Analytical Investigation of Shear Friction Strength

Heba Ali Abdel Rahman / Searcher, Housing and Building National Research Center, Cairo, Egypt
Email: hebaali1985@yahoo.com

ABSTRACT

Shear friction theory forms the basis for shear transfer models. The transfer of shear across uncracked plane is the subject of this analytical investigation. Finite element idealization is made to model concrete and reinforcing bars behavior, cracking, bond-slip characteristics and post yielding state of loading. ANSYS program is used to achieve the idealization. Sixteen push off specimens were modeled to study the load- deformation behavior, the cracking load, the failure load, the strain in the clamping reinforcing bars as the load is increased up to failure. The predicted shear strength is compared with the strength calculated using ACI,AASHTO, and the Egyptian Code ECP .The levels of conservatism implied by adopting codes equations are reported. The influences of concrete strength and the area of clamping reinforcement on the shearing strength are assessed.
Keywords : Dowels, Concrete, Reinforcement, Friction, shear

1.INTRODUCTION

Compared to the axial and flexural counterparts, the shear behavior of concrete structures is less predictable, due to the complexity of shear transfer mechanisms and the difficulties in numerical modeling. Shear plays an important role in the overall structural behavior of reinforced concrete members [1] .The dowel action of reinforcing bars is one of the component actions for shear transfer in a cracked concrete structure.

According to R.Park et.al. [1], the shear resistance of a cracked concrete structure is constituted of:
(1) Direct transfer of shear force by uncracked concrete;
(2) Direct tensile forces in stirrups;
(3) Aggregate interlock at crack surface;
(4) Dowel action of reinforcing bars crossing the crack. Figure (1) shows the above internal forces pertaining to a cracked concrete beam.

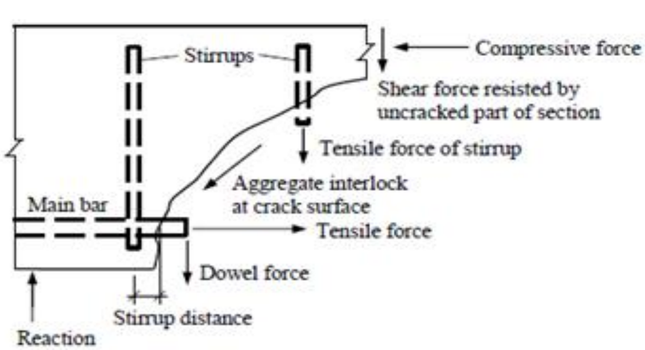

Figure (1): Internal Forces in Cracked Beam

D. Figueira et al. [2], focused on the contribution of dowel action. The strength of a dowel subjected to monotonically increasing load was predicated. They concluded that reinforcement kinking effect arises in concrete interfaces at large slip values.

Cheo et al, [3], studied experimentally the dowel behavior of the rebars embedded in a small concrete block .Test variables were concrete compressive strength, dowel rebar diameter and yield strength, specimen thickness, and dowel rebar spacing. The maximum dowel force increased as concrete compressive strength and dowel rebar diameter increased. The shear slip at the maximum dowel force decreased as the dowel rebar diameter increased. There weren't considerable effects of specimen thickness and dowel rebar spacing on the maximum dowel force.

E.Júlio et al, [4], described the strengthening operations of RC structures as follows :(a) determine the concrete-to-concrete interface debonding stress (at the instant adhesion is lost), for different percentages of reinforcement crossing the interface; (b) analyze the corresponding behavior, after debonding of the interface, and determine the interface shear strength; (c) verify the difference between having the reinforcement placed before casting the substrate concrete and having it inserted into the hardened concrete substrate; (d) for this second situation, analyze the efficiency of two commercial products used to anchor the steel connectors; and (e) compare test results with values determined according to design codes.

They concluded that:

1. The reinforcement crossing the interface does not significantly increase the interface debonding stress.
2. The shear strength of the interface increases with the increase of reinforcement crossing the interface.
3. For low reinforcing ratios, the shear strength of the interface corresponds to the debonding stress.
4. For higher reinforcing ratios, the shear strength of the interface is not reached immediately on debonding but only after an important slip.
5. There is a difference of 6.6% to 8.3% between having the reinforcement placed before casting the substrate and having it inserted into hardened substrate.
6. Results obtained with each of the two commercial epoxy resins used to anchor the steel connectors were only marginally different.
7. Higher shear strength of the interface is achieved with sandblasted surfaces than with surfaces cast against steel formwork.

K.N.Rahal et al, [8], studied experimentally 15 non-precracked push off specimens to study the shear behavior of normal strength and high-strength SCC. They concluded that increasing compressive strength of the concrete significantly increased the ultimate shear strength but had a limited effect on the cracking and the residual strengths. also suggested that a using the shear friction general equation with a coefficient of cohesion $c = 0$, a coefficient of friction $\mu = 1.0$, and an upper limit on the stress equal to 5.5 MPa provides adequate calculation of the residual strength in push off specimens which were not pre-cracked.

In this investigation, modeling of sixteen push off specimens was achieved using ANSYS program. The behavior before and after yielding of clamping reinforcement was studied.

2-GEOMETERY OF MODELED SPECIMENS

Sixteen models were studied. The specimens were divided into four groups. Each group consisted of four specimens of same dimensions 300 * 300 * 150mm as shown in figure (2). Specimens have equal shear and flexure reinforcement. The test specimens varied in dowel diameter, and concrete compressive strength. The lengths of dowels as multiplier of bar diameter (ϕ) was 15 time. The diameter of dowels varied between 8, 10, 12, and 16mm.The designation system of specimens used in this investigation is given in figure (3).

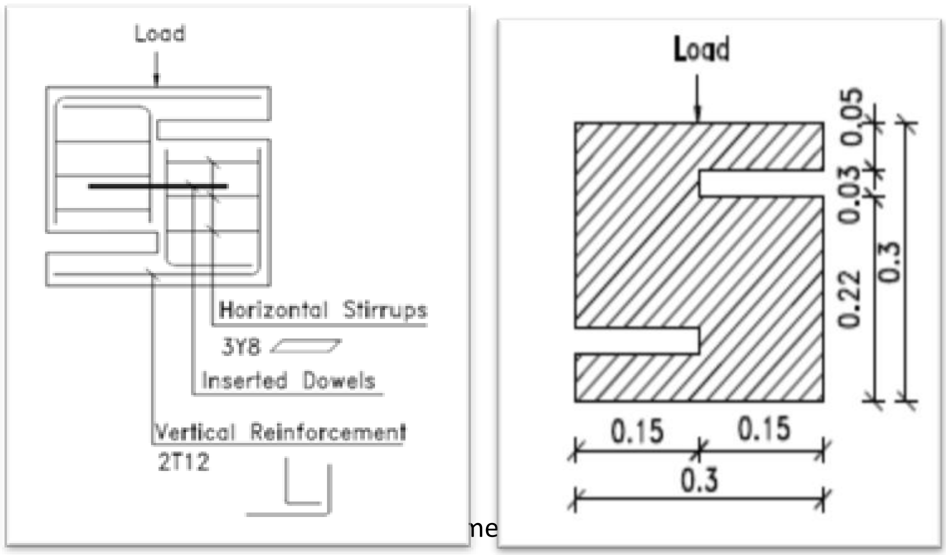

Figure (2): Specimen Dimensions & Reinforcement

Designation of specimen:

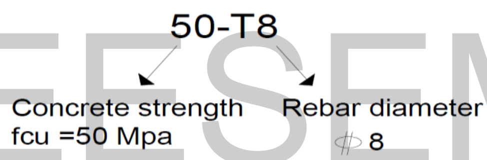

Figure (3): Designation System of Modeled Specimens

2. FINITE ELEMENT MODELLING

The analysis of reinforced concrete beams beyond cracking requires a mathematical model that considers crack opening, concrete crushing, and materials nonlinearities. The nonlinear behavior of concrete and steel puts an early limit on the validity of linear mathematical models .The sources of nonlinearity in the relationship between stresses and strains include effects of concrete cracking, concrete crushing, steel yielding, steel strain hardening and tension stiffening. The finite element method offers the most suitable approach to form theoretical models which consider these sources of nonlinearity. The 3-D models consider the effect of confinement through consideration of deformations in the out –of – plane. The computerized models used for the nonlinear analysis of the investigated beams were formed by elements of the library of the program namely Ansys 5.4 [7].The wire frame meshes for the finite element models of beams are shown in figure (4).

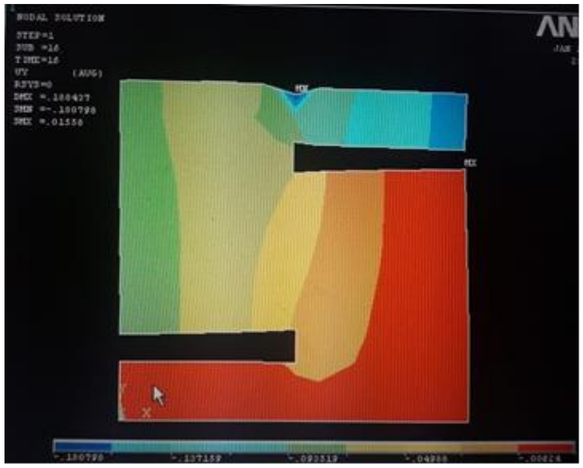

Figure (4) Arrangement of Concrete Solid Elements

4. ANALYTICAL RESULTS

4.1 Shear strength

The predicated shear strength results are summarized in Table 1.

Table (1): Analytical Results of Shear Strength

Specimen Label	Failure Load(KN)	Shear strength(Mpa)	Specimen Label	Failure Load(KN)	Shear strength(Mpa)
20-T8	68	3.28	**30-T8**	89.3	4.25
20-T10	72.4	3.45	**30-T10**	90	4.3
20-T12	74	3.5	**30-T12**	92	4.4
20-T16	74.2	3.5	**30-T16**	92	4.4
40-T8	112	5.35	**50-T8**	138	6.6
40-T10	114	5.42	**50-T10**	145	6.9
40-T12	114.7	5.45	**50-T12**	157.5	7.5
40-T16	114.7	5.45	**50-T16**	157.5	7.5

The shear strength increases as the compressive strength increases. The shear strength increases as the clamping bar area increases for the small bar diameters (8mm and 10 mms). For larger diameters the increase in shear strength is unnoticeable. This result indicates the validity of adopting maximum limit on the shear strength depending on the characteristic compressive strength of concrete (fcu).

4.2 Load-shear deflection characteristics

The load-shear deformation relationship is plotted in figure (5), for dowel bar diameter of 8mm as an example for the relationship for other diameters. As the load increases, three distinct zones are recognized. The first zone ends with the development of cracks along the shear- transfer plane. The second zone is associated with yielding of clamping steel. The third zone ends at attaining the ultimate load. The capability of sustaining significant shear deformation at nearly constant shear load is evident. The residual strength after steel yielding stage is present.

The load-versus shear deformation across the transfer plane is plotted for the specimens of concrete strength of 20 $N/mm^{2.}$ In figure (6) the effect of the area of clamping bars is illustrated. There is insignificant difference between the specimens for the relatively low levels of load. At this load level the concrete is mainly responsible for the shear resistance. After cracking, the clamping reinforcement becomes more effective in the mechanism of shear resistance.

The cracking load levels are distinguished by the relative softening of the curves as compared to the initial stiffness which is associated with uncracked state. The bearing stress on the concrete at the transfer plane under the clamping bar is of significant influence on the initiation of cracking. This issue has its impact on shear deformation and overall behavior. The role of the high strength of concrete on the ultimate load may be assessed based on the level of bearing stress under the clamping bar. This confirms the validity of the common assumption in shear –friction models [5] for the pre cracked and the uncracked shear interfaces with respect to mechanism of shear – friction.

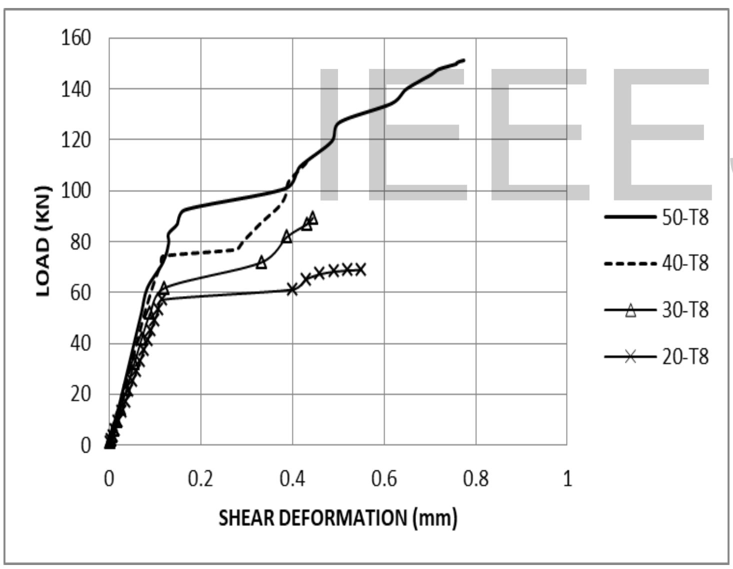

Figure (5): Load-Shear Deformation Diagrams-Clamping Bar Diameter =8mm

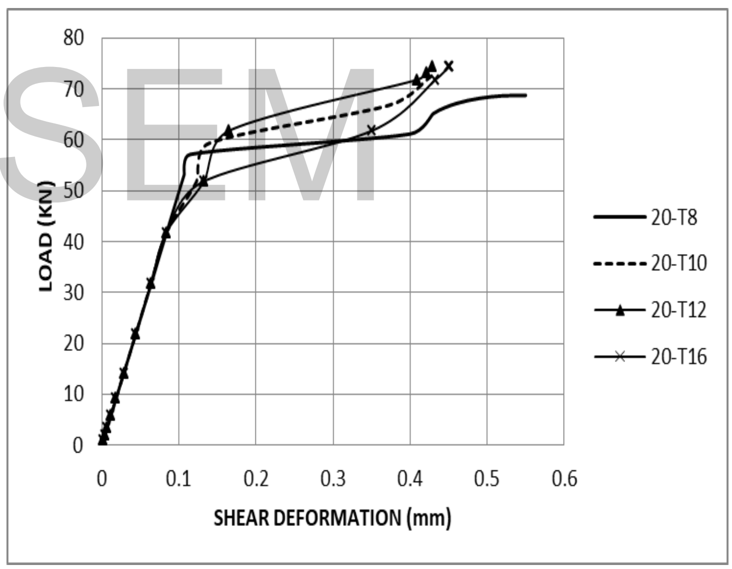

Figure (6): Load-Shear Deformation Diagrams-Concrete Strength fcu=20N/mm2

4.3 Effect of Concrete Compressive Strength.

The results indicate that the shear capacity due to the dowel behavior of the rebars is significantly influenced by the compressive strength of the concrete rather than by the yield strength of the rebars. The maximum dowel force of the rebars increases by increasing concrete strength. .This result is in agreement with previous models [5,6], which showed that the maximum dowel force is proportional to the square root of concrete compressive strength. The primary parameters considered in these models were concrete compressive strength, dowel rebar yield strength, and dowel rebar diameter. The governing equations are given in table (2).

Table (2): Randl and MC10 Governing Equations

Model	Equations
Randl [5]	Simple model $D\max = 1.5 A s \sqrt{f y} \sqrt{f cwm}$
MC10 [6]	$D\max = k_{2,max} A s \sqrt{f co f y} \leq (A s f y/\sqrt{3})$

Where Dmax: Maximum dowel force (N), fcwm is compressive strength of concrete cube,
$K_{2,max}$ is Interaction coefficient for flexural resistance .It is taken 1.6 for compressive concrete strength 20 to 50 N/mm2
The present investigation confirms that the effect of the strength of the dowel rebars is not as significant as that of concrete compressive strength; It can be seen from the analyses that concrete compressive strength has a stronger effect on the shear strength, as compared to the yield strength of dowel rebars. The increase in concrete strength leads to increased bearing strength under dowel rebar, this bearing strength has strong effect on the shear strength

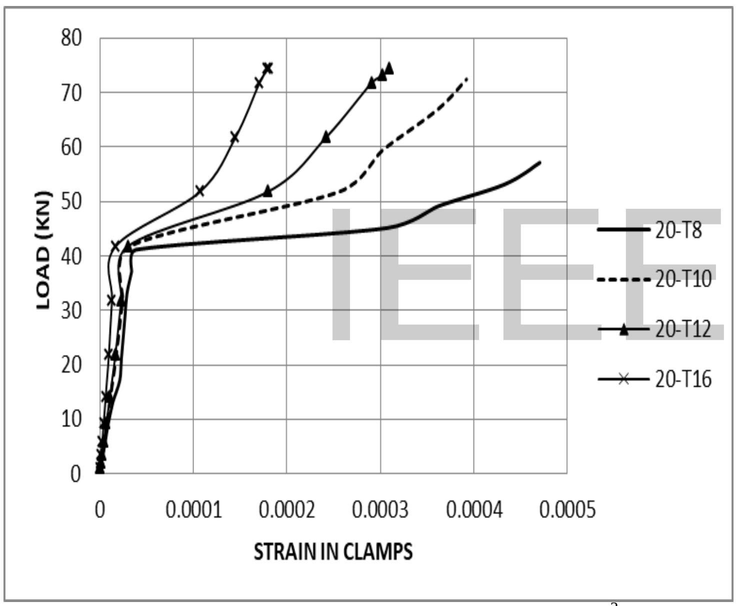

Figure (7) Strain in Clamps of Specimen with fcu=20N/mm^2

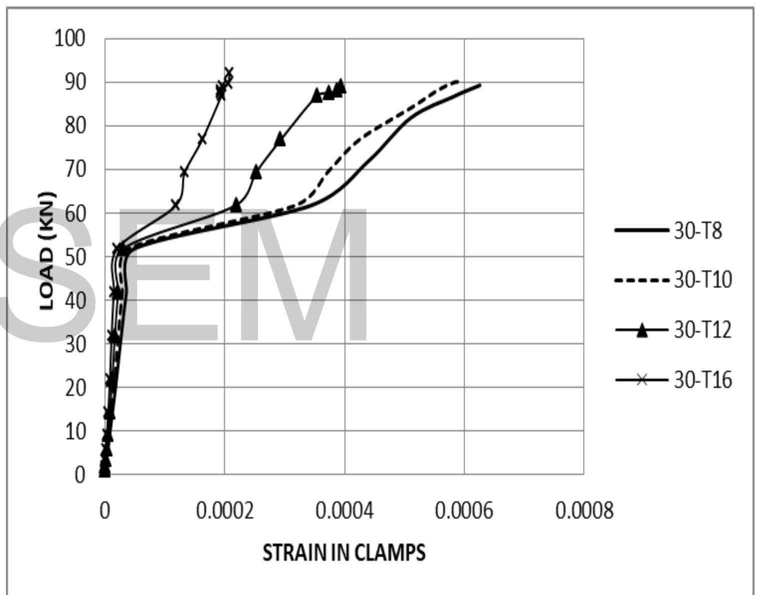

Figure (8) Strain in Clamps of Specimen with fcu=30N/mm^2

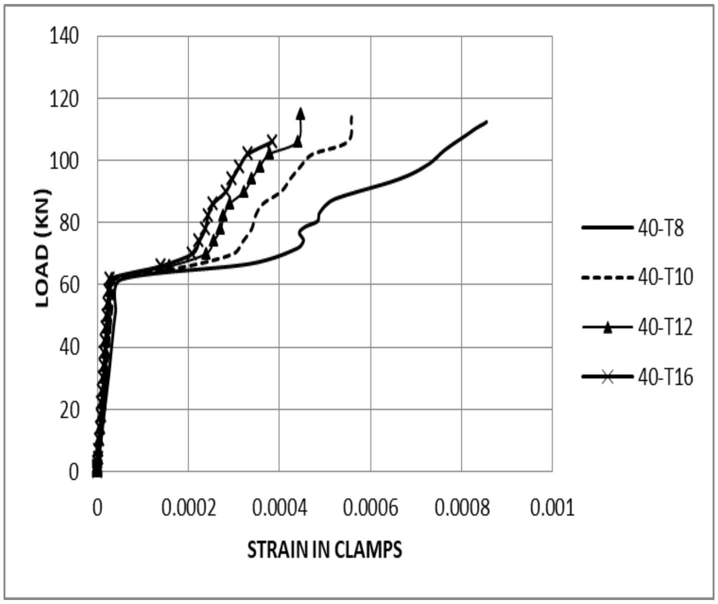

Figure (9) Strain in Clamps of Specimen with fcu=40N/mm^2

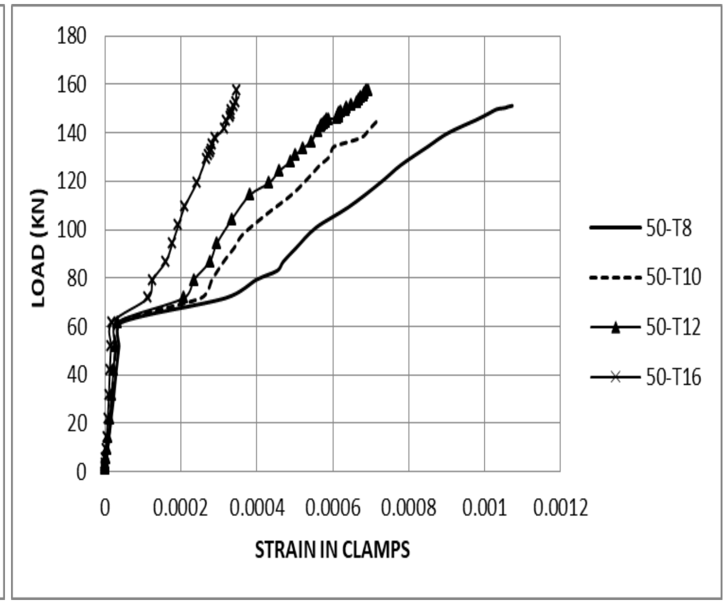

Figure (10) Strain in Clamps of Specimen with fcu=50N/mm^2

5. Codes Comparison

The ACI, AASHTO, and ECP codes are applicable to the case of monolithic construction. They are used to calculate the ultimate strength of the specimens. The codes equations are given in table (3).Table (4) present the results of applying the codes to the investigated specimens to estimate the dependable shear strength. The calculated values are also given for comparison.

Table (3): Codes equations

Code	Formula	Upper limit
ECP	$Q = \mu_f A_{sf} fy \leq$	$0.225fcu/\gamma c$ 5.5Mpa
ACI-318	$U_{ACI} = \mu \rho_{vf} fy \leq$	$0.2f'_c$ 3.3+0.08f'c 11Mpa
AASHTO LRFD	$U_{AASHTO} = C + \mu \rho_{vf} fy \leq$	$0.25f'_c$ 10.3Mpa

ρv ratio of clamping reinforcement perpendicular to shear transfer plane The term μ is a coefficient to account for friction. It is taken as 1.4 for concrete cast monolithically, where the terms (c) and (μ_f) are taken as 2.8 MPa and 1.4 for monolithic construction.

Table (4): Shear Strength – Code Values versus Values Calculated by Modeling.

Specimen label		ACI Code value (N/mm^2)		AASHTO LRFD(N/mm^2)		ECP (N/mm^2)		ANSYS calculated by model (N/mm^2)
		Formula value	Upper limit value	Formula value	Upper limit value	Formula value	Upper limit value	
Fcu=20 N/mm2	20-T8	2.4	3.2	5.2	4	2.06	3	3.28
	20-T10	3.65		6.45		3.13		3.45
	20-T12	5.4		8.2		4.61		3.5
	20-T16	9.6		12.4		8.3		3.5
Fcu=30 N/mm2	30-T8	2.4	4.8	5.2	6	2.06	4.5	4.25
	30-T10	3.65		6.45		3.13		4.3
	30-T12	5.4		8.2		4.61		4.4
	30-T16	9.6		12.4		8.3		4.4
Fcu=40 N/mm2	40-T8	2.4	5.86	5.2	8	2.06	5.5	5.35
	40-T10	3.65		6.45		3.13		5.42
	40-T12	5.4		8.2		4.61		5.45
	40-T16	9.6		12.4		8.3		5.45
Fcu=50 N/mm2	50-T8	2.4	6.5	5.2	10	2.06	5.5	6.6
	50-T10	3.65		6.45		3.13		6.9
	50-T12	5.4		8.2		4.61		7.5
	50-T16	9.6		12.4		8.3		7.5

For characteristic strength of concrete of 20 N/mm2, The ACI and ECP codes results are conservative than the AASHTO code. The AASHTO code isn't conservative for all specimens. The best correlation average was achieved by ACI's code. The AASHTO code overestimates the shear strength of specimens with concrete characteristic strength 20N/mm2.

For characteristic strength of concrete of 30 N/mm2, The ACI and ECP codes results are conservative, but the AASHTO code isn't conservative at bar diameter exceeding (T10). The best correlation average was achieved by ACI's and ECP models. AASHTO code formula is applicable for specimens not exceeding clamps diameter (T10) at concrete characteristic strength 30N/mm2.

For characteristic strength of concrete of 40 N/mm2, The ECP code results are significantly more conservative than other codes, but the ACI code is slightly conservative for bar diameter exceeding (T12).The AASHTO code isn't conservative for all specimens except specimen with clamp diameter (T8). The best correlation average was achieved by ECP's model.

For characteristic strength of concrete is 50 N/mm2, , The ACI and ECP codes results are more conservative. The best correlation average was achieved by ACI's and ECP models. AASHTO code formula is applicable for specimens not exceeds clamps diameter (T10) at concrete characteristic strength 50N/mm2.

6. Conclusions

Sixteen analytical models for push-off specimens were made to investigate shear- friction behavior. The variables of the investigation include the area of the clamping reinforcement and the concrete strength. The predicated shear strength was compared with code values.
Based on the results, the following conclusions are presented:-

1. In all specimens, splitting cracks at failure occurred in the concrete under the dowel rebars. It can be inferred from the failure mode observed through the process of load increase that splitting cracks have a strong effect on the dowel behavior of the rebars embedded in a small concrete member.

2. After cracking the clamping reinforcement becomes more effective in the mechanism of shear friction. The strain in the reinforcement increases significantly after cracking.

3. The shear strength increases as the clamping bar increases for the relatively small ratios of bar area to shear plane area of concrete. For large diameter of clamping bars, the increases are unnoticeable. The result confirms the validity of placing a limit associated with concrete strength on the dependable shear strength.

4. The development of tensile strains in the clamping reinforcement passes through three stages namely, before cracking stage, yielding of reinforcement stage and residual strength stage. The large strain at yielding of bars provides the beneficial ductility of the shear transfer mechanism.

5. The ACI and ECP code equations provide conservative estimates of shear strength while AASHTO code may lead to un-conservative estimation especially at concrete strength exceeding $40N/mm^2$.

6. The ECP code is conservative particularly for the relatively low ratio of area of clamping reinforcement to the shear cross sectional area. For relatively high concrete strength the ACI and ECP codes are conservative when compared to the prediction of the analytical models.

7. The shear capacity due to the dowel behavior of the rebars is significantly influenced by the compressive strength of the concrete rather than by the yield strength of the rebars. The maximum dowel force of the rebars increases by increasing concrete strength.

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