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COMPARISON OF MODELS FOR SHEAR AT INTERFACE BETWEEN CONCRETE CAST AT DIFFERENT TIMES

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Abstract
Dissimilar models for shear at interface between concrete cast at different times have been developed and included in European Standard EN 1992-1-1 (EN), next generation European Standard prEN 1992-1-1 (prEN) and American Concrete Institute Standard ACI 318-19 (ACI) based on previous research. It is necessary to compare models to identify dissimilarities and the need for further investigation. Two types of surfaces were chosen for comparison – very smooth and indented according to EN classification. Five concrete strength classes were selected for comparison – C20/25, C25/30, C30/37, C35/45 and C40/50 according to European Standard EN 206. Design shear resistance for each surface type and each concrete strength class corresponding to the assumed values of reinforcement ratio was calculated according to EN, prEN and ACI specifications. Models for shear at interface between concrete cast at different times included in standards EN, prEN and ACI provide dissimilar results. There is a negligible difference between design shear resistance at a lower reinforcement ratio for a very smooth surface. However, maximum design shear resistance varies significantly – up to 38%. There is a significant variation between design shear resistance for the indented surface at all values of reinforcement ratio. Maximum design shear resistance varies up to 27%.
Key words: adhesion, concrete, design shear resistance, friction, interface, shear connection.

Introduction

Shear at the interface between concrete cast at different times has been studied since the 1960s. The shear friction hypothesis has been formulated (Birkeland & Birkeland, 1966). Tests have been performed to investigate shear transfer in reinforced concrete, formulate a hypothesis for the behaviour of connections and present equations for the design (Mattock & Hawkins, 1972). A model for shear transfer of keyed connections has been developed (Tassios & Tsoukantas, 1978). Results of the research have been summarised in technical publications such as fib Bulletin 43. Dissimilar models have been included in European Standard EN 1992-1-1 (EN) and American Concrete Institute Standard ACI 318-19 (ACI). The main difference between the models – there is no coefficient for adhesion involved in the ACI model.

It has been found that finite element analysis gives a significantly better estimation of capacity for keyed shear joints than the use of equations presented in EN (Herfelt *et al*., 2016). This shows the need to analyse and improve the model included in the EN. New models for shear joints taking into account the dowel action of the reinforcement have been proposed (Sorensen *et al*., 2017). The results of recent studies have been included in the next generation of European Standard prEN 1992-1-1 (prEN).

The aim of the study is to compare models for shear at the interface between concrete cast at different times, given in standards EN, prEN and ACI and used by most European and American structural engineers, to identify dissimilarities and the need for further investigation.

Materials and Methods

Two types of surfaces were chosen for comparison – very smooth and indented according to EN classification. A very smooth surface is surface cast against steel, plastic or specially prepared wooden moulds. An indented surface is a surface with indentations (Figure 1). Surfaces, conditions of surfaces and corresponding factors for adhesion, c and friction, μ according to EN are shown (Table 1).

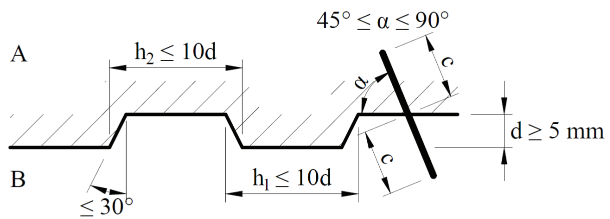

Figure 1. Indented surface according to EN.

A – new concrete, B – old concrete, c – anchorage of reinforcement, d – depth of indentations, h_1 and h_2 – the height of indentations, α – the angle between the reinforcement and surface plane. Figure prepared based on Figure 6.9 of EN.

Table 1

Surfaces, conditions and corresponding factors according to EN

Surface	Conditions of surface	Factor for adhesion[a], c	Factor for friction[b], μ
Very smooth	A surface cast against steel, plastic or specially prepared wooden moulds	0.025 to 0.10	0.5
Indented	A surface with indentations (Figure 1)	0.5	0.9

[a] Adhesion is the molecular force of attraction in the area of contact between bodies;
[b] Friction is the force resisting the sliding of one solid body against another.

The indented surface is named as 'keyed' in prEN. Minimum key height, h_1 and h_2, is given as 3d, where d is the depth of keys (Figure 2). Limits for ratio h_1 / h_2 are given as 0.5 to 2. The minimum α value for the interface reinforcement is reduced from 45° to 35°. It is stated that the key area must be calculated by multiplying key width, $b_{i,eff}$ by key length, $l_{i,eff}$ and factors for keyed interface shall be applied for the area of each key considering its concrete strength. Different symbols of factors for adhesion and friction are used, c_{v1} and μ_v, respectively. Next generation European Standard prEN 1992-1-1 (prEN) specifies lower factor values for adhesion to both very smooth and indented surfaces, 0.0095 and 0.37, respectively. However, factors for friction are the same – 0.5 and 0.9. Surfaces, conditions of surfaces and corresponding factors for adhesion, c_{v1} and friction, μ_v, according to prEN, are shown (Table 2).

ACI specifies contact surface conditions and corresponding coefficients of friction, μ. No coefficients for adhesion are involved. Contact surface condition when concrete is placed against hardened concrete that is clean, free of cement laitance, and not intentionally roughened was compared to a very smooth surface. Contact surface condition when concrete is placed against hardened concrete that is clean, free of cement laitance, and intentionally roughened to a full amplitude of approximately 1/4 in (6.35 mm) was compared to the indented surface. ACI specifies higher coefficient values for friction for normal weight concrete to both very smooth and indented surfaces, 0.6 and 1.0, respectively.

Five concrete strength classes were selected for comparison – C20/25, C25/30, C30/37, C35/45 and C40/50 according to European Standard EN 206. Corresponding characteristic cylinder compressive

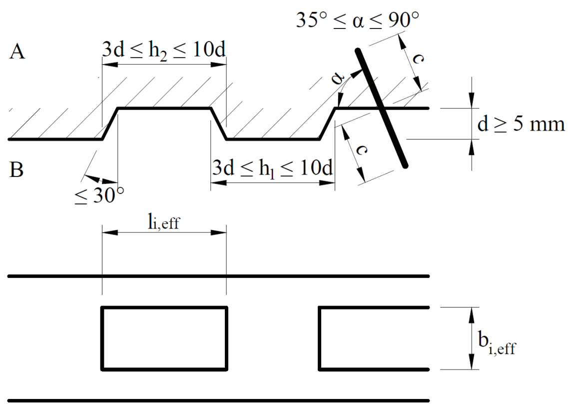

Figure 2. Keyed interface according to prEN.

A – new concrete, B – old concrete, $b_{i,eff}$ – width of key, c – anchorage of reinforcement, d – depth of keys, h_1 and h_2 – the height of keys, $l_{i,eff}$ – length of the key, α – the angle between interface plane and reinforcement. Figure prepared based on Figure 8.15 of prEN.

Table 2

Surfaces, conditions and corresponding factors according to prEN

Surface	Conditions of surface	Factor for adhesion, c_{v1}	Factor for friction, μ_v
Very smooth	A surface cast against steel, plastic or specially prepared wooden moulds	0.0095	0.5
Keyed	A surface with shear keys (Figure 2)	0.37	0.9

strength, f_{ck} values were used in calculations according to EN and prEN. Specified compressive strength of concrete, f_c' values used in calculations according to ACI were assumed to be the same as f_{ck} values.

EN specifies that the characteristic yield strength of reinforcement, f_{yk}, must be 400 to 600 N mm^{-2}. Next generation European Standard prEN 1992-1-1 (prEN) defines six reinforcing steel strength classes with corresponding characteristic values of yield strength of reinforcement, f_{yk} from 400 N mm^{-2} to 700 N mm^{-2}. ACI states that specified yield strength for non-prestressed deformed reinforcement, f_y for shear friction design must not exceed 60 000 psi (414 N mm^{-2}). Characteristic yield strength of reinforcement, f_{yk} for calculations according to EN and prEN was assumed to be 400 N mm^{-2}. Specified yield strength for non-prestressed reinforcement, f_y, used in calculations according to ACI, was assumed to be the same as f_{yk}, 58 015 psi, respectively.

Equation (6.25) of the EN was used for the calculation of design shear resistance at the interface, v_{Rdi}:

$$v_{Rdi} = cf_{ctd} + \mu\sigma_n + \\ + \rho f_{yd}(\mu \sin\alpha + \cos\alpha) \leq 0.5\nu f_{cd} \quad (1)$$

where:

c is a factor for adhesion that depends on the roughness of the interface (Table 1). For a very smooth surface value of c was taken equal to 0.025 in this study;

f_{ctd} is the design tensile strength of concrete, N mm^{-2}. The value of α_{ct} was taken equal to 1 and the value of γ_C was taken equal to 1.5 when calculating design tensile strength of concrete;

μ is a factor for friction that depend on the roughness of the interface (Table 1);

σ_n is stress per unit area caused by the minimum external force perpendicular to the interface plane that acts simultaneously with the shear force, N mm^{-2}. In this study the normal stress was disregarded;

ρ is the reinforcement ratio. Values of ρ were taken in the range from 0 to 0.4 with the step of 0.001 in this study;

f_{yd} is the design yield strength of reinforcement, N mm^{-2}. The value of γ_S was taken equal to 1.15 when calculating design yield strength of reinforcement. The value of f_{yd} equal to 347.8 N mm^{-2} was used in this study;

α is the angle between the reinforcement and surface plane and should be limited by 45° ≤ α ≤ 90° (Figure 1). Angle α was taken as 90° in this study;

ν is a strength reduction factor for concrete cracked in shear;

f_{cd} is the design compressive strength of concrete, N mm^{-2}. The value of α_{cc} was taken equal to 1 when calculating design compressive strength of concrete;

Equation (8.60) of the prEN was used for the calculation of design shear stress resistance at the interface, τ_{Rdi}:

$$\tau_{Rdi} = c_{v1}\sqrt{f_{ck}}\,/\,\gamma_C + \mu_v\sigma_n + \\ + \rho_i f_{yd}(\mu_v \sin\alpha + \cos\alpha) \leq 0.25 f_{cd} \quad (2)$$

where:

c_{v1} is a factor for adhesion that depends on the roughness of the interface (Table 2). The factor for the keyed interface was applied for the area of keys which was taken as half of the joint area in this study. The factor for very smooth interface was applied to the remaining area;

f_{ck} is the lowest compressive strength of the concretes at the interface, N mm^{-2};

γ_C is a partial factor for concrete. The value of γ_C was taken equal to 1.5 in this study;

μ_v is a factor for friction that depends on the roughness of the interface (Table 2). The factor for the keyed interface was applied for the area of keys which was taken as half of the joint area in this study. The factor for very smooth interface was applied to the remaining area;

σ_n is the compressive stress over the interface area A_i, caused by the minimum external axial force across the interface that acts simultaneously with the shear force, N mm^{-2}. The value of σ_n was taken equal to 0 N mm^{-2} in this study;

ρ_i is the reinforcement ratio. Values of ρ_i were taken in the range from 0 to 0.4 with the step of 0.001 in this study;

f_{yd} is the design yield strength of reinforcement, N mm^{-2}. The value of γ_S was taken equal to 1.15 when calculating design yield strength of reinforcement. The value of f_{yd} equal to 347.8 N mm^{-2} was used in this study;

α is the angle between interface plane and reinforcement and should be limited by 35° ≤ α ≤ 90° (Figure 2). Angle α was taken as 90° in this study;

f_{cd} is the design compressive strength of concrete, N mm^{-2}. The value of η_{cc} was taken equal to 1, the value of k_{tc} was taken equal to 1 and the value of γ_C was taken equal to 1.5 when calculating design compressive strength of concrete.

Equation (22.9.4.3) of the ACI was used for the calculation of nominal shear strength across the assumed shear plane, V_n:

$$V_n = A_{vf} f_y(\mu \sin\alpha + \cos\alpha) \quad (3)$$

where:

A_{vf} is the area of reinforcement crossing the assumed shear plane to resist shear, mm^2;

f_y is the specified yield strength of reinforcement, N mm^{-2}. The value of f_y was taken equal to 400 N mm^{-2} in this study;

Table 3

Maximum nominal shear strength according to ACI

Conditions of surface	Maximum nominal shear strength, V_n, N	
Concrete placed against hardened concrete that is clean, free of cement laitance, and not intentionally roughened	Lowest value of	$0.2f_c'A_c$; $5.52A_c$
Concrete placed against hardened concrete that is clean, free of cement laitance, and intentionally roughened to a full amplitude of approximately 1/4 in (6.35 mm)	Lowest value of	$0.2f_c'A_c$; $(3.31 + 0.08f_c')A_c$; $11.03A_c$

μ is the coefficient of friction;

α is the angle between shear-friction reinforcement and the assumed shear plane. Angle α was taken as 90° in this study.

ACI specifies that the nominal shear strength across the assumed shear plane, V_n, shall not exceed the limits (Table 3).

For comparison purposes, nominal shear strength, V_n and specified yield strength of reinforcement, f_y, were divided by A_c in Equation (3). Nominal shear strength, V_n, was multiplied by the strength reduction factor, ϕ, to obtain the design shear strength. The value ϕ was taken equal to 0.75 in this study.

Results and Discussion

The relationship between reinforcement ratio, ρ and design shear resistance, v_{Rdi}, for a very smooth surface for concrete strength classes selected for comparison are shown in Figure 3. There are negligible variations between values of design shear resistance determined using models of different standards at lower reinforcement ratio for all concrete strength classes considered. Maximum design shear resistance, $v_{Rdi,max}$ is different for a very smooth surface (Table 4).

The highest maximum design shear resistance, $v_{Rdi,max}$ for a very smooth surface for all concrete strength classes obtained by calculations according to EN – values are 1 to 38% higher depending on the concrete strength class and standard. The lowest design shear resistance for all concrete strength classes obtained when calculated according to ACI – values are 10 to 38% lower compared to those obtained according to prEN.

The relationship between reinforcement ratio, ρ and design shear resistance, v_{Rdi} for the indented

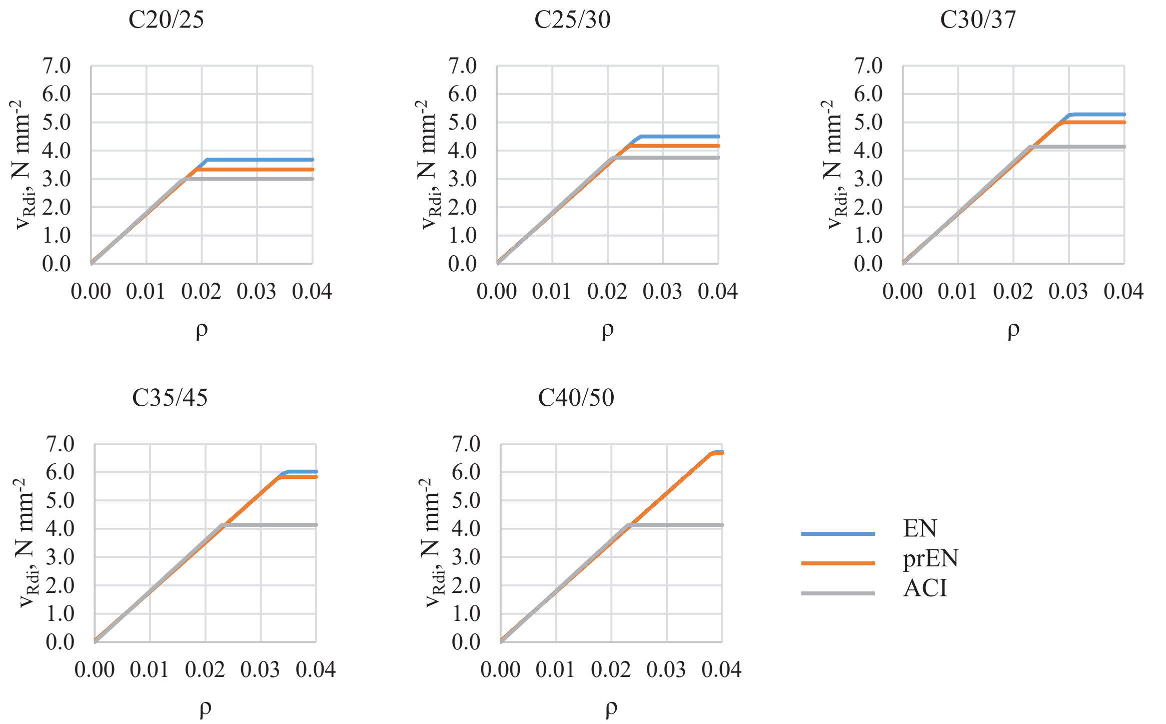

Figure 3. Relationship between reinforcement ratio, ρ and design shear resistance, v_{Rdi} for a very smooth surface.

Table 4

Comparison of maximum design shear resistance for a very smooth surface

Concrete strength class	Maximum design shear resistance, $v_{Rdi,max}$, N mm^{-2}, according to			Ratios	
	EN	prEN	ACI	prEN / EN	ACI / EN
C20/25	3.7	3.3	3.0	0.91	0.82
C25/30	4.5	4.2	3.8	0.93	0.83
C30/37	5.3	5.0	4.1	0.95	0.78
C35/45	6.0	5.8	4.1	0.97	0.69
C40/50	6.7	6.7	4.1	0.99	0.62

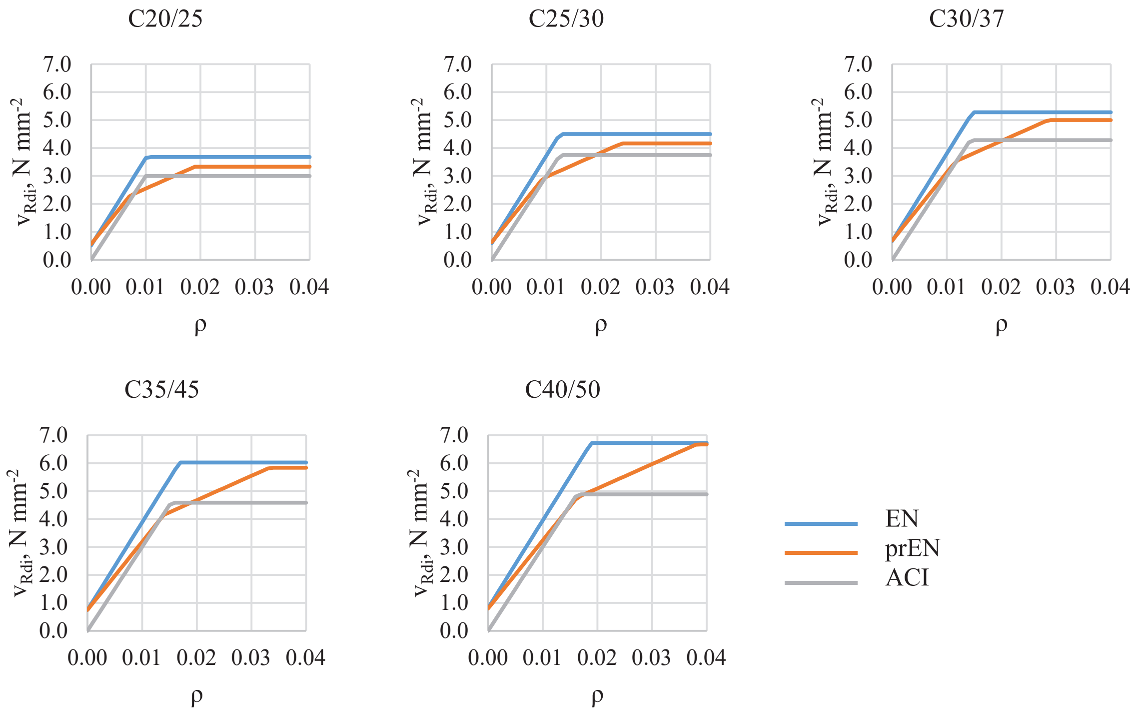

Figure 4. Relationship between reinforcement ratio, ρ and design shear resistance, v_{Rdi} for the indented surface.

surface for concrete strength classes selected for comparison are shown in Figure 4. There are variations between values of design shear resistance determined using models of different standards for all concrete strength classes considered. A comparison of design shear resistance, $v_{Rdi,0.001}$ for the indented surface at a reinforcement ratio value of 0.001 is shown in Table 5.

The highest design shear resistance, $v_{Rdi,0.001}$ for the indented surface at reinforcement ratio, ρ value of 0.001 for all concrete strength classes obtained by calculations according to EN – values are 2 to 73% higher depending on the concrete strength class and standard. The lowest design shear resistance for all concrete strength classes obtained when calculated according to ACI – values are 63 to 71% lower compared to those obtained according to prEN. A comparison of maximum design shear resistance, $v_{Rdi,max}$ for the indented surface is shown in Table 6.

The highest maximum design shear resistance, $v_{Rdi,max}$ for the indented surface for all concrete strength classes obtained by calculations according to EN – values are 1 to 27% higher depending on the concrete strength class and standard. The lowest design shear resistance for all concrete strength classes obtained when calculated according to ACI – values are 27 to 90% lower compared to those obtained according to prEN.

There is no coefficient for adhesion involved in the ACI model. Nevertheless, there is only negligible variation between design shear resistance determined using models of different standards for a

Table 5

Comparison of design shear resistance for the indented surface

Concrete strength class	Design shear resistance, $v_{Rdi,0.001}$[a], N mm^{-2}, according to			Ratios	
	EN	prEN	ACI	prEN / EN	ACI / EN
C20/25	0.83	0.81	0.30	0.98	0.36
C25/30	0.91	0.88	0.30	0.96	0.33
C30/37	0.99	0.94	0.30	0.95	0.30
C35/45	1.06	0.99	0.30	0.93	0.28
C40/50	1.13	1.04	0.30	0.92	0.27

[a] Design shear resistance, $v_{Rdi,0.001}$, given at reinforcement ratio, ρ value of 0.001.

Table 6

Comparison of maximum design shear resistance for the indented surface

Concrete strength class	Maximum design shear resistance, $v_{Rdi,max}$, N mm^{-2}, according to			Ratios	
	EN	prEN	ACI	prEN / EN	ACI / EN
C20/25	3.7	3.3	3.0	0.91	0.82
C25/30	4.5	4.2	3.8	0.93	0.83
C30/37	5.3	5.0	4.3	0.95	0.81
C35/45	6.0	5.8	4.6	0.97	0.76
C40/50	6.7	6.7	4.9	0.99	0.73

very smooth surface at a lower reinforcement ratio. A higher value of the coefficient for friction defined in the ACI compensates for the lack of coefficient for adhesion.

There are factors for adhesion with relatively high values for the indented surface involved in the models of EN and prEN. Therefore, there is significant variation between the design shear resistance obtained using models of EN and prEN compared to that derived using a model of ACI at a lower reinforcement ratio. The variations between values determined according to EN and prEN increase as the reinforcement ratio increases. This is because factors for keyed interface were applied for the area of keys, according to requirements of prEN, which was taken half of the joint area in this study. To the remaining area, factors for a very smooth interface were applied.

Maximum design shear resistance determined using models of different standards for very smooth and indented surfaces is varied for all concrete classes considered. The variations between the values determined according to EN and prEN decrease as the strength class of the concrete increases, while the variations between the values determined according to EN and ACI increase. The upper limit of the shear strength defined in the standards is different.

Conclusions

Models for shear at interface between concrete cast at different times included in European Standard EN 1992-1-1, in the next generation European Standard prEN 1992-1-1 and American Concrete Institute Standard ACI 318-19 give dissimilar results. There is a negligible difference between design shear resistance at a lower reinforcement ratio for a very smooth surface. However, maximum design shear resistance varies significantly – up to 38%. There is a significant variation between design shear resistance for the indented surfaces at all values of reinforcement ratio. Maximum design shear resistance varies up to 27%.

In future research, results obtained using models included in standards need to be validated using the nonlinear finite element analysis and experimental load tests. It is necessary to develop a model for economical solutions with the required level of reliability.

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