains test data of 2145 reinforced concrete beams without web reinforcement made with normal as well as high strength concrete.

Using the shear database, an evaluation was conducted to assess the predictive accuracy of shear design equation of Euro Code EC2. The results indicate for beams of normal as well as high strength concrete, the Euro Code EC2 design equation is adequate to accurately predict the shear capacity of reinforced concrete beams over the range of variables considered in this study.

2. Development of Shear Database

The ACCESS shear data base contains 8 fields. These include two fields for authors name along with year of publication, and beam designation, and remaining 6 fields for storing the experimental information for major influencing factors that are, concrete compressive strength

f'_c , shear span to depth ratio $\left(\frac{a}{d}\right)$, ratio of tension reinforcement (ρ), width (b) and depth of beam (d), and measured ultimate shear load (V_u).

The ACCESS Shear database developed in this study was initially populated with test results of 157 reinforced concrete beams without web reinforcement tested from 2002 to 2009 [16-21]. All the beams were high strength reinforced concrete beams having effective depth of 300mm. Out of these 157 test beams, 35 beams have width of 230 mm and the rest have a width of 150mm. The ratio of tension reinforcement (ρ) is $\leq 2\%$ and the shear span to depth ratio varies 1 to 6. The database was further populated with published test results of 439 reinforced concrete beams without web reinforcement, contained in the database of Karl-Heinz Reineck et al [22] and 1849 reinforced concrete beams without web reinforcement contained in the database of Michael P. Collins et al [23]. Thus the experimental data and results of 2145 reinforced concrete beams without web reinforcement made with normal as well as high strength concrete are contained in the ACCESS shear database.

Of the 2145 reinforced concrete beams without web reinforcement in the database, 1959 beams are simply supported rectangular reinforced concrete beams, 8 are continuous reinforced concrete beams and 178 are T-beams. The database contains test data of 1478 beams

with $\frac{a}{d} < 2.5$ and 667 beams with $\frac{a}{d} \geq 2.5$. There are 629 beams with high strength concrete ($f'_c > 40\text{MPa}$) and 1516 beams with normal strength concrete ($f'_c \leq 40\text{MPa}$).

3. Evaluation of EuroCode EC2 Design Equation

The design equation in Euro Code EC2 (Eq.6.2a) [24], for predicting the shear capacity of reinforced concrete beams without web reinforcement is:

$$\mathbf{V} = \left(\frac{0.18}{\gamma_c} K (100\rho_l f_{ck})^{1/3} + 0.15\sigma_{cp} \right) \mathbf{bd} \quad (1)$$

$$\geq \left(0.035k^{3/2} f_{ck}^{1/2} \right) \mathbf{bd}$$

Where γ_c = material constant, $k = 1 + \sqrt{\frac{200}{d}} \leq 2$, ρ_l = longitudinal steel ratio and σ_{cp} = Axial stress in case of pre-stressed members.

In order to evaluate the predictive accuracy of Euro Code EC2 (Eq. 6.2.a) Eq-1, 593 test beams with shear span to depth ratio $\frac{a}{d} \geq 2.5$, effective depth $d \geq 200$ mm,

concrete compressive strength $f'_c < 106$ MPa and ratio of tension reinforcement $\rho \leq 0.02$ were selected from ACCESS shear database. In order to evaluate the predictive accuracy of the Euro Code EC2, variables k and

f_{ck} satisfies the relations $k = 1 + \sqrt{\frac{200}{d}} \leq 2$ and $f_{ck} \leq$

100Mpa mentioned in in Euro Code EC2. The material constant γ_c has been taken as 1.40 (as per Norwegian Code, NS 3473E), and the characteristic cylinder strength f_{ck} is taken equivalent to concrete cylindrical strength as $f_{ck} = f'_c - 1.60$ MPa [22]. The term $0.15\sigma_{cp}$ was not taken into consideration as beams used in this study to evaluate the predictive accuracy of the Euro Code EC2 were non-prestressed reinforced concrete beams.

Figure 1 shows the plot of the experimental (measured) ultimate shear force (V_{exp}) and predicted ultimate shear force (V_{pre}), for the Euro Code EC2 .Two major factors are studied, the concrete compressive strength f'_c and the size effect. Table 2 shows the summary of results

showing the Average Margin of Safety $\left(\frac{V_{exp}}{V_{pre}} \right)_{avg}$ with

coefficient of correlation (COR) for NSC ($f'_c < 6000\text{psi}$) and HSC ($f'_c \geq 6000\text{psi}$) reinforced slender beams including the size effect.

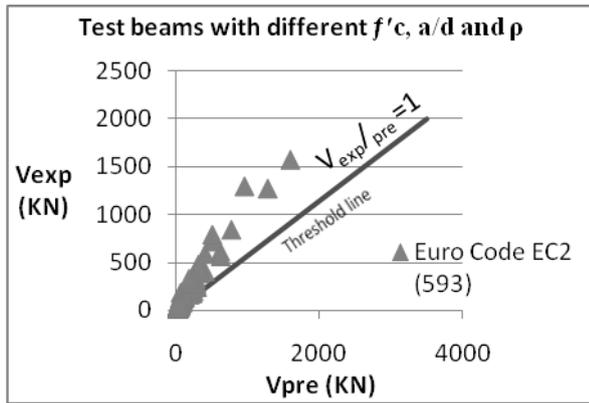


Figure 1. Plot of the experimental (measured) ultimate shear force (V_{exp}) and predicted ultimate shear force (V_{pre}).

It can be seen from Table 2 that in case of NSC beams, COR for Euro code EC2 Code is 0.974, where as in case of HSC beams, COR for Euro code EC2 is 0.974. It can be also seen from Table 2 that in case of beams with effective

depth $d < 300\text{mm}$ the COR for Euro code EC2 is 0.985 where as in case of beams with effective depth $d \geq 300\text{mm}$ the COR for Euro code EC2 is 0.975. The results indicate that the Euro Code EC2 design equation is adequate to accurately predict the shear capacity of reinforced concrete beams over the range of variables considered in this study.

4. Summary and Conclusions

In this study an ACCESS shear data base has been developed and is populated with experimental results for shear capacity of 2145 reinforced concrete beams without web reinforcement made with normal strength as well as high strength-high performance concrete. From the evaluation study of the Euro Code EC2 equation, it is found that the Euro Code EC2 design equation is adequate to accurately predict the shear capacity of reinforced concrete beams over the range of variables considered in this study.

Table 2. Summary of results showing the Average Margin of Safety $\left(\frac{V_{exp}}{V_{pre}}\right)_{avg}$ with coefficient of correlation for NSC and HSC reinforced slender beams including the size effect

NO	Code	Strength of Concrete				Size Effect		
		No. of Beams used for evaluation	Beams-NSC	Average Margin of Safety $\left(\frac{V_{exp}}{V_{pre}}\right)_{avg}$	COR	d<300mm	Average Margin of Safety $\left(\frac{V_{exp}}{V_{pre}}\right)_{avg}$	COR
			Beams-HSC			d≥300mm		
1-	Eurocode EC2	593	370	1.60	0.974	292	1.35	0.985
			223	1.14	0.974	301	1.20	0.975

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