SHEAR STRENGTH OF PRECAST PRESTRESSED CONCRETE HOLLOW CORE SLABS

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ABSTRACT

Since early eighties, the precast prestressed concrete hollow core slab cross sections with non-circular voids became gradually popular, first in 400 mm thick slabs, then in 500 mm thick slabs. However, it is evidenced that this type of deeper slab sections have subjected to initial web shear cracking when they are provided with longer supports and resist for heavy line loads acting closer to the supports. Therefore, the objective of this study is to review the equations specified in American Concrete Institute (ACI), Eurocode 2 (EC2) and Canadian Standards Association (CSA) to evaluate the shear strength of a member having no transverse reinforcement as in the case of the hollow core slabs. For this purpose, the experimental test data of the hollow core slabs are collected from past experimental programmes and detailed finite element analyses are performed. Based on experimental and numerical results, the conclusions are drawn. The evaluation of shear strength by the equations specified in ACI, EC2 and CSA are conservative for the slab cross sections with circular voids while ACI and EC2 predictions are not conservative for deeper slab sections with flat webs. However, the calculations based on CSA for all types of hollow core slab sections are more conservative than the latter based on ACI and EC2.

Key words**:** Shear strength, Precast, Prestressed hollow core slab

1. INTRODUCTION

Prestressed hollow core concrete slabs were developed in the 1950s and they have subjected to only little changes for more than 30 years. These slabs which are made of high-strength concrete are prefabricated concrete members with large hollow proportions. In practice, they are interconnected after assembly by joint grouting compound. In contrast to the conventional concrete members, the prestressed hollow-core concrete slabs have many advantages such as saving material, energy and reducing the weight of transportation. Since early eighties, the slab cross sections with non-circular voids became gradually popular. These deeper slab units are increasingly used in industrial buildings and office buildings where it is provided large open parking spaces on ground floors. As a consequence, the deeper hollow core slabs are designed to resist higher loads and to support for longer span. However, they have subjected to the initial web shear cracking. The experimental studies by Pajari [7] and Hawkins and Ghosh [6] have also identified that web-shear cracking strengths in end regions can be less than strengths determined by the equations specified in ACI [1] and EC2 [5]. Therefore, first, this study discusses the shear design approaches of 3 leading design codes: ACI [1], EC2 [5] and CSA [3] briefly. ACI [1] equation is empirically derived using lower bound average shear stress while the EC2 (2005) equation is derived from the Mohr's circle of stresses at the centroid and using the Jourawski's approach (1856) that the maximum shear occurs at the centroid of a section. The equation in CSA (2001) is based on the Simplified Modified Compression Field Theory (Vecchio et al. (1986), Collins (1997) and Angelakos et al. (2001)) which considers the post-cracking shear strength of a member. This study also compares observed shear strength values obtained from the experiments to the code predicted shear strength values. Furthermore, this study presents the results of finite element analyses of typical hollow core slabs with wide range of depths to explore why the deeper slabs with flat webs subject to initial web shear cracking at the load well below the shear capacity evaluated by the equations in ACI [1] and EC2 [5]. For this purpose, 220, 300, 400, and 500mm deep sections are selected and the details of these sections are taken from a manufacturer of prestressed hollow core slabs.

2. SHEAR STRENGTH

The use of shear reinforcement is generally not feasible for hollow core slabs and, therefore, the shear strength may be limited to the shear strength of the concrete. The section 11.4 of ACI [1] gives the requirements for evaluating the shear strength of concrete member. The provisions of the section 11.4.3 are generally used in the design of hollow core slabs if shear is a govening factor in the design. The factored shear force V_u is limited to the lesser of φV_{ci} and φV_{cw}, where V_{ci} is the flexure-shear cracking strength and V_{cw} is the web-shear cracking strength. For simply supported hollow core slabs, the shear cracking strength of the web adjacent to the support usually governs the design, if the heavy, non-uniform loads are applied on the slabs. The φ value is 0.75 for shear calculations. The nominal shear strength provided by concrete (web-shear cracking strength) V_{cw} is expressed in the following equation as given in ACI [1]:

$$V_{cw} = (0.29\sqrt{f_c^{'}} + 0.3 f_{pc}) b_w d + V_P \quad (1)$$

Where $fpc=P/A$ is the axial stress due to prestressing force, $d= yt+e$ is the flextural liver arm but not less than 0.8 times the depth of the section, bw is the width of the section at the centroidal axis, V_P is the vertical component of the prestressing force and f_c is the design compressive strength.

In prestressed single span members without shear reinforcement in regions uncracked in bending (where the flexural tensile stress is smaller than f_{ctk}), the shear resistance should be limited by the tensile strength of the concrete. It is expressed in the following form as given in EC2 [5]:

$$V_{Rd,c} = \frac{I b_w}{S}\sqrt{(f_{ctd})^2 + \alpha_1 \sigma_{cp} f_{ctd}} \quad (2)$$

where I is the second moment of area, b_w is the width of the cross-section at the centroidal axis, S *is* the first moment of area above and about the centroidal axis, α_l equal to $l_x/l_{pt2} \leq 1.0$ for pretensioned tendons and otherwise it equals to 1, l_x is the distance between the section considered from the starting point of the transmission length and the section considered at the distance of half of the slab thickness, l_{pt2} is the upper bound value of the transmission length of the prestressing element according to the expression 8.18 in EC2 [1], σ_{cp} is the concrete compressive stress at the centroidal axis due to axial loading or prestressing ($\sigma_{cp} = N_{Ed}/A_c$ in MPa, $N_{Ed} > 0$ in compression) and f_{ctd} is defined as the design tensile strength.

The equation for the evaluation of shear strength in CSA [3] is based on the Simplified Modified Compression Field Theory (SMCFT) which considers the post-cracking shear strength of the member. Factored shear strength V_c shall be determined by the provision 11.3.4 in CSA [3] as:

$$V_c = \phi_c \lambda \beta \sqrt{f_c^{'}} b_w d_v \quad (3)$$

$$\beta = \frac{0.4}{(1+1500\varepsilon_x)} * \frac{1300}{(1000+S_{Ze})} \quad (4)$$

$$\varepsilon_x = \frac{M_f/d_v + V_f - A_P f_{po}}{2(E_p A_p + E_c A_{ct})} \quad (5)$$

Where M_f and V_f shall be taken as positive quantities and M_f shall not be taken less than $(V_f - V_p)/d_v$

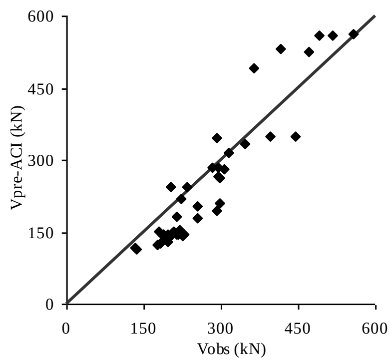
$$S_{Ze} = \frac{35 S_z}{15 + a_g} \quad (6)$$

However, S_{Ze} shall not be taken as less than $0.85S_Z$ and S_Z shall be taken as effective depth d_v. a_g is maximum size of coarse aggregate and effective web width b_w shall be taken as the minimum concrete web width within the depth. The prestressing force may be assumed varying linearly from zero to full development in the transfer length which is assumed to be 50 times the diameter of strand as in ACI [1]. The resistance factor for concrete φ_c is taken as 0.65 while for low density concrete it is equal to 1.

3. COMPARISON OF CODE PREDICTIONS WITH EXPERIMENTAL DATA

As mentioned before, the main objective of this study is to validate the accuracy of the evaluation of shear strength of precast prestressed concrete hollow core slabs by the code equations specified in ACI [1], EC2 [5] and CSA [3]. For this purpose, test data from forty four specimens are selected from the research report by Pajari [7]. It is also important to note that those specimens are simply supported and loaded with transverse uniformly distributed line loads. The test specimens that have excluded are only those in which the slabs have grouting at the loaded end, some important data such as the measured compression strength are missing, the shear span (distance from support to the nearest line load) is less than 2.4 times the slab thickness and the slippage of strands is greater than the acceptable limit. However, 15 different nominal geometries for concrete cross section are identified in the accepted test specimens.

Figure 1(a), (b) and (c) compares shear strength values obtained from the tests to the predicted shear strength values by ACI [1], EC2 [5] and CSA [3], respectively. V_{obs} refers the shear strength obtained from the test (shear force at support) while V_{pre} refers the predicted shear strength by the code equations.



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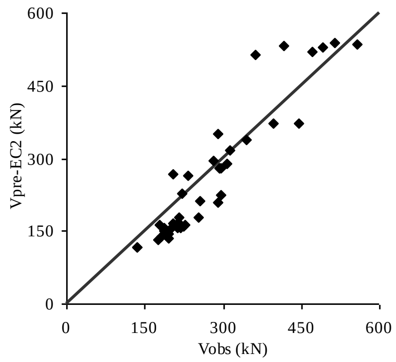

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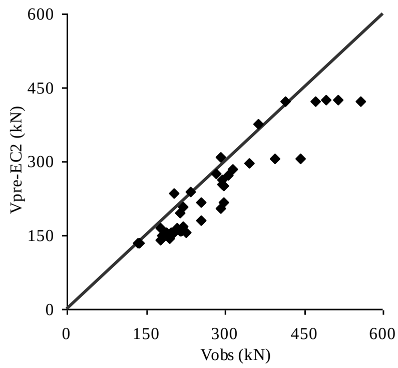

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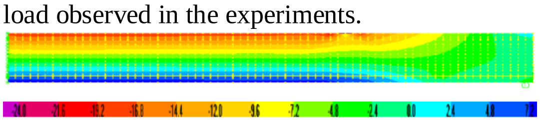
Figure 1: Comparison of observed shear strength to the predicted shear strength by (a) ACI, (b) EC2 and (c) CSA.

Furthermore, it is important to highlight that the predicted shear strength by ACI [1] and CSA [3] are evaluated using the material safety factors of 1.0 while the predicted shear strength by EC2 [5] is evaluated using the characteristic tensile strength for this comparison. It is clear from the comparison that the shear strength values predicted by ACI [1] and EC2 [5] for the shallow sections with circular voids are mostly conservative, but they are unconservative for the deeper sections with non circular voids. However, CSA [3] predicts conservative estimation of shear strength for all the sections selected for this comparison.

4. RESULTS FINITE ELEMENT ANALYSIS

Figure 2 and 3 illustrate the distributions of direct axial, shear and principle tensile stress components at the mid section of the 300 mm deep slab with the circular voids and the 400mm deep slab with flat web, respectively. It is important to note that the stress distributions are corresponding to the failure load observed in the experiments.



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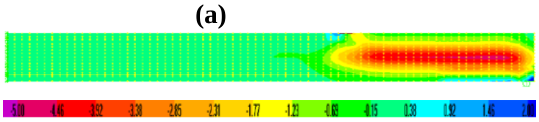

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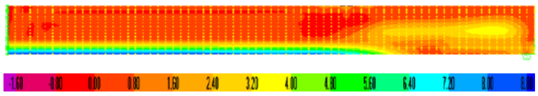

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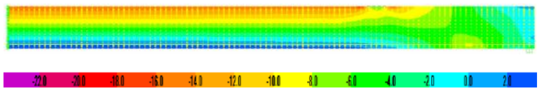
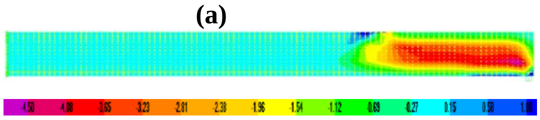
Figure 2. Distribution of (a) direct stress, (b) shear stress and (c) principle tensile stress in MPa of 300mm deep section with circular voids



(a)



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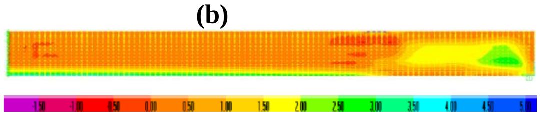

(c)

Figure 3. Distribution of (a) direct stress, (b) shear stress and (c) principle tensile stress in MPa of 300mm deep section with circular voids

It is clear from Figure 2 that the maximum shear and principle tensile stresses are developed at the centroidal axis of the section as it is assumed in deriving the code equations. Therefore, finite element analysis supports strongly the fact that the code predictions are conservative.

Unlikely previous results, Figure 3 indicates that the maximum shear and principle tensile stresses are more concentrated towards the bottom of the beam due to upward deformation resulting in highly eccentric prestressing force. As a consequence, principle tensile stresses reach its capacity at a significantly lower shear force than the ACI [1] and EC2 [5] predictions. Usually, this region is called a disturb region as observed between the support and the loading point and it violates the concept of plane section remained in plane.

5. CONCLUSIONS

ACI [1], EC2 [5] and CSA [3] propose equations to evaluate the shear strength of a member which have no transverse reinforcement. To check the validity of these equations, finite element analyses and 44 experimental tests on precast prestressed hollow core slabs with thickness varying from 220 to 500 mm have been used. Based on the results, the following conclusions can be drawn.

According to the experimental test data of 265 and 320 mm deep sections with circular voids, ACI [1], EC2 [5] and CSA [3] predictions are conservative. Finite element analyses illustrate that 220, 300 mm deep sections with circular voids follow the assumption of Jourawski (1886) that the maximum shear stress occurs at the mid depth of the slab. Therefore, the results of finite element analyses give strong support that the code predictions are conservative.

As the slab depth becomes larger with flat web, the maximum tensile and shear stresses are concentrated towards the bottom of the beam. So, Jourasky's (1886) prediction is no longer valid. The maximum value of shear stress is much higher than the predicted shear stress by code equations and therefore, the maximum principal tensile stress reaches its capacity at a significant low shear force. As a result of that, the equations in ACI [1] and EC2 [5] estimate the non conservative strength values for deeper prestressed hollow core slabs with flat webs.

CSA [3] prediction on the shear capacity is based on the Simplified Modified Compression Field Theory. The prediction is conservative for all kind of sections used in this study because the modified compression field theory treat concrete as a diagonally cracked material and interface shear stress, often called aggregate interlocking, is estimated by average tensile stress which is comparatively lower than the tensile stress at the first crack.

Compressive strength of concrete used in precast prestressed hollow core slabs is comparatively high. High strength concrete member are smoother than in normal strength concrete members with cracks propagating through coarse aggregate particles rather than around them. So the tensile strength at cracking of the members with high strength concrete may be lower than the tensile strength at cracking used in the specifications like ACI [1] and EC2 [5]. This also should be considered in the design of prestressd hollow core slabs.

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