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A STRENGTH MODEL FOR CONCRETE CONFINED WITH COMPOSITE FABRICS

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ABSTRACT: Fiber reinforced polymers (FRP) as materials for concrete structure rehabilitation are having increased applications all over the world. Nowadays engineering societies are regarding them as the most promising material to rehabilitate the deteriorated or undersigned structures. For rehabilitation purpose design formula or equations are desired in civil engineering practice. This work presents design equations to strength concrete columns using composite fabrics for an increased strength sought. On the light of proposed strength model of confined concrete, modifications to ACI equations are suggested for determining load capacity of a concrete column.

KEYWORDS: Composite Materials, Rehabilitation, Columns

INTRODUCTION

In recent years, tests performed by karbhari and Eckel (1993), Demers and Neale (1994), Howie and karbhari (1994), and saadatmanesh et al. (1994) have confirmed that the use of fiber reinforced plastic sheets as additional confinement to the concrete compression member could be an effective technique to strengthen further its load carrying capacity or repair deteriorated column for the designed load considered. As an attempt to the application of composite fabrics where strengthening or retrofitting of structural member is the prime concern, several researchers have proposed models for assessment of gain in strength and ductility of confined concrete. For example, Saadatmanesh et al. [1994] employed an analytical model to assess gain in strength and ductility of concrete column confined by high strength fiber composite strap. They also conducted parametric study to determine the effect of design parameters such as thickness, spacing of composite straps, strength of concrete and type of composites on the performance of reinforced concrete columns. But, the strength model of Saadatmanesh et al. [1994] and that of Restropol and DeVino [1994], as applied to the columns confined by composite straps, are the same model which was originally developed by Mander et al. [1998] for concrete confined with tie reinforcements. Thus these models need to be verified against the test results of concrete specimens confined with composite fabrics.

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Miyauchi et al.[1997] estimated the strengthening effect of carbon fiber reinforced polymer (CFRP) sheet by employing to the strength equation proposed by Richart et al. [1929] for concrete confined with tie reinforcement. He introduced an effectiveness coefficient k_e equals to 0.85 (from test results) to modify the equation of Richart et al. Most recently, Kono et al. [1998] developed linear models for *strength index*, I_s (the ratio of the confined concrete strength to the unconfined concrete strength) and the *strain index*, I_e (the ratio of strain at maximum confined strength to the strain maximum unconfined strength) to measure the strengthening effect of composite strap confinement. The models are based on the results of concrete cylinder tests carried out by Fujimaki et al. [1996] and themselves. But the models of Miyauchi et al.[1997] and Kono et al.[1996] are linear model which contradicts the findings of earlier investigations of saatcioghe and Razvi [1992], states that, for low confining pressure range, the strength enhance factor decreases with the increasing confining pressure.

Recently, a model for the strength of concrete confined by fiber composite sheet was proposed by Samaan et al. [1998]. They carried out an experimental program to determine the strength of 22 cylinder specimens of 150mm diameter confined with continuous E-glass fabrics. This model was obtained by employing the technique as proposed by Saatcioglu and Razvi [1992] for assessing confinement effect of ties which involves the calibration of strength enhance factors against confining pressure. In the very recent Spoelstra and Monti [1999] developed strength equation for FRP-confined concrete, They considered the confining pressure as imposed by the FRP jacket to be varying continuously in a nonlinear manner during loading as expected in reality.

The models discussed above are based on small scale specimens which need to be evaluated in predicting the behavior of large scale or full scale column specimens. In this work, strength model for confined concrete using composite fabrics is proposed for full scale specimens. A strength reduction factor to incorporate the size effect is included in the model.

SIZE EFFECT

Most of the research works to assess the strength of concrete compression member confined with composite materials has included mainly small scale specimens i.e. concrete cylinders. But, in reality, the strength of large size compression members i.e. concrete columns may be lower than that of small scale specimen, In the very recent, Harries et al.[1998] investigated the strength of two different sizes of compression members. The sizes considered were 150 mm diameter concrete cylinders and 508 mm diameter concrete columns. They also used three different types of composite fabrics such as 0°/±45° orientation E-glass fiber, 0° orientation E-glass and carbon fibers as external confinenment to the specimens. The confined concrete strength for two different specimen sizes as obtained by Harries et al.[1998] are shown in Table 1 . It is evident from statics that the confining pressure corresponding to one layer fabric to the 50mm diameter cylinder is slightly higher than that of three layers of fabric

Table 1. Confined strength ration of concrete for different specimen sizes [adapted from Harris, et al. (1998)]

Specimen diameter mm	Type of composi te fabric	Number of layers	Unconfined strength Mpa	Confined strength Mpa	Ratio of confined to unconfined strength
150	0/±45° E-glass	1	26.2	33.50	1.27
508		3	32.8	37.43	1.14
150	0° E-glass	1	26.2	38.4	1.46
508		3	32.8	38.69	1.21
150	Carbon	1	26.2	50.6	1.93
508		3	32.8	52.2	1.59

to the 508mm diameter column. Since the difference between the confining pressure fo two different sizes is negligible, for comparison the test results of the larger size as shown in Table 1 is interpolated corresponding to the confining pressure of small size specimen. It can be observed that the gain in strength due to confinement for 508mm column specimen is lower than that of 150mm cylinder specimen. Thus, the gain in strength due to confinement decreases with the increase in sizes which is expected in reality.

PROPOSED STRENGTH MODEL

The strength model originally proposed by Saatcioglu and Razvi [1992] for concrete with confinement of tie reinforcement can be used for fabrics as external reinforcement with the following modifications.

$$f_{co} = f_{co} + \alpha k f_e \quad (1)$$

Where
k = the strength enhancement factor
f_c = the effective confining pressure
α =a reduction factor

A value of 0.8 to 0.9 is suggested for column specimen depending upon size (higher value for smaller column size). The enhancement factor k can be expressed in the form of a power equation [1992], i.e.,

$$k = c_1 (f_e) c_2 \quad (2)$$

where c_1 and c_2 are constants. To determine the values of those constants, the confining pressure and corresponding k values are first calculated from the test results available in literature using Equation 1. Table 2 shows the calculated values of k for different confining pressure employed by various researchers. The constants c_1 and c_2 are then evalueated by least square method as shown in Fig. 1 to fit the power curve (k vs. f_e). Thus the values are obtained as follows:

$c_1 = 4.0$ (3)

$c_2 = -0.21$

Table 2. Values of k as calculated from Eq. (1) for different confinement pressure;

Sample No.	Source of test results (Ref. No.)	Unconfined concrete strength Mpa	Confining pressure Mpa	Confined strength Mpa	Value of k
1	[Harris]	26.2	5.11	38.4	2.38
2	[Picher]	39.7	6.00	56.0	2.72
3	[Harris]	26.2	7.73	50.6	3.15
4	[Samaan]	30.86	9.93	53.66	2.29
5	[Do]	30.86	9.93	56.50	2.58
6	[Do]	29.64	9.93	55.29	2.58
7	[Do]	29.64	9.93	60.23	3.08
8	[Do]	31.97	9.93	59.06	2.73
9	[Do]	31.97	9.93	60.79	2.90
10	[Harris]	26.2	10.21	52.5	2.57
11	[Kono]	35.0	12.76	57.4	1.76
12	[Do]	35.0	12.76	64.9	2.34
13	[Do]	32.33	12.76	61.8	2.31
14	[Do]	32.33	12.76	57.7	1.99
15	[Do]	34.8	12.76	57.8	1.80
16	[Do]	34.8	12.76	55.6	1.63
17	[Do]	34.8	12.76	50.7	1.25
18	[Harris]	26.2	15.46	64.0	2.45
19	[Samaan]	30.86	16.75	72.92	2.51
20	[Do]	30.86	16.75	65.67	2.08
21	[Do]	30.86	16.75	77.99	2.81
22	[Do]	29.64	16.75	74.56	2.68
23	[Do]	29.64	16.75	71.74	2.51
24	[Do]	31.97	16.75	77.35	2.71
25	[Do]	31.97	16.75	77.08	2.69
26	[Do]	30.86	25.04	85.72	2.19
27	[Do]	30.86	25.04	86.76	2.23
28	[Do]	29.64	25.04	86.22	2.26
29	[Do]	29.64	25.04	87.44	2.31
30	[Do]	31.97	25.04	86.11	2.16
31	[Do]	31.97	25.04	83.99	2.07
32	[Kono]	32.33	25.59	80.2	1.87
33	[Do]	34.8	25.59	82.7	1.87
34	[Do]	32.33	38.20	86.9	1.43
35	[Do]	32.33	38.20	90.1	1.51
36	[Do]	34.8	38.20	103.3	1.79
37	[Do]	34.8	38.20	110.1	1.97

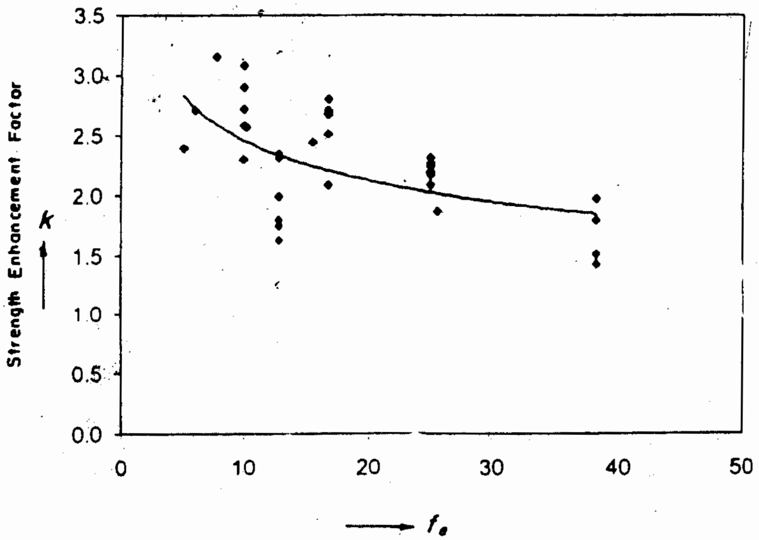

Fig 1. Variation of Strength Enhance Factor, k

Substituting the values of c_1 and c_2 in Equations 1 and 2, the ultimate strength of confined concrete can be obtained as:

$$f^1_{cc} = f^1_{co} + \alpha\left[4.0(fe)^{0.79}\right] \tag{4}$$

The effective confining pressure depends on the arrangement (spacing of fabric straps) and the cross-sectional shape of the compression member. In general the effective pressure is given by the following expression:

$$f_e = k_e f_l \tag{5}$$

Where, k_e Saadat manesh, et al. (1994) and Mander, etal. (1998) is the effective confinement coefficient that account for horizontal and vertical arching of the concrete enclosed by fabrics and, f_l is the lateral passive confining pressure. The expressions of effective confinement coefficients and lateral passive confinement pressure for columns are provided in Appendix-A.

MODEL PERFORMANCE

In order to investigate how the predicted strength using the proposed model is close to the test results, a comparison of the strengths with those of experiments is carried out. Table 3 shows the results using the proposed model along with the test results. The strengths as obtained by other available models are also included in Table 3. The confining pressures are calculated according to the formulation given in the previous section. A reduction factor equal to 0.9 is used for large scale specimen (508mm dia.). However for small scale specimen (100mm and 152mm) it is taken to be 1.0.

Table 3. A comparison of the predicted strengths using the proposed model with those of other models

Unconfined strength (sample size)	Confining pressure	Confined strength by test	Proposed model	Sadaatmanesh et al. Model [1994]	Samaan et al. Model [1998]	Spoelstra and Monti [1996]	Confined Strength Ratio			
f_{co} MPa	f_l MPa	f_{cc} MPa (1)	f_{cc} MPa (2)	f_{cc} Mpa (3)	f_{cc} Mpa (4)	f_{cc} Mpa (5)	(1)/(2)	(1)/(3)	(1)/(4)	(1)/(5)
30.86 (152)a	9.93	53.7 56.5	55.38	72.6	60.8	58.7	0.97 1.02	0.74 0.78	0.88 0.93	0.92 0.96
31.97 (152)a	9.93	59.1 60.8	56.49	74.2	61.9	59.9	1.05 1.08	0.80 0.82	0.95 0.98	0.99 1.02
30.86 (152)a	16.75	72.9 65.7	67.93	88.1	74.0	74.4	1.07 0.97	0.83 0.75	0.98 0.89	0.98 0.88
29.64 (152)a	16.75	74.9 71.7	66.71	84.6	72.8	72.8	1.11 1.07	0.88 0.85	1.02 0.98	1.03 0.99
30.86 (152)a	25.04	85.7 86.8	81.79	101.0	88.0	89.6	1.05 1.06	0.84 0.86	0.97 0.99	0.96 0.97
31.97 (152)a	25.04	86.1 84.0	82.90	103.4	89.1	91.3	1.04 1.01	0.83 0.81	0.97 0.94	0.94 0.92
32.33 (100)b	25.59	80.2	84.14	105.0	90.4	92.8	0.95	0.76	0.89	0.86
34.80 (100)b	25.59	82.7	86.61	110.3	92.8	96.5	0.95	0.75	0.89	0.86
32.33 (100)b	38.20	90.1	103.4	117.9	109.2	111.9	0.87	0.76	0.83	0.81
34.80 (100)b	38.20	103.3	105.9	124.5	111.6	116.3	0.98	0.83	0.93	0.89
39.70 (152)c	6.00	56.0	56.17	70.9	60.7	54.2	1.00	0.79	0.92	1.03
26.20 (150)d	7.73	50.6	46.32	59.7	51.3	47.9	1.09	0.85	0.99	1.06
32.80 (508)d	6.85	50.0	49.26	65.7	55.9	51.5	1.02	0.76	0.89	0.97

a: Samaan, b: Kono, C: Picher, D: Harries

The sizes of he specimen are given within parenthesis in the second column. First 6 rows (152mm diameter) correspond to the tests by Samaan et al.[1998]. next 4 rows (100mm diameter) by Koto et al.[1998], next (152mm diameter) by Picher et al.[1996] and last 2 rows (150 and 508mm diameter) by Harries et al.[1998]. The ratios of test results to those of model predictions are presented in the last 4 columns of Table 3. A value of ratio close to 1.0 indicates a very good agreement of the model's results with the experiments. It can be observed from the table that the ratios of the strengths by experiments to those using the proposed model are very close to 1.0 compared to the model predictions of Sadaatmanesh et al.[1994]. Moreover about half of strengths using the proposed model is observed to be conservatives (rarios greater than 1.0). On the other hand, the models of Saadatmanesh et al.[1994] predict considerable higher strengths particularly, for high confinement pressure. The proposed model gives strengths which are more conservative to the predictions of Samaan et al.[12] and Spoelstra and Monti [1999] when compared to the test results. The comparison between the proposed model and Samaa's et al. [1998] model is more pronounced when considering large scale specimen. It is also noted that model of Spoelstra and Monti[1999] yields more unconservative strengths at high confining pressure compared to Samaan's et al. [1998] model.

PROPOSED MODIFIED ACI EQUATION

The existing ACI (American Concrete Institute) equations for determining the axial load capacity of reinforced concrete column are as follows:

For spirally reinforced column

$$P_n = 0.85\lfloor 0.85'' f'_c(A_g - A_{st}) + f_y A_{st} \rfloor \quad (6)$$

and for tied column

$$P_n = 0.80\lfloor 0.85 f'_c(A_g - A_{st}) + f_y A_{st} \rfloor \quad (7)$$

These have been modified to include the strengthening effect of confinement with composite fabrics. The strength enhancement portion of the poropsed model for ultimate strength of concrete, f'_{cc}, as presented in Equ, (4) is summed to the strength portion of unconfined concrete strength, f'_c of the ACI design equation. A values of 0.8 is used as reduction factor, α, for the enhanced strength due to confinement. This value is the lower bound of $\propto$ as proposed. Thus the suggested modified ACI design equation for spirally reinforced column is:

$$P_n = 0.85[\{0.85 f'_c + 0.8 \times 4.0 (f_e)^{0.79}\}(A_g - A_{st}) + f_y A_{st}]$$

Or

$$P_n = 0.85[0.85\{f'_c + 3.75\ (f_e)^{0.79}\}(A_g - A_{st}) + f_y A_{st}] \quad (8)$$

And for tied column

$$P_n = 0.80[0.85\{f'_c + 3.75 (f_e)^{0.79}\}(A_g - A_{st}) + f_y A_{st}] \quad (9)$$

CONCLUSIONS

Strengthening of concrete columns using composite fabrics is discussed. The strength model as proposed in this study predicts the strength of FRP confined concrete conservatively. The strength model of Sadatmanesh et al. appears to give considerably high strength compared to other models. The proposed modified ACI equation for column strengthened with FRP fabric is simple in nature. The performance of the proposed modified ACI Equation needs to be investigated when test results on large or full-scale speciments is available.

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REFERENCES

Karbhari, V. M. and Eckel, D. A. (1993) "Strengthning of Concrete Column Stubs Through Resin Infused Composite Warps", Journal of Thermoplastic Composite Matrerils, Vol. 6, April, pp. 92-107.

Demers, M. and Neale, K.W. (1994). "Strengthening of Concrete Columns With Unidirectional Composite Sheets," Developments in Short and Medium Span Bridge Engineering 94, Edited by: A. A. Mufti, B. Bakht and L.G. Jaeger, Canadian Society for Civil Engineering, pp. 895-905.

Howie, I. And Karbhari, V. M. (1994). "Effect of Materials Architecture on Stengthening Efficiency of Composite Warps for Deteriorating Columns in North-East," Proceedings of the Third Materials Engineering Conference on Infrastructure: New Materials and Methods of Repair, San Diego, pp. 199-206.

Saadatmanesh, H.; Ehsani, M. R. and Li, M. W. (1994) "Strength and Ductility of Concrete Columns Externally Reionforced With Fiber Composite Straps", ACI Structural Journal, Vol. 91, No.4, July-August.

Restropol J. I. And DeVino, B. (1994) "Enhacement of The Axial Load Carrying Capacity of Reinforced Concrete Columns by Means of Fiberglass-Epoxy Jackets", Proceedings of Advanced Composite Materials in Bridges and Structures, Edited by: M. M. El-badry, Canadian Society for Civil Engineers, Montreal, Quebec, pp. 547-53.

Mander, J.; Priestly, M. and Park, R. (1988) "Theoretical Stress Strain Model for Confined Concrete", ASCE Journal of the Structural Division, Vol. 114, No. 8, pp. 1804-1826.

Miyauchi, K.; Nishibayashi, S. and Inoue, S. (1997) "Estimation of Strengthening Effects with Carbon Fiber Sheet for Concrete Column", Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Sapporo, Japan, October, Vol. 1, pp. 217-224.

Richart, F. E.; Brandtzaeg, A. and Brown, R. L. (1929) "The failure of Plain and Spirally Reinforced Concrete in Compression", Bulletin No. 190, University of Illinois, Engineering Experimental Station, Urbana.

Kono, S.; Inazumi, M. Kaku, T. (1998) "Evaluation of Confining Effects of CFRP Sheets on Reinforced Concrete Members", Proceedings of the

Second International Conference on Fiber Composites in Infrastructures, Edited by: H. Saadatmaneh and M. R. Ehasani, Tucson, Arizona. pp. 343-355.

Fujimaki, T.; Iso, M. Watabe, M. and Honda, Y. (1996). "Experimental Study on Concrete Confined With FRP Sheets, No. 1, Confining Effects" Proceedings of AIJ Annual Meeting, Sept., pp. 137-138.

Satcioglu M. and Razvi, S. R. (1992). "Strentgth and Ductility of confined Concrete," ASCE Journal of Sturctural Engineering, Vol. 118, No. 6, June, pp. 1590-1607.

Samaan, M.; Mirmiran, A. and Shahawy, M. (1998). "Model of Concrete confined by Fiber Composites," ASCE Journal of Structural Engineering, Vol. 124, No. 9, September, pp. 1025-1031.

Spoelstra, M. R. and Monti, G. (1999). "FRP-Confined Concrete Model," ASCE Journal of Composites for Construction, Vol. 3, No. 3, August, pp. 143-150.

Harries, K. A.; Kestner, J.; Pessiki, S. and Sause, R. (1998), "Axial Behaviour of Reinforced Concrete Columns Retrofit with FRPC Jackets," Proceedings of the Second International Conference on Composites in Infrastructures, Edited by: H. Saadatmanesh and M. R. Ehsani, Tucson, Arizona, pp. 411-425.

Picher, F.; Rochette, P. and Labossiere, P. (1996). "Confinement of Concrete Cylinders With CFRP." Proceedings of the First International Conference on Fiber Composites in Infrastructures, Edited by: H. Saadatmanesh and M. R. Ehsani, Tucson, Arizona, pp. 829-841.

APPENDIX – A

Effective Confinement Coefficient, k_e

The effective confinement coefficient, K_e, defined as the ratio of effectively confined concrete core area, A_e by the fabric to the effective core area concrete, A_{cc}. In other words k_e, is given by:

$$K_e = \frac{A_e}{A_{cc}} \qquad \text{(A1)}$$

i) Circular section [Fig. 2)s

k_e=1.0 for continuous warp of fabric

$$K_e = \frac{\left(1 - \frac{s}{2d}\right) - \rho_s}{1 - \rho_s} \quad \text{for separate strap of fabric} \qquad \text{(A2)}$$

Where,

s' = clear gap between the warp of fabric

ρ_s = the longitudinal reinforcement area ratio

d= diameter of column

ii) Rectangular Section

$$k_e = \frac{1-\left[\dfrac{(b-2r)^2+(h-2r)^2}{3bh}\right] \div \rho_s}{1-\rho_s} \quad \text{for continuous strap [5]} \tag{A3}$$

$$k_e = \frac{\left[1-\dfrac{(b-2r)^2+(h-2r)^2}{3bh}\right] \times \left[\left(1-0.5\frac{s'}{b}\right)\right]\left(1-0.5\frac{s'}{h}\right)}{1-\rho_s} \quad \text{for separate strap} \tag{A4}$$

Were,
b=width of column
h=depth of column
r=radius of corner

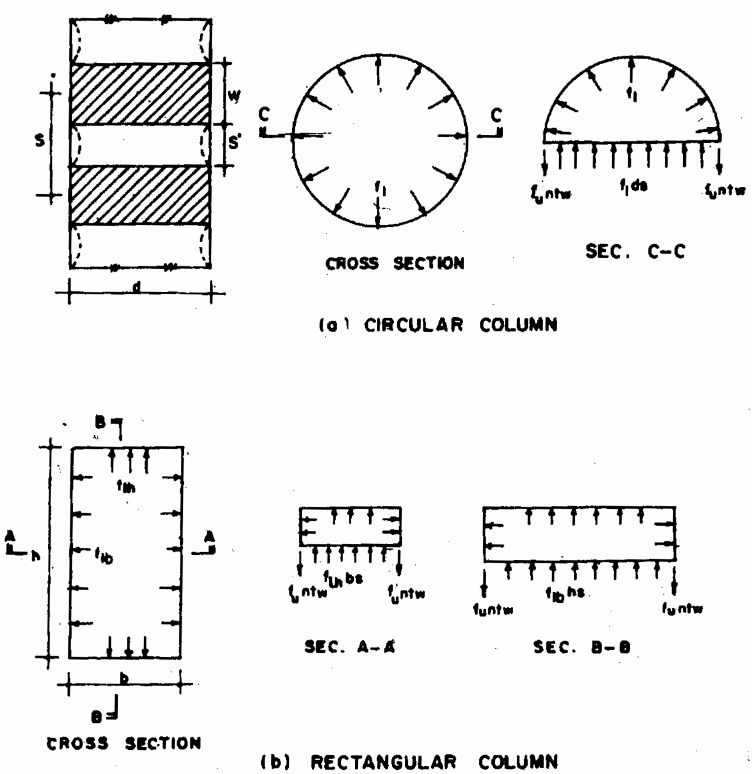

Fig 2. Confining pressure and force Equilibrium system in columns.

The confining pressure, F_l
i) circular column [Fig. 2]:

$$f_l = \frac{2ntwf_u}{ds} \quad \text{(A5)}$$

where,
n= the number of layers of fabric
t = thickness of one layer of fabric
w= width of fabric
f_u=tensile strength of fabric
s=spacing of fabric

ii) Rectangular column [Fig.2]

$$f_{el} = \frac{bf_{lh} + hf_{lb}}{b+h} \quad \text{(A6)}$$

$$f_{lb} = \frac{2ntwof_u}{hs} \quad \text{(A7)}$$

$$f_{lh} = \frac{2ntw'' f_u}{bs}$$