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Data Driven Appraisal for One-way and Two-way Shear Design of Lightweight Concrete and FRP-reinforced Concrete Elements

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Abstract - One-way and Two-way Shear failure of reinforced concrete elements is catastrophic and sudden; thus, researchers have given these topics special attention [1, 2]. In addition, construction is implementing new materials every day. Thus, design codes need to be refined for these cases. Moreover, extensive experimental databases are becoming massive every day. Finally, American and European design codes are being updated for these special cases. In this communication, several design code appraisals developed by Deifalla and co-workers for various cases are outlined. Those cases include the following: (1) FRP-reinforced concrete elements under one-way and two-way shear [3-4]; (2) Lightweight concrete elements under one-way shear [5-7]. Those appraisals were developed based on experimentally observed behavior in terms of identifying effective parameters and multi-variable nonlinear regression for extensive experimental databases. Developed code appraisals are compared to existing design codes. Concluding remarks are outlined. Future areas of research are outlined.

Keywords**:** one-way shear, two-way shear, FRP, lightweight concrete

1. Introduction

One-way and two-way shear strength of concrete elements is a complicated issue influenced with so many parameters and mechanisms. One-way shear is more advanced in terms of research studies and findings [1-7]; however, both one-way and two-way shear is still a dilemma with many hidden factors to be revealed. Those factors include the size effect and dowel action. Thus, worldwide investigations are tackling the shear design of RC specimens in an attempt to develop an accurate and reliable design provisions, yet simple [8-20]. In addition, new advancement in the concrete construction technology is adding to this dilemma for example lightweight concrete (LC) and fiber reinforced polymer (FRP)–reinforced concrete. Thus, design code development should include special provisions for LC and FRP-reinforced concrete elements [21-27].

The shear strength is governed by several types of shear cracks and a large number of basic variables; therefore, it continues to be an area of investigation in RC structures. The basic variables of the shear strength are the cross-section dimensions, the span length, the loading configuration, the reinforcement configuration, and the material mechanical properties. Shear cracks are either initiated by shear or flexure as shown in Fig. 1. Although LC has been utilized all over the world, yet, the known about the shear behavior of LC is not much [21, 24-26]. LC has a significantly better insulation and ductility, while it has a lower weight, splitting resistance and aggregate interlock shear resistance compared to normal-weight concrete (NC) [21]. Which is due to Cracking of LC passes through aggregates rather than around aggregate as shown in fig. 2. Although shear design of NC elements is well developed, not much was changed regarding LC design since the 60s'.

FRP-reinforced concrete specimens are different than conventional steel reinforced concrete specimens in many aspects including the following: (1) Different mechanical properties for various types; (2) Lower longitudinal stiffness and transversal shear resistance; (3) Linear up to failure with no yield plateau or post ultimate behavior (i.e., concrete for ductility), thus Brittle in nature; and (4) Wider concrete cracks and larger deformations. Very limited design codes are developed for FRP reinforced concrete under one-way and two-way shear is still need further development.

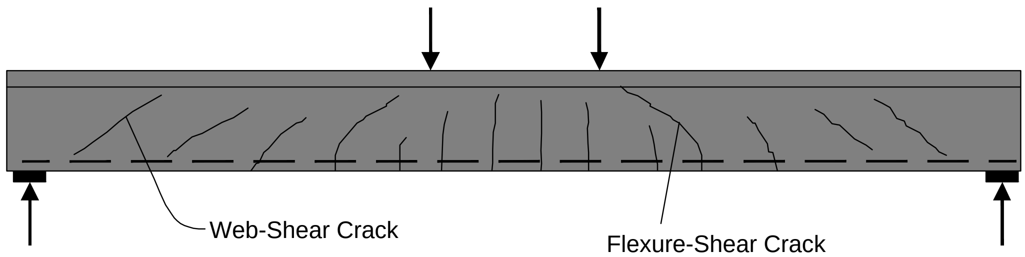

Fig. 1. Shear cracking.

Fig. 2. Shear cracking a) normal weight and b) lightweight aggregates.

In this current study an extensive experimental database of LC and FRP-reinforced concrete elements tested under one-way and two-way shear was compiled. A multi-variable nonlinear equation for each case was developed based on the measured strength of theses experimental databases. The shear resistance of elements was calculated using proposed equations and compared with that calculated using selected design codes. Design codes include the ACI, the EC2, the MC, the JSCE, and the CSA [22, 23, 27-30]. The consistency, accuracy, and the safety of the proposed equations are discussed. In addition, the variation of the safety of selected design codes versus selected parameters is discussed. Concluding remarks were outlined.

2. One-way and Two-way Shear Mechanisms

Making physical sense of the behavior of LC elements under shear is in need of further digging, due to its complexity at many levels. After the first onset of cracking, stress distribution becomes complex, while being affected by a combination of several parameters and mechanisms. In the late 90's, the ASCE-ACI Committee 445 [1], reported significant shear transfer mechanisms as follows: (1) shear in the un-cracked compression zone of the element; (2) shear in the cracking interface due to aggregate interlock as well as the surface roughness along inclined cracks; (3) dowel action of the longitudinal reinforcement; (4) residual tensile stresses across inclined cracks; and (5) arch mechanism as shown in fig. 3. In addition, the Arch Action Mechanism, which is a dominant shear transfer mechanism in case of non-slender elements (i.e., $a/d < 2.5$), where the shear forces are transmitted directly to the supports via an inclined strut.

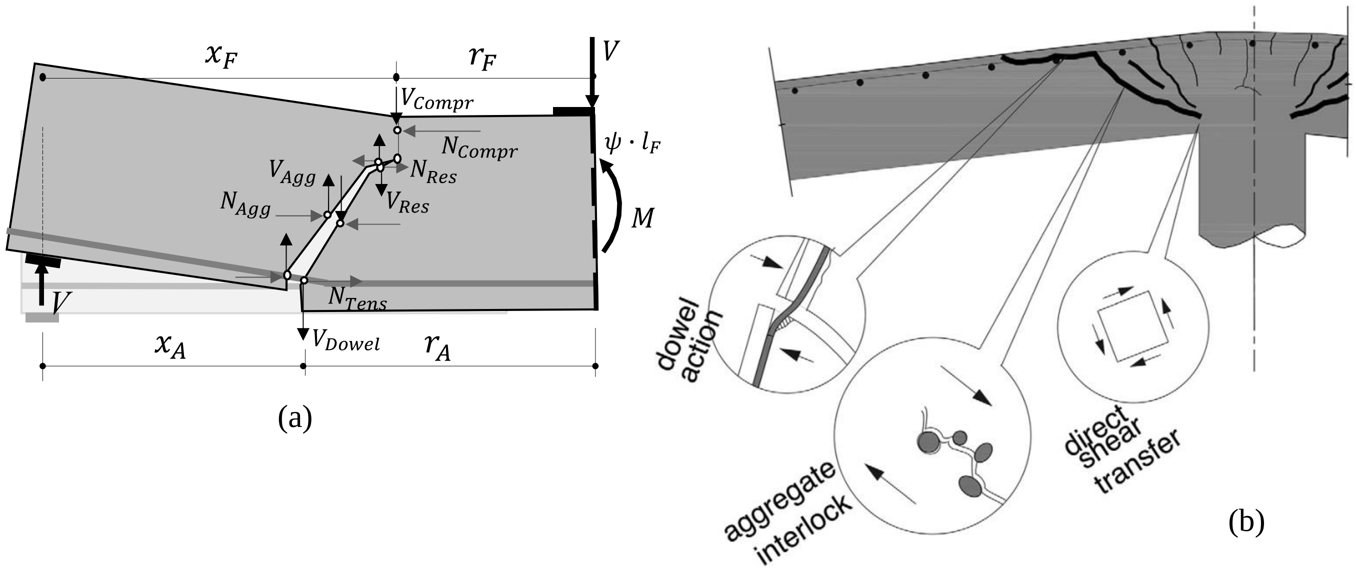

Fig. 3. Shear mechanism a) one-way and b) two-way.

3. Experimental Databases for One-way Shear and Two-way Shear

The present study adopts the most comprehensive database for LC and FRP-Reinforced concrete elements available, consisting of 700 specimens tested in 70 studies [3-7].

4. Appraisals for One-way Shear and Two-way Shear of LC elements

4.1. One-way shear

For one-way shear, the critical shear crack theory (CSCT) was adapted for the development of the new European design code draft (prEC2); however, it was slightly modified, where the aggregate interlock is not reduced, and the full nominal maximum aggregate size is considered. Therefore, the one-way shear resistance is such that:

$$V = 0.6\left(100\rho f_c{}' \frac{d_{dg}}{r}\right)^{1/3} bd \geq 10bd\sqrt{\frac{f_c{}'}{f_y}\frac{d_{dg}}{d}} \tag{1}$$

, where ρ is flexure reinforcement ratio, $f_c{}'$ is concrete compressive strength, d is effective depth, f_y is reinforcement yield strength , b is the width of element, $\mathrm{d_{dg}}$ is taken $16 + \mathrm{d_g}$, $16 + \left(\frac{\mathrm{d_g}}{\mathrm{f_c}'}\right)^2$ for $\mathrm{f_c}' \leq 60$ MPa, and for $\mathrm{f_c}' > 60$ MPa, and r is taken the least of $\sqrt{\frac{\mathrm{a}}{4}\mathrm{d}}$ and d.

4.2. Two-way shear

For two-way shear, the effective parameters were identified based on the principles of linear fracture mechanics, the CSCT, and the experimentally observed behavior of LC. Further, using nonlinear multi-variable regression, a proposed design model, where the two-way shear strength is calculated such that:

$$V = \left(6.5\mu\frac{d}{b_o}\right)^{1/2}\left(100\rho f_c{}' \frac{\lambda d_{dg}}{d}\right)^{1/3} b_o d \leq 0.6\sqrt{f_c{}'} \tag{2}$$

, where ρ is flexure reinforcement ratio, $f_c{}'$ is concrete compressive strength, d is effective depth, f_y is yield strength , b_o is the perimeter of critical section, $\mathrm{d_{dg}}$ is taken $16 + \mathrm{d_g}$, $16 + \left(\frac{\mathrm{d_g}}{\mathrm{f_c}'}\right)^2$ for $\mathrm{f_c}' \leq 60$ MPa, and for $\mathrm{f_c}' > 60$ MPa, μ is 9, 5, 2 for inner, edge, and corner columns, λ is taken as $1 - 0.9^{\gamma_c}/_{2200}$.

5. Appraisals for One-way Shear of FRP-reinforced elements

For one-way shear, the prEC2, which is based on the CSCT, was adapted. Applying multi-variable nonlinear regression for the experimental data base, the experimentally observed behavior, and the prEC2, thus, the one-way shear resistance is such that:

$$\mathrm{V} = 0.35\lambda_{sh}(E\rho)^{1/4}(f_c{}')^{1/4}\left(\frac{1}{1+{}^{d}/_{200}}\right)^{1/2}\left(\frac{d}{a}\right)^{\lambda_a} bd \tag{3}$$

, where ρ is flexure reinforcement ratio, $f_c{}'$ is concrete compressive strength, d is effective depth, b is the width of element, a is the shear span, E is the flexure reinforcement young's modulus, λ_{sh} is taken as 1 and 0.75 for rectangular and circular cross sections, respectively, λ_a is taken as 1 and 1/3 for slender and non-slender elements, respectively, and a is the shear span.

6. Comparison between Appraisals and Existing Deign Codes

Tables 1-3 shows the comparison between the proposed models and selected models from the literature. It is clear that proposed models predicted the strength more accurately and consistently compare

Table 1: One-way of LC elements.

Measure	**ACI**	**EC2**	**MC(I)**	**MC(II)**	**CSA**	**JSCE**	**Eq. (1)**
Mean	1.65	2.31	1.49	1.57	0.82	1.63	1.08
C.O.V.	39%	44%	41%	80%	58%	43%	36%
Lower 95%	1.53	2.12	1.37	1.32	0.73	1.50	1.00

Table 2: Two-way shear of LC elements.

Measure	**ACI**	**EC2**	**MC(I)**	**MC(II)**	**MC (III)**	**Eq. (2)**
Mean	1.58	1.46	2.03	1.62	1.44	1.01
C.O.V.	37%	25%	42%	48%	46%	25%
Lower 95%	1.48	1.40	1.79	1.49	1.33	1.01

Table 3: One-way shear of FRP-reinforced elements.

Model/Code		**Mean**	**COV**	**99 % L.L.**
CSA-S806-12	Slender	1.07	28%	1.04
	non-Slender	2.54	65%	2.41
ACI-440-15	Slender	2.03	43%	1.93
	non-Slender	6.81	57%	6.40
CAN/CSA S6-14	Slender	0.76	36%	0.73
	non-Slender	3.11	68%	2.83
Eq. (3)	Slender	1.05	47%	0.99
	non-Slender	1.18	61%	0.98

5. Conclusion

Three extensive experimental databases for lightweight concrete and FRP reinforced concrete elements under one-way shear and two-way shear were gathered and used to calculate the strength. Multi-variable nonlinear regression and experimental observations were implemented in order to develop a design code appraisal for the four cases. A comparison between the proposed equations and the existing design codes shows that the proposed models are more accurate, consistent and simple enough for the purpose of design.

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