EVALUATION OF SHEAR STRENGTH OF PRESTRESSED CONCRETE BEAMS WITH HIGH STRENGTH MATERIALS

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ABSTRACT

Shear behavior of prestressed concrete beams has been studied for many years and some equations were already proposed in several codes. However, these equations do not correctly evaluate which resulting in conservative design or dangerous design. One hundred sixty-eight (168) data from 14 papers published in Japan during 1981 to 2004 are used in analysis. Equations provided by Japanese PC standard 1998 and ACI 318-05 are studied using these data. Based on analysis, equation 71.2a of Japan PC standard 1998 was the best design equation to predict shear strength of prestressed concrete beams among six equations. However, the equation has following shortcomings. It is quite conservative for I-section and un-bonded rectangular section. On the other hand, it overestimate shear strength of pre-cast prestressed concrete and rectangular beam using high strength steel as shear reinforcement. To improve its performance, the arch contribution was isolated by choosing beams with un-bonded tendon or specimens without shear reinforcement. Then, the modification was made to; the effect of prestressing force on the compressing strength of concrete strut, confining effect provided by shear reinforcement on the compressive strength of concrete strut and the effective width of the web for I-sections. On the other hand, truss contribution was not modified except for I-section. Proposed modification has produced satisfying results. Average experiment-to-prediction ratio is getting closer to 1.0 and scatter of data is getting small.

Keywords: Prestressed concrete, Japanese PC standard 1998.

INTRODUCTION

Use of prestressed concrete (PC) has became popular for building structure recently because it provides advantages such as high performance, high durability and other benefits from economic point of view. In developed country such as America and Japan, this type of structure already applied for many types of buildings such as residents, offices, universities, hospitals and sports facilities.

On the other hand, research in PC field has been conducted by several institutions and researchers around the world. Moreover, some equations were already proposed to predict behavior of PC beams. However, these equations do not correctly evaluate especially for shear behavior. Comparing with flexural behavior which is already able to be predicted easily, the exact shear behavior of member is still unpredictable. Due to that reason, most of codes in the world prefer to use higher safety factor due to accommodate the uncertainty behavior of shear. Therefore, evaluation of equation provided by code should be done to achieve more efficient design.

The purpose of this thesis is to gain more understanding about shear behavior of PC beams and to propose some consideration for modifying existing standard to get more efficient and reasonable result in predicting shear strength of PC beams

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STATE OF THE ART

Shear Mechanism

According to the discussion of America Concrete Institute (ACI) committee 445 in 1998, shear resistance capacity for concrete members without shear reinforcements is contributed by five components, namely un-cracked concrete and flexural compression zone (V_c), aggregate interlock (V_a), dowel action of longitudinal reinforcement (V_d), residual tensile stress across crack and Arch action. The amount of contribution will depend on geometry of members, type of loading, steel ratio, type of web reinforcement and prestressed reinforcement (CTA, 1976). On the other hand, shear reinforcement plays important role to ensure that shear failure will not occur. The contribution of shear reinforcement is to improve contribution of dowel action, suppressing flexural tensile stresses, limiting the opening of diagonal cracks, providing confinement and preventing the breakdown of bond when splitting cracks develop in anchorage zones (Park and Paulay, 1997).

Equation 71.2a of Japanese PC Standard 1998

Equation 71.2a (presented by eq.1) was developed based on superposition of arch and truss mechanism. Left part of equation presents truss mechanism and right part presents arch mechanism.

$$Q_u = b_0 j_0 p_{ww} f_y + \frac{b_0 D}{2}\left(\nu f'_c - 2 p_{ww} f_y\right)\tan\theta \qquad (1)$$

where, b_0 is width of beam, j_0 is distance between compressive and tensile strength, D is depth of beam. Besides, p_w is reinforcement ratio of stirrup, f'_c is compression strength of concrete, ν factor is effectiveness factor. This factor is influenced by the shear span to depth ratio, axial force which represented by effective prestressed stress and compressive strength of concrete. It amount is limited to the range of 0.65 to 1. This limitation introduced to represent maximum, 100 % of compressive strength of concrete can contributes in arch mechanism. Besides, shear reinforcement effect is considered in terms of shear reinforcement ratio.

DATABASE

There are 14 prestressed concrete research had been done during 1981 to 2004 in Japan and at least 168 specimens were tested. 50 specimens are prestressed beam without shear reinforcement and 118 specimens with shear reinforcement. Compressive strength of concrete which was used for the specimens is varied from 27 MPa to 110 MPa. The ratio of longitudinal reinforcement varies from 0.35 to 2 %. The ratio of prestressed reinforcement is varying from 0.2 up to 3.6 % and ratio of shear reinforcement is from 0.2 to 1.4 %. The shear spans to depth ratio of specimen varies from 1 to 3.2. Besides, specimens can be divided into two group; rectangular shape and "I" shape. At least 107 specimens are rectangular shape section and 60 specimens are "I" shape section. Rectangular section can be divided into 2 types; bonded prestressed reinforcement (90 data) and un-bonded prestressed reinforcement (17 data). Meanwhile, "I" shape section only use bonded prestressed reinforcement. Data in this study were compiled from journal as shown in table 1.

Table 1. Source of database

Author	Publisher	Volume and Page	Year
Funakoshi M, Okamoto T	1	Vol.3, 365-368	1981
Funakoshi M, Okamoto T, Tanaka E	1	Vol.4, 297-300	1982
Fukui, Ookuma A, Hamahara M, Suetsugu H,	2	C-2, Structures IV, 877-880	1996
Fukui T, Nagasawa T, Hamahara M, Suetsugu H	2	Structures II, 1023-1028	1994
Funakoshi M, Tanaka H, Tani M	1	Vol.6, 469-472	1984
Matsizaki Y, Hirayama A, Kobayashi A, Sakai M	2	Vol.59, 1683-1684	1984

Table 1. Source of database (continued)

Author	Publisher	Volume and Page	Year
Matsizaki Y, Suzuki K, Matsutani T, Shirahama S, Takayama Y	2	C-2, Structures IV, 887-890	1996
Muguruma Hiroshi, Watanabe Fumio, Fujii Masanori	2	Vol.58, 2549-2550	1983
Ogawa T, Saito A, Iida S, Fukui T, Suetsugu H, Sakiyama K, Hamahara M	2	C-2, Structures IV, 1077-1082	1999
Ohtaka K, Yuasa N, Hamahara M	2	C-2, Structures IV, 991-994	2002
Ookuma A, Fukui T, Hamahara M, Suetsugu H	2	C-2, Structures IV, 847-852	1997
Wakamatsu S, Takizawa K, Takagi H, Shiraishi I	2	C-2, Structures IV, 1039-1044	1998
Yuasa N, Ogawa T, Kamakura M, Fukui T, Uchida R, Hamahara M		C-2, Structures IV, 965-970	2000
Yuasa N, Ohtaka K, Fukui T, Hamahara M	2	C-2, Structures IV, 955-960	2001

[1] Proceedings of the Japan Concrete Institute.

[2] Summaries of technical papers of Annual Meeting Architectural Institute of Japan.

RESULTS AND DISCUSSION

Modification of the Arch Contribution in Equation 71.2a of PC standard 1998

In general, equation 71.2a of PC standard 1998 shows best performance in predicting behavior of shear strength among six studied equations. However, the equation has following shortcomings and some modification should be done for applying this equation to rectangular un-bonded and "I" shape section beams to get more efficient design.

Modification of the arch contribution for rectangular un-bonded beams

Truss mechanism can not exist for un-bonded specimen because it comes from internal force which resulted from bonded condition. Therefore, absence of bond will distinguish truss mechanism. Figure 1 show specimens without shear reinforcement or with p_w = 0% has ratio of experiment-to- prediction in range of 1 to 1.75. Average experiment-to-prediction ratio is 1.5 and it standard deviation is 0.5. Therefore, some modification should be done to get more accurate prediction result. Circled data in figure 1 will be neglected for next analysis since it has different specification than other data.

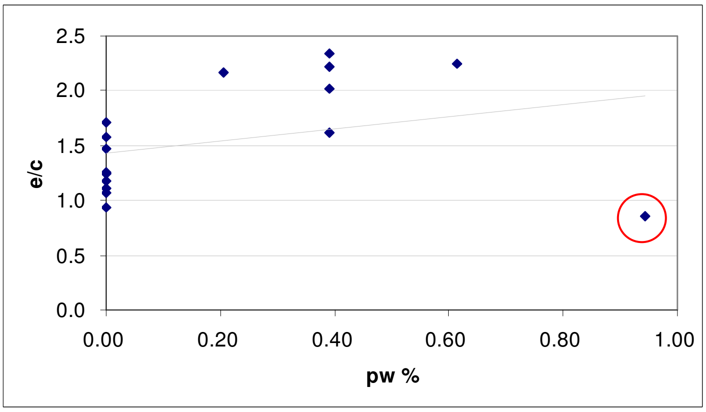

Figure 1. Performance of equation 7 with varying shear reinforcement ratio for un-bonded rectangular section specimens

The effect of axial force of prestressed reinforcement could be one factor which produces higher contribution of compressive strength of concrete in arch mechanism. Therefore, term of ν factor in eq. 71.2a to represent the contribution of axial force may not be correctly evaluated. For instant, neglect the upper limitation of ν factor as shown in eq. 2 can be used to represent higher contribution of axial force. Meanwhile, bottom limit of this equation is kept to guarantee at least 65 % of its compressive strength will contribute in resisting shear force. Proposed equation to obtain modified ν factor is presented by eq. 2.

$$\nu_{\text{mod}} = \alpha L_r \left(1 + \frac{\sigma'_g}{f_c}\right) \quad 0.65 \le \nu_{\text{mod}} \tag{2}$$

Contribution of shear reinforcement in resisting shear for un-bonded specimen could be neglected due to the absence of bond which play important role for truss mechanism. However, based on experiment result, the contribution of shear reinforcement still exists. It is expected that shear reinforcement confines the core of concrete and compression strength of the concrete increases Amount of shear reinforcement contribution in un-bonded specimens can be solved by using eq. 3. However, advanced research should be done to evaluate this equation.

$$c_1 = 1.7\ pw + 1 \tag{3}$$

where, c_1 is coefficient of confining contribution and p_w is shear reinforcement ratio in percent.

Finally, we propose equation 4 as modification of equation 71.2a to predict more accurate of shear strength rectangular un-bonded beams.

$$Q_u = \frac{b_0 D}{2} c_1 \nu_{\mathrm{mod}} f'_c \tan\theta \tag{4}$$

By using equation 4, prediction result becomes closer to experiment result. Average ratio of experiment-to-prediction decrease from 1.5 to 1.1 and it standard deviation decrease from 0.50 to 0.13. It can be said that our proposal is working well to predict shear strength of un-bonded PC beams. Figure 2 shows performance of proposed equation for un-bonded rectangular section.

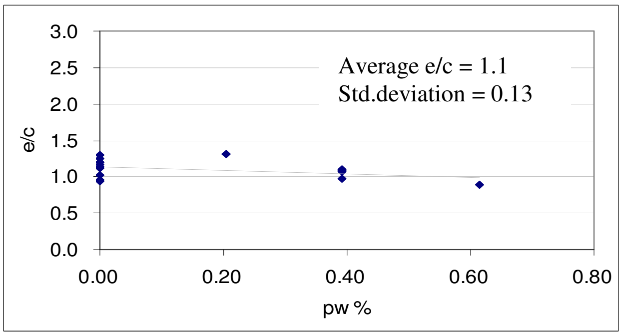

Figure 2. Performance of eq. 4 in predicting shear strength of un-bonded rectangular section specimens

Modification of the arch contribution for "I" shape section beams

Based on figure 3, we can observe that the accuracy of this equation is getting worse for p_w = 0 %. Ratios between experiment and prediction are located in range 2 to 3. It means the results are too conservative. For specimens without shear reinforcement, shear strength of PC member is only contributed by arch action.

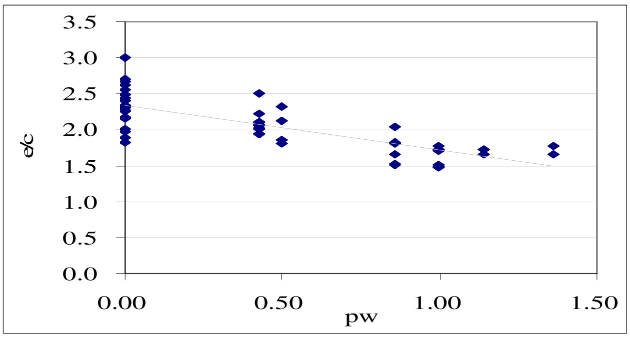

Figure 3. Performance of eq.71.2.a with varying shear reinforcement ratio for I section specimens

Therefore, we can assume that equation for arch action part is not correctly evaluated. Based on statistic approach, we get an average of experiment-to-prediction ratio is 2.1 and standard deviation is 0.34. We were trying to apply the same modification for ν factor as well as we did for un-bonded specimens. Equation 2 is used to replace original term of ν factor in original equation. On the other hand, we are modifying term of b_0 since using this term in calculation produced conservative results.

We found that ratio of gross section area to the depth of specimens is resulting best result to replace term of b_0. This ratio can be called as effective width (b_{eff}). Finally, we proposed equation 5 to predict shear strength of I-section PC beams.

$$Q_u = b_{eff}\, j_0\, p_{ww}\, f_y + \frac{b_{eff}\, D}{2}\left(\nu_{\mathrm{mod}}\, f'_c - 2\, p_{ww}\, f_y\right)\tan\theta \qquad (5)$$

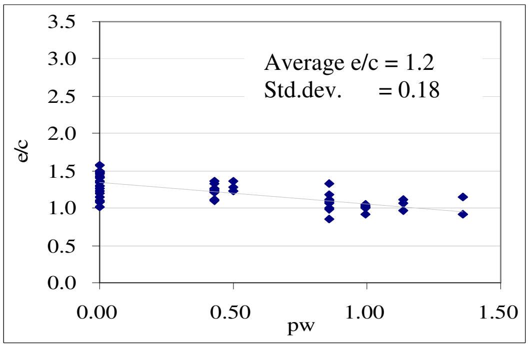

Figure 4. Performance of proposed modification (eq.5) for "I" section specimens

Equation 5 produces better result. Average experiment to prediction ratio was reduced from 2.1 to 1.2 and it standard deviation was reduced from 0.34 to 0.18. Moreover, data of experiment to prediction ratio which less than 0.95 is less than 5%. Therefore, this proposal is efficient and safe to be adopted. Figure 4 shows performance of equation 5. We can observe that the results are more consistent with specimens with and without shear reinforcement which represented by small gradient of its results. This tendency shows arch and truss mechanisms are represented well by using this consideration.

Rectangular bonded beams

Equation 71.2a works well in predicting shear strength of bonded rectangular specimens. Average ratio of experiment-to-prediction result is 1.0 and its standard deviation is 0.22. However, 16 of 90 specimens can not be predicted well by this equation. The equation tends to overestimates shear strength of specimens which using high strength steel (960 MPa). On the other hand, from 8 data which can be collected, all of them have the ratio of experiment-to-prediction results in range of 0.5 to 0.6. Another situation which could not be predicted well by equation 71.2a is using of pre-cast system. Equation 71.2a tends to overestimate shear strength of pre-cast specimens using strand 70 as prestressed tendon. Three of 4 specimens have shows this tendency. The ratio of experiment to prediction result for these specimens is around 0.75 to 0.85. Besides, for pre-cast system using high strength bar as prestressed reinforcement, equation 71.2a produces conservative results.

Based on previous approach in increasing performance of equation 71.2a, similar modification was applied to bonded rectangular section specimens. Term of modified "ν" factor which obtained from equation 2 was used. Therefore, modified equation 71.2a can be written as eq. 6.

$$Q_u = b_o\, j_0\, p_{ww}\, f_y + \frac{b_o\, D}{2}\left(\nu_{\mathrm{mod}}\, f'_c - 2\, p_{ww}\, f_y\right)\tan\theta \qquad (6)$$

Figure 5 show performance of equation 6 for monolithic rectangular bonded specimen only.

Equation 6 produce slightly change in predicting shear strength of rectangular bonded specimen. By using equation 6, average experiment-to-prediction ratio was reduced from 1.08 to 1.00 and it standard deviation is 0.14. Therefore, equation 6 is proposed only for monolithic rectangular bonded PC beams. Figure 5 shows performance equation 6 with varying shear reinforcement ratio for monolithic bonded rectangular beams.

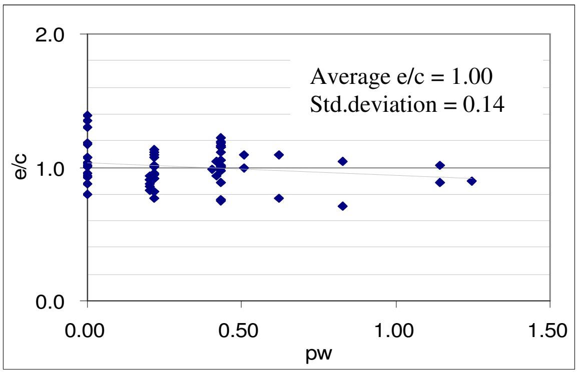

Figure 5. Performance of equation 6 for monolithic bonded rectangular section specimens

CONCLUSIONS

Shear behavior of prestressed concrete beams has been studied for many years and some equations were already proposed by several codes. However, these equations were not correctly evaluated. One hundred sixty-eight (168) data from 14 papers published in Japan during 1981 to 2004 were used in analysis. The equations provided by Japanese PC standard 1998 and ACI 318-05 were studied using these data. Based on analysis, equation 71.2a of Japan PC standard 1998 was the best design equation to predict shear strength of prestressed concrete beams among six equations. Average of experiment-to-prediction ratio for all types of specimens is 1.8. Besides, its standard deviation is 0.6. However, the equation has following shortcomings. It is quite conservative for I-section and un-bonded rectangular section. On the other hand, it overestimates shear strength of pre-cast PC and beam using high strength shear reinforcement.

In order to improve the performance of equation 71.2a, the arch contribution was isolated by choosing beams with un-bonded tendon or specimens without shear reinforcement. The modification was made to; the effect of prestressing force on the compressing strength of concrete strut, confining effect provided by shear reinforcement on the compressive strength of concrete strut and the effective width of the web for I-sections. Meanwhile, truss contribution was not modified except for I-section. Equations for I-sections and rectangular section were separated and then modifications for each type of beam were proposed. For rectangular un-bonded specimens, we proposed neglecting of upper limit of ν factor and considering confining effect by shear reinforcement. Average ratio of experiment-to prediction for proposed modification has decreased from 1.5 to 1.1 and it standard deviation has decreased from 0.50 to 0.13. For I-shape section, using of effective width and neglecting upper limit of ν factor were proposed. Effective width can be obtained from ratio of gross area of section by depth of beams. Its average experiment-to-prediction ratio was reduced from 2.1 to 1.2 and it standard deviation was reduced from 0.34 to 0.18. For rectangular-bonded specimens, equation 6 is proposed. However, the equation is valid only for monolithic rectangular bonded beams. Average experiment-to-prediction ratio was reduced slightly from 1.08 to 1.00 and it standard deviation is remain 0.14

RECOMMENDATION

Some modifications have already been proposed to increase performance of equation 71.2a of Japan PC Standard 1998. However, some conditions still can not be satisfied by proposed modifications. Shear strength of specimens using of high strength shear reinforcement and shear strength of pre-cast PC beams needs to be evaluated. Moreover, contribution of axial force provided by prestressing force is not clearly determined. Furthermore, truss contribution was not evaluates except for I-section. Therefore, further study to observe these conditions should be done.

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