CHAPTER 4

COMPARISON OF PUSH-OUT TEST RESULTS WITH EXISTING STRENGTH PREDICTION METHODS

4.1 General

Several stud strength prediction methods have been developed since the 1970s. Three of these methods are part of the specifications used in the US, in Canada, and in Europe. These are the AISC specification (*Load* 1993), the Canadian specification (*Steel* 1994), and the Eurocode 4 specification (*EN* 2001). Other methods that have been proposed include Lloyd and Wright (1990), Mottram and Johnson (1990), Lawson (1992), and Johnson and Yuan (1997). Lyons et al (1994) compared their push-out test data with predictions from all of the above methods, except for Johnson and Yuan (1997), and showed that these methods are generally unconservative.

The push-out test results in this study confirm that most of these methods give unconservative predictions for the strength of studs in composite slabs. Below, the solid slab test results are compared to the predicted strengths from the AISC specification equation (*Load* 1993). The results from the composite slab tests are compared to the predicted strengths from the AISC specification (*Load* 1993), the Canadian specification (*Steel* 1994), the Eurocode 4 specification (*EN* 2001), and a method recently proposed by Johnson and Yuan (1997). These methods are presented in detail in Section 1.2. Predictions were all made using measured material properties.

4.2 Solid Slab Ultimate Strength Comparison

The results of the solid slab push-out tests are compared to the strengths found from the strength prediction equation in the AISC specification (*Load* 1993). The development of this equation is discussed in Section 1.2. The equation was developed by Ollgaard et al (1971), and is repeated below. The strength of a stud in a solid slab is a function of the concrete strength and the area of the stud, and has an upper limit equal to the tensile strength of the stud.

$$Q_{SOL} = 0.5 A_s \sqrt{f_c' E_c} \leq 1.0 A_s F_u \tag{4.1}$$

where Q_{SOL} = strength of stud in a solid slab

A_s = cross-sectional area of stud

f'_c = compressive strength of concrete

E_c = modulus of elasticity of concrete = $33 w^{1.5} \sqrt{f_c'}$

w = unit weight of concrete

F_u = tensile strength of stud

The AISC predicted strengths are compared to the experimental strengths in Table 4.1 and Fig. 4.1, and appear to be adequate. The predictions are conservative for standard tests, where sheet metal was not placed between the steel beam and concrete slab and 10% normal load was applied. For Tests 1-12 and 19-21, which were standard push-out tests, the average of Q_e/Q_{AISC} is 1.11, with a standard deviation of 0.078 and a coefficient of variation of 7.0%. For Tests 22-24, which had no normal load applied, the average of Q_e/Q_{AISC} is 0.9, with a standard deviation of 0.063 and a coefficient of variation of 7.1%.

Table 4.1 AISC Ultimate Strength Comparison for Solid Slab Tests

Series	Test	Q_e (k)	Q_{SOL}* (k)	A_sF_u~ (k)	Q_{AISC}** (k)	Q_e/Q_{AISC}
1	1	25.76	23.03	28.66	23.03	1.12
1	2	28.83	23.03	28.66	23.03	1.25
1	3	25.56	23.03	28.66	23.03	1.11
2	4	28.42	23.03	28.66	23.03	1.23
2	5	25.19	23.03	28.66	23.03	1.09
2	6	25.85	23.03	28.66	23.03	1.12
3	7	22.88	23.03	28.66	23.03	0.99
3	8	26.66	23.03	28.66	23.03	1.16
3	9	27.51	23.03	28.66	23.03	1.19
4	10	26.03	23.03	28.66	23.03	1.13
4	11	25.41	23.03	28.66	23.03	1.10
4	12	24.40	23.03	28.66	23.03	1.06
5	13	24.03	29.84	28.66	28.66	0.84
5	14	24.59	29.84	28.66	28.66	0.86
5	15	22.74	29.84	28.66	28.66	0.79
6	16	24.59	29.84	28.66	28.66	0.86
6	17	24.03	29.84	28.66	28.66	0.84
6	18	25.76	29.84	28.66	28.66	0.90
7	19	29.71	30.86	28.66	28.66	1.04
7	20	28.64	30.86	28.66	28.66	1.00
7	21	29.71	30.86	28.66	28.66	1.04
8	22	23.59	30.86	28.66	28.66	0.82
8	23	26.67	30.86	28.66	28.66	0.93
8	24	26.79	30.86	28.66	28.66	0.93

~F_u = 64.9 ksi (measured stud property provided by manufacturer)

* $Q_{SOL} = 0.5 A_s \sqrt{f'_c\, E_c}$

** Q_{AISC} = minimum of Q_{SOL} and A_sF_u

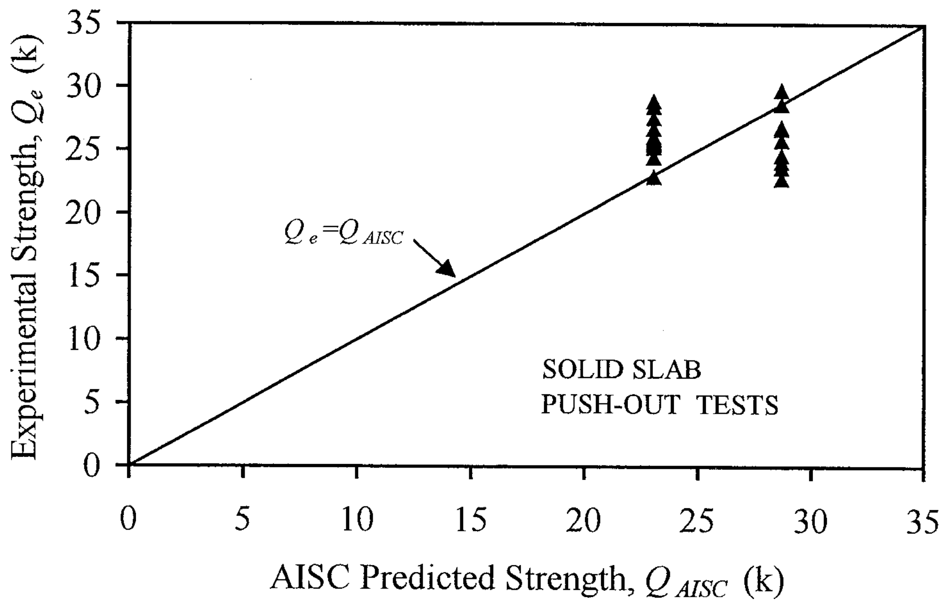

Fig. 4.1 Experimental Strength vs. AISC Predicted Strength for Solid Slab Push-Out Tests

For Tests 13-18, which had flat sheet metal placed between the steel beam and concrete slab, the average of Q_e/Q_{AISC} is 0.85, with a standard deviation of 0.036 and a coefficient of variation of 4.2%.

The tests performed by Lyons et al (1994) showed that the AISC equations were slightly unconservative (the ratios of Q_e/Q_{AISC} were less than 1.0). When the AISC predicted strength was governed by the concrete strength, the average ratio was 0.92, and when the strength was governed by the tensile strength of the stud, A_sF_u, the average ratio was 0.83. The reason that Lyons' tests exhibited smaller strengths than most of the ones in this test program is that the authors did not use normal load on the solid slab specimens. The strengths of their tests were close to the strengths of Tests 22-24 in this test program, where no normal load was used.

4.3 Composite Slab Ultimate Strength Comparison

4.3.1 AISC Specification Provisions

The results of the composite slab push-out tests are compared to the predicted strengths based on the AISC specification (*Load* 1993). The development of these equations is discussed in Section 1.2. The equation was developed by Ollgaard et al (1971), and is repeated below for convenience. The strength of a stud in a solid slab, Q_{SOL}, is a function of the concrete strength and the area of the stud, and has an upper limit equal to the tensile strength of the stud. A strength reduction factor, *SRF*, is multiplied by the solid slab stud strength to obtain the strength of a stud in a composite slab. The *SRF*, which should not be taken greater than 1.0, is a function of the deck geometry and the number of studs in a rib.

$$Q_{SOL} = 0.5A_s\sqrt{f_c^{'}E_c} \leq 1.0A_sF_u \tag{4.1}$$

$$SRF = \left(\frac{0.85}{\sqrt{N_R}}\right)\left(\frac{H_S - h_R}{h_R}\right)\left(\frac{w_R}{h_R}\right) \leq 1.0 \tag{4.2}$$

$$Q_{AISC} = SRF \times 0.5A_s\sqrt{f_c^{'}E_c} \leq 1.0A_sF_u \tag{4.3}$$

where Q_{SOL} = strength of stud in a solid slab

A_s = cross-sectional area of stud

f'_c = compressive strength of concrete

E_c = modulus of elasticity of concrete = $33w^{1.5}\sqrt{f_c^{'}}$

w = unit weight of concrete

F_u = tensile strength of stud

SRF = strength reduction factor for a stud in a composite slab

N_R = number of studs per rib

H_S = height of stud

h_R = height of deck rib

w_R = average width of deck rib

Q_{AISC} = AISC predicted strength of a stud in a composite slab

The AISC predicted strengths are compared to the experimental strengths in Table 4.2 and Fig. 4.2. All of the experimental strengths, except for five of the tests, were significantly less than the AISC predicted strengths, which makes the equations unconservative. The strengths of the strong positions studs were much closer to the predicted strengths than the strengths of the weak position studs. The average ratio for all tests in Table 4.2 of Q_e/Q_{AISC} is 0.709, the minimum is 0.347, and the maximum is 1.183; the standard deviation is 0.169, and the coefficient of variation is 23.8%

4.3.2 CSA Provisions

The results of the composite slab push-out tests are compared to the strengths from the strength prediction equations in the Canadian Standards Association (CSA) specification (*Steel* 1994). The equation for the strength of a stud in a solid slab was developed by Ollgaard et al (1971). It is the same equation as the one in the AISC specification. The equations for the strength of a stud in a composite slab were developed

Table 4.2 AISC Ultimate Strength Comparison

Series	Test	Stud Layout	Q_e (k)	Q_{SOL} (k)	SRF	SRF x Q_{SOL} (k)	Meas. A_sF_u (k)	Q_{AISC} (k)	Q_e/Q_{AISC}
D1	D1	S	9.77	12.66	1.00	12.66	14.54	12.66	0.771
D1	D2	S	7.29	12.66	1.00	12.66	14.54	12.66	0.576
D1	D3	S	9.23	12.66	1.00	12.66	14.54	12.66	0.729
D2	D4	2S	8.95	12.66	1.00	12.66	14.54	12.66	0.707
D2	D5	2S	8.76	12.66	1.00	12.66	14.54	12.66	0.692
D2	D6	2S	7.16	12.66	1.00	12.66	14.54	12.66	0.565
D3	D7	W	6.16	12.66	1.00	12.66	14.54	12.66	0.486
D3	D8	W	8.01	12.66	1.00	12.66	14.54	12.66	0.632
D3	D9	W	7.44	12.66	1.00	12.66	14.54	12.66	0.587
D4	D10	S	12.53	14.30	1.00	14.30	22.28	14.30	0.876
D4	D11	S	13.54	14.30	1.00	14.30	22.28	14.30	0.947
D4	D12	S	15.55	14.30	1.00	14.30	22.28	14.30	1.087
D5	D13	W	15.08	14.30	1.00	14.30	20.56	14.30	1.054
D5	D14	W	11.65	14.30	1.00	14.30	20.56	14.30	0.815
D5	D15	W	10.90	14.30	1.00	14.30	20.56	14.30	0.762
D6	D16	2S	11.87	14.30	1.00	14.30	22.28	14.30	0.830
D6	D17	2S	15.42	14.30	1.00	14.30	22.28	14.30	1.078
D7	D19	S	8.86	16.28	1.00	16.28	14.54	14.54	0.609
D7	D20	S	9.14	16.28	1.00	16.28	14.54	14.54	0.629
D7	D21	S	6.63	16.28	1.00	16.28	14.54	14.54	0.456
D8	D22	2S	9.23	16.28	1.00	16.28	14.54	14.54	0.635
D8	D23	2S	10.30	16.28	1.00	16.28	14.54	14.54	0.708
D8	D24	2S	11.46	16.28	1.00	16.28	14.54	14.54	0.788
D9	D25	W	9.17	16.28	1.00	16.28	14.54	14.54	0.631
D9	D26	W	7.32	16.28	1.00	16.28	14.54	14.54	0.503
D9	D27	W	6.88	16.28	1.00	16.28	14.54	14.54	0.473
D10	D28	S	20.01	42.24	1.00	42.24	29.08	29.08	0.688
D10	D29	S	18.72	42.24	1.00	42.24	29.08	29.08	0.644
D10	D30	S	21.80	42.24	1.00	42.24	29.08	29.08	0.750
D11	D32	2S	17.49	42.24	1.00	42.24	29.08	29.08	0.602
D11	D33	2S	20.89	42.24	1.00	42.24	29.08	29.08	0.718

Table 4.2 AISC Ultimate Strength Comparison (cont'd.)

Series	Test	Stud Layout	Q_e (k)	Q_{SOL} (k)	SRF	SRF x Q_{SOL} (k)	Meas. A_sF_u (k)	Q_{AISC} (k)	Q_e/Q_{AISC}
D12	D34	W	15.05	42.24	1.00	42.24	29.08	29.08	0.518
D12	D35	W	12.03	42.24	1.00	42.24	29.08	29.08	0.414
D12	D36	W	15.67	42.24	1.00	42.24	29.08	29.08	0.539
D13	D37	S	16.18	20.83	1.00	20.83	22.28	20.83	0.777
D13	D38	S	17.07	20.83	1.00	20.83	22.28	20.83	0.819
D13	D39	S	14.53	20.83	1.00	20.83	22.28	20.83	0.698
D14	D40	2S	14.70	20.83	1.00	20.83	22.28	20.83	0.706
D14	D41	2S	16.95	20.83	1.00	20.83	22.28	20.83	0.814
D14	D42	2S	17.43	20.83	1.00	20.83	22.28	20.83	0.837
D15	D43	W	9.12	20.83	1.00	20.83	22.28	20.83	0.438
D15	D44	W	11.14	20.83	1.00	20.83	22.28	20.83	0.535
D15	D45	W	11.07	20.83	1.00	20.83	22.28	20.83	0.531
D16	D46	S	5.89	6.63	1.00	6.63	8.75	6.63	0.889
D16	D47	S	5.18	6.63	1.00	6.63	8.75	6.63	0.781
D16	D48	S	5.36	6.63	1.00	6.63	8.75	6.63	0.809
D18	D52	W	4.05	6.63	1.00	6.63	8.75	6.63	0.611
D18	D53	W	4.54	6.63	1.00	6.63	8.75	6.63	0.685
D18	D54	W	4.81	6.63	1.00	6.63	8.75	6.63	0.726
D20	D58	S	6.03	8.03	1.00	8.03	8.53	8.03	0.751
D20	D59	S	8.10	8.03	1.00	8.03	8.53	8.03	1.009
D20	D60	S	9.50	8.03	1.00	8.03	8.53	8.03	1.183
D22	D64	W	5.40	8.03	1.00	8.03	8.53	8.03	0.673
D22	D65	W	6.68	8.03	1.00	8.03	8.53	8.03	0.832
D22	D66	W	6.46	8.03	1.00	8.03	8.53	8.03	0.805
D26	D77	S	22.54	31.09	1.00	31.09	29.08	29.08	0.775
D27	D79	S	23.12	31.09	1.00	31.09	29.08	29.08	0.795
D27	D80	S	19.35	31.09	1.00	31.09	29.08	29.08	0.666
D27	D81	S	24.39	31.09	1.00	31.09	29.08	29.08	0.839
D28	D82	W	13.90	30.01	1.00	30.01	29.08	29.08	0.478
D28	D83	W	18.85	30.01	1.00	30.01	29.08	29.08	0.648
D28	D84	W	10.10	30.01	1.00	30.01	29.08	29.08	0.347
D29	D86	W	20.71	30.01	1.00	30.01	29.08	29.08	0.712
D29	D87	W	19.91	30.01	1.00	30.01	29.08	29.08	0.685

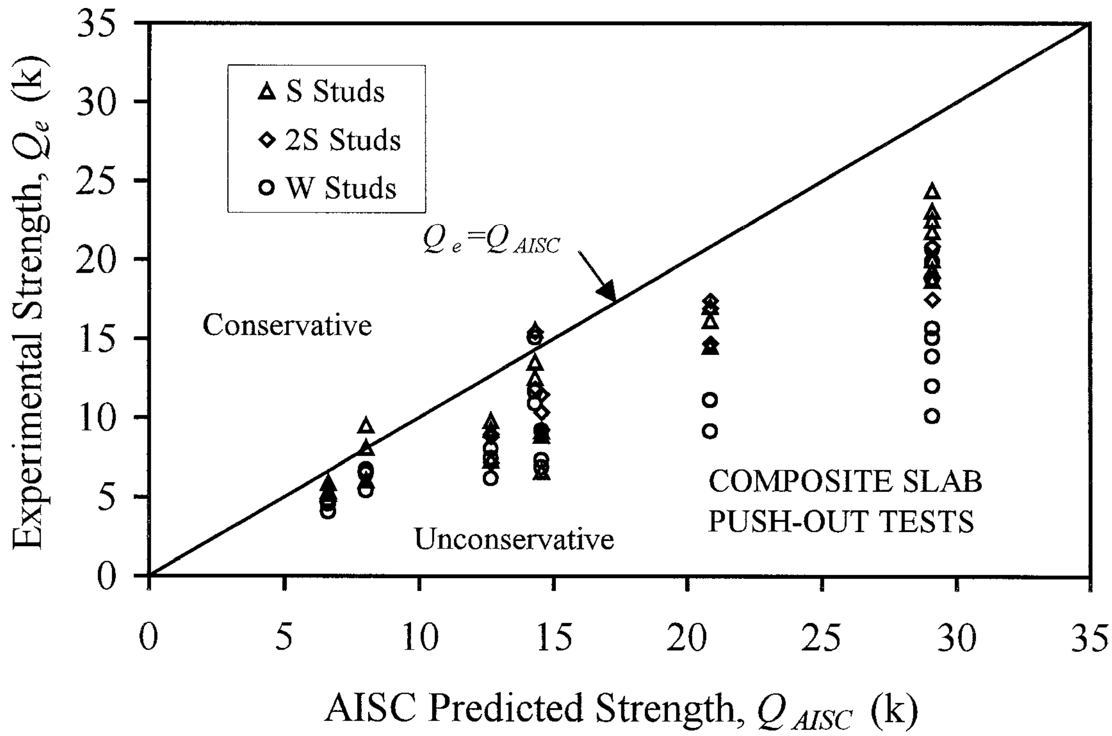

Fig. 4.2 Experimental Strengths vs. AISC Predicted Strengths for Composite Slab Push-Out Tests

by Jayas and Hosain (1988). The approach is based on a concrete pull-out model, developed by Hawkins and Mitchell (1984), in which the failure surface is a pyramidal cone of concrete which propagates downward from the underside of the stud head. Jayas and Hosain (1988) developed separate equations, from which the stud strength cannot be taken greater than the strength of a stud in a solid slab, for 1.5 in. and 3 in. deck. The development of these equations, which are repeated below, is discussed in Section 1.2. For 2 in. deck, a constant of 6.2 was used in the equation for Q_{CP}, instead of 4.2 for 3 in. deck or 7.3 for 1.5 in. deck. The CSA predicted strength, Q_{CSA}, is taken as the minimum of Q_{SOL} and Q_{CP}.

$$Q_{SOL} = 0.5 A_s \sqrt{f'_c E_c} \leq 1.0 A_s F_u \tag{4.1}$$

$$Q_{CP} = 4.2 \rho A_p \sqrt{f'_c} \quad \text{for } h_R = 3 \text{ in.} \tag{4.4}$$

$$Q_{CP} = 7.3 \rho A_p \sqrt{f'_c} \quad \text{for } h_R = 1.5 \text{ in.} \tag{4.5}$$

where Q_{SOL} = strength of stud in a solid slab

A_s = cross-sectional area of stud

f'_c = compressive strength of concrete

E_c = modulus of elasticity of concrete = $33 w^{1.5} \sqrt{f'_c}$

w = unit weight of concrete

F_u = tensile strength of stud

Q_{CP} = concrete pull-out strength of a stud in a composite slab

ρ = 1.0 for normal density concrete
= 0.85 for semi-low density concrete

A_p = concrete pull-out area. For a single stud, the apex of the pull-out area, with four sides sloping at 45, is taken as the center of the top surface of the head of the stud. For a pair of studs, the pull-out area has a ridge extending from stud to stud.

h_R = height of deck rib

for $h_p < w_l/2$,

$$A_p(ss) = 2\sqrt{2}\left(H_s w_R\right) \tag{4.6}$$

$$A_p(ds) = 2\sqrt{2} H_s w_R + \sqrt{2} w_R s \tag{4.7}$$

for $h_p > w_l/2$,

$$A_p(ss) = 2\sqrt{2}\left(2h_p^2 + h_R w_R\right) \tag{4.8}$$

$$A_p(ds) = 2\sqrt{2}\left(2h_p^2 + h_R w_R + h_p s\right) \tag{4.9}$$

where $h_p = H_s - h_R$

H_s = height of stud

w_R = average rib width

w_1 = over-all trough width

To use these equations, H_s/d_s must not be less than 4.0, (H_s-h_R) must not be less than two stud diameters, and the transverse spacing must not be less than four stud diameters.

The CSA predicted strengths, most of which were governed by the equation for Q_{SOL}, are compared to the experimental strengths in Table 4.3 and Fig. 4.3. Fig. 4.3 shows that the CSA method is unconservative for all except five tests. The average ratio of Q_e/Q_{CSA} is 0.726, the minimum is 0.414, and the maximum is 1.183; the standard deviation is 0.172, and the coefficient of variation is 23.7%.

4.3.3 Eurocode 4 Provisions

The results of the composite slab push-out tests are compared to the strengths found from the strength prediction equations in Eurocode 4 (*EN* 2001). The equations are similar to the AISC equations, except the constant 0.5 is changed to 0.37 in the equation for the strength of a stud in a solid slab, and the upper limit on this strength is 80% of the tensile strength of the stud. The strength reduction factor is also similar, except the

Table 4.3 CSA Ultimate Strength Comparison

Series	Test	Stud Position	Q_e (k)	Q_{SOL} (k)	Q_{CP} (k)	Q_{CSA} (k)	Q_e/Q_{CSA}
D1	D1	S	9.77	12.67	23.34	12.67	0.771
D1	D2	S	7.29	12.67	23.34	12.67	0.575
D1	D3	S	9.23	12.67	23.34	12.67	0.729
D2	D4	2S	8.95	12.67	30.93	12.67	0.707
D2	D5	2S	8.76	12.67	30.93	12.67	0.692
D2	D6	2S	7.16	12.67	30.93	12.67	0.565
D3	D7	W	6.16	12.67	23.34	12.67	0.486
D3	D8	W	8.01	12.67	23.34	12.67	0.632
D3	D9	W	7.44	12.67	23.34	12.67	0.587
D4	D10	S	12.53	14.30	18.94	14.30	0.876
D4	D11	S	13.54	14.30	18.94	14.30	0.947
D4	D12	S	15.55	14.30	18.94	14.30	1.087
D5	D13	W	15.08	14.30	15.62	14.30	1.054
D5	D14	W	11.65	14.30	15.62	14.30	0.815
D5	D15	W	10.90	14.30	15.62	14.30	0.762
D6	D16	2S	11.87	14.30	25.09	14.30	0.830
D6	D17	2S	15.42	14.30	25.09	14.30	1.078
D7	D19	S	8.86	14.54	26.92	14.54	0.609
D7	D20	S	9.14	14.54	26.92	14.54	0.628
D7	D21	S	6.63	14.54	26.92	14.54	0.456
D8	D22	2S	9.23	14.54	35.66	14.54	0.635
D8	D23	2S	10.30	14.54	35.66	14.54	0.708
D8	D24	2S	11.46	14.54	35.66	14.54	0.788
D9	D25	W	9.17	14.54	26.92	14.54	0.631
D9	D26	W	7.32	14.54	26.92	14.54	0.503
D9	D27	W	6.88	14.54	26.92	14.54	0.473
D10	D28	S	20.01	29.08	29.51	29.08	0.688
D10	D29	S	18.72	29.08	29.51	29.08	0.644
D10	D30	S	21.80	29.08	29.51	29.08	0.750
D11	D32	2S	17.49	29.08	39.10	29.08	0.602
D11	D33	2S	20.89	29.08	39.10	29.08	0.718

Table 4.3 CSA Ultimate Strength Comparison (cont'd.)

Series	Test	Stud Position	Q_e (k)	Q_{SOL} (k)	Q_{CP} (k)	Q_{CSA} (k)	Q_e/Q_{CSA}
D12	D34	W	15.05	29.08	29.51	29.08	0.518
D12	D35	W	12.03	29.08	29.51	29.08	0.414
D12	D36	W	15.67	29.08	29.51	29.08	0.539
D13	D37	S	16.18	20.83	24.07	20.83	0.777
D13	D38	S	17.07	20.83	24.07	20.83	0.819
D13	D39	S	14.53	20.83	24.07	20.83	0.698
D14	D40	2S	14.70	20.83	31.89	20.83	0.706
D14	D41	2S	16.95	20.83	31.89	20.83	0.814
D14	D42	2S	17.43	20.83	31.89	20.83	0.837
D15	D43	W	9.12	20.83	24.07	20.83	0.438
D15	D44	W	11.14	20.83	24.07	20.83	0.535
D15	D45	W	11.07	20.83	24.07	20.83	0.531
D16	D46	S	5.89	6.63	21.99	6.63	0.889
D16	D47	S	5.18	6.63	21.99	6.63	0.781
D16	D48	S	5.36	6.63	21.99	6.63	0.809
D18	D52	W	4.05	6.63	21.99	6.63	0.611
D18	D53	W	4.54	6.63	21.99	6.63	0.685
D18	D54	W	4.81	6.63	21.99	6.63	0.726
D20	D58	S	6.03	8.03	22.36	8.03	0.751
D20	D59	S	8.10	8.03	22.36	8.03	1.009
D20	D60	S	9.50	8.03	22.36	8.03	1.183
D22	D64	W	5.40	8.03	22.36	8.03	0.673
D22	D65	W	6.68	8.03	22.36	8.03	0.832
D22	D66	W	6.46	8.03	22.36	8.03	0.805
D26	D77	S	22.54	29.08	24.80	24.80	0.909
D27	D79	S	23.12	29.08	24.80	24.80	0.932
D27	D80	S	19.35	29.08	24.80	24.80	0.780
D27	D81	S	24.39	29.08	24.80	24.80	0.983
D28	D82	W	13.90	29.08	24.02	24.02	0.579
D28	D83	W	18.85	29.08	24.02	24.02	0.785
D28	D84	W	10.10	29.08	24.02	24.02	0.421
D29	D86	W	20.71	29.08	24.02	24.02	0.862
D29	D87	W	19.91	29.08	24.02	24.02	0.829

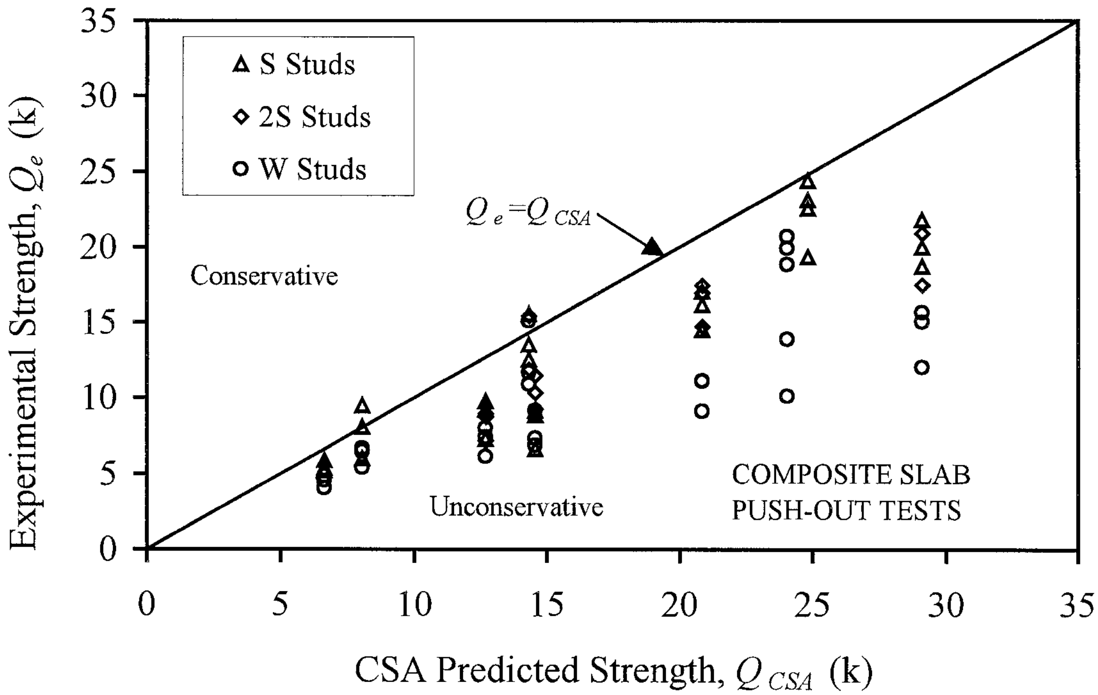

Fig. 4.3 Experimental Strengths vs. CSA Predicted Strengths for Composite Slab Push-Out Tests

constant 0.85 is changed to 0.7. These equations are presented below.

$$Q_{SOL} = 0.37\alpha A_s\sqrt{f_c' E_c} \leq 0.8 A_s F_u \quad (4.10)$$

$$SRF = \left(\frac{0.7}{\sqrt{N_R}}\right)\left(\frac{H_S - h_R}{h_R}\right)\left(\frac{w_R}{h_R}\right) \quad (4.11)$$

An upper limit is placed on SRF as follows:

For studs welded through deck greater than 1.0 mm (0.039 in.) thick,

1.0 for single studs

0.80 for multiple studs

For studs welded through deck less than 1.0 mm (0.039 in.) thick, 0.85 for single studs

0.70 for multiple studs

For 19 mm (3/4 in.) or 22 mm (7/8 in.) studs welded through holes in deck,

0.75 for single studs

0.60 for multiple studs

$$Q_{EC4} = SRF \times Q_{SOL} \tag{4.12}$$

where Q_{SOL} = strength of stud in a solid slab

$$\alpha = 0.2\left[\left(\frac{H_s}{d}\right)+1\right] \text{ for } 3 \leq \frac{H_s}{d} \leq 4$$

A_s = cross-sectional area of stud

f'_c = compressive strength of concrete

E_c = modulus of elasticity of concrete = $33w^{1.5}\sqrt{f_c'}$

w = unit weight of concrete

F_u = tensile strength of stud

SRF = strength reduction factor for a stud in a composite slab

N_R = number of studs per rib ≤ 2

H_S = height of stud

h_R = height of deck rib

w_R = average width of deck rib

Q_{EC4} = Eurocode 4 predicted strength of a stud in a composite slab

The Eurocode 4 predicted strengths, most of which are unconservative, are compared to the experimental strengths in Table 4.4 and Fig. 4.4. The strengths of strong position studs are adequately predicted, but the strengths of weak position studs are not. The average ratio of Q_e/Q_{EC4} is 1.150, the minimum is 0.535, and the maximum is 2.082; the standard deviation is 0.313, and the coefficient of variation is 27.2%.

4.3.4 Johnson and Yuan Model

The results of the composite slab push-out tests are compared to the strengths found from the strength prediction equations from Johnson and Yuan (1997). Five modes of failure are considered for transverse sheeting: shank shearing (SS), rib punching (RP), rib punching with shank shearing (RPSS), rib punching with concrete pull-out (RPCP), and concrete pull-out (CPT). Theoretical models for each failure mode are given below.

For shank shearing failure of studs in slabs that are reinforced so that splitting cannot spread, the shear strength is found from Eurocode 4:

$$P_{rs} = 0.37 A_s \left(f_c E_{cm} \right)^{0.5} \le 0.8 A_s f_u \tag{4.13}$$

where P_{rs} = shear strength of stud in a solid slab

A_s = cross-sectional area of stud

f_c = cylinder strength of concrete

E_{cm} = modulus of elasticity of concrete

f_u = ultimate strength of stud

Table 4.4 Eurocode 4 Ultimate Strength Comparison

Series	Test	Stud Position	Q_e (k)	Q_{SOL} (k)	SRF	SRF* Q_{SOL} (k)	$0.8A_sF_u$ (k)	Q_{EC4} (k)	Q_e/Q_{EC4}
D1	D1	S	9.77	9.37	0.85	7.97	11.63	7.97	1.226
D1	D2	S	7.29	9.37	0.85	7.97	11.63	7.97	0.915
D1	D3	S	9.23	9.37	0.85	7.97	11.63	7.97	1.158
D2	D4	2S	8.95	9.37	0.70	6.56	11.63	6.56	1.364
D2	D5	2S	8.76	9.37	0.70	6.56	11.63	6.56	1.335
D2	D6	2S	7.16	9.37	0.70	6.56	11.63	6.56	1.091
D3	D7	W	6.16	9.37	0.85	7.97	11.63	7.97	0.773
D3	D8	W	8.01	9.37	0.85	7.97	11.63	7.97	1.005
D3	D9	W	7.44	9.37	0.85	7.97	11.63	7.97	0.934
D4	D10	S	12.53	10.58	0.85	9.00	17.83	9.00	1.393
D4	D11	S	13.54	10.58	0.85	9.00	17.83	9.00	1.505
D4	D12	S	15.55	10.58	0.85	9.00	17.83	9.00	1.729
D5	D13	W	15.08	10.58	0.85	9.00	16.45	9.00	1.676
D5	D14	W	11.65	10.58	0.85	9.00	16.45	9.00	1.295
D5	D15	W	10.90	10.58	0.85	9.00	16.45	9.00	1.212
D6	D16	2S	11.87	10.58	0.70	7.41	17.83	7.41	1.602
D6	D17	2S	15.42	10.58	0.70	7.41	17.83	7.41	2.082
D7	D19	S	8.86	11.63	0.85	9.89	11.63	9.89	0.896
D7	D20	S	9.14	11.63	0.85	9.89	11.63	9.89	0.924
D7	D21	S	6.63	11.63	0.85	9.89	11.63	9.89	0.670
D8	D22	2S	9.23	11.63	0.70	8.14	11.63	8.14	1.133
D8	D23	2S	10.30	11.63	0.70	8.14	11.63	8.14	1.265
D8	D24	2S	11.46	11.63	0.70	8.14	11.63	8.14	1.407
D9	D25	W	9.17	11.63	0.85	9.89	11.63	9.89	0.927
D9	D26	W	7.32	11.63	0.85	9.89	11.63	9.89	0.740
D9	D27	W	6.88	11.63	0.85	9.89	11.63	9.89	0.696
D10	D28	S	20.01	23.26	0.85	19.77	23.26	19.77	1.012
D10	D29	S	18.72	23.26	0.85	19.77	23.26	19.77	0.947
D10	D30	S	21.80	23.26	0.85	19.77	23.26	19.77	1.103
D11	D32	2S	17.49	23.26	0.70	16.28	23.26	16.28	1.074
D11	D33	2S	20.89	23.26	0.70	16.28	23.26	16.28	1.283

Table 4.4 Eurocode 4 Ultimate Strength Comparison (cont'd.)

Series	Test	Stud Position	Q_e (k)	Q_{SOL} (k)	SRF	SRF* Q_{SOL} (k)	$0.8A_sF_u$ (k)	Q_{EC4} (k)	Q_e/Q_{EC4}
D12	D34	W	15.05	23.26	0.85	19.77	23.26	19.77	0.761
D12	D35	W	12.03	23.26	0.85	19.77	23.26	19.77	0.608
D12	D36	W	15.67	23.26	0.85	19.77	23.26	19.77	0.793
D13	D37	S	16.18	15.41	0.85	13.10	17.83	13.10	1.235
D13	D38	S	17.07	15.41	0.85	13.10	17.83	13.10	1.303
D13	D39	S	14.53	15.41	0.85	13.10	17.83	13.10	1.109
D14	D40	2S	14.70	15.41	0.70	10.79	17.83	10.79	1.362
D14	D41	2S	16.95	15.41	0.70	10.79	17.83	10.79	1.571
D14	D42	2S	17.43	15.41	0.70	10.79	17.83	10.79	1.615
D15	D43	W	9.12	15.41	0.85	13.10	17.83	13.10	0.696
D15	D44	W	11.14	15.41	0.85	13.10	17.83	13.10	0.850
D15	D45	W	11.07	15.41	0.85	13.10	17.83	13.10	0.845
D16	D46	S	5.89	4.91	0.85	4.17	7.00	4.17	1.413
D16	D47	S	5.18	4.91	0.85	4.17	7.00	4.17	1.242
D16	D48	S	5.36	4.91	0.85	4.17	7.00	4.17	1.286
D18	D52	W	4.05	4.91	0.85	4.17	7.00	4.17	0.971
D18	D53	W	4.54	4.91	0.85	4.17	7.00	4.17	1.089
D18	D54	W	4.81	4.91	0.85	4.17	7.00	4.17	1.154
D20	D58	S	6.03	5.94	0.85	5.05	6.82	5.05	1.194
D20	D59	S	8.10	5.94	0.85	5.05	6.82	5.05	1.604
D20	D60	S	9.50	5.94	0.85	5.05	6.82	5.05	1.881
D22	D64	W	5.40	5.94	0.85	5.05	6.82	5.05	1.069
D22	D65	W	6.68	5.94	0.85	5.05	6.82	5.05	1.323
D22	D66	W	6.46	5.94	0.85	5.05	6.82	5.05	1.279
D26	D77	S	22.54	23.01	0.85	19.56	23.26	19.56	1.153
D27	D79	S	23.12	23.01	0.85	19.56	23.26	19.56	1.182
D27	D80	S	19.35	23.01	0.85	19.56	23.26	19.56	0.989
D27	D81	S	24.39	23.01	0.85	19.56	23.26	19.56	1.247
D28	D82	W	13.90	22.21	0.85	18.88	23.26	18.88	0.736
D28	D83	W	18.85	22.21	0.85	18.88	23.26	18.88	0.999
D28	D84	W	10.10	22.21	0.85	18.88	23.26	18.88	0.535
D29	D86	W	20.71	22.21	0.85	18.88	23.26	18.88	1.097
D29	D87	W	19.91	22.21	0.85	18.88	23.26	18.88	1.055

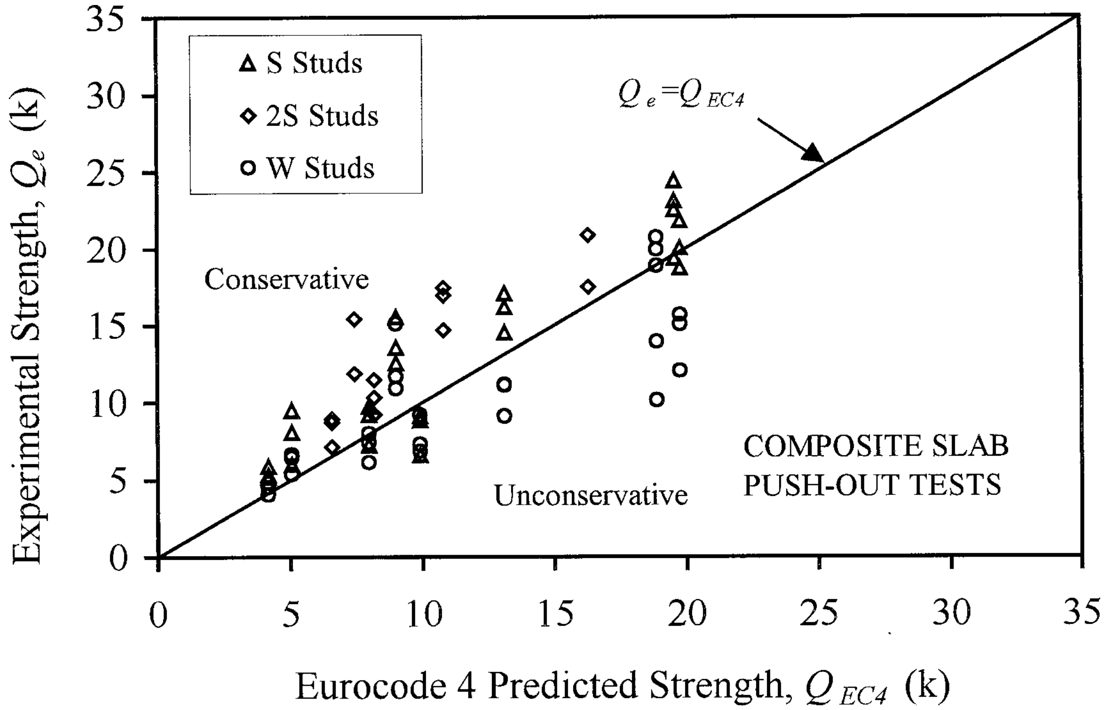

Fig. 4.4 Experimental Strengths vs. Eurocode 4 Predicted Strengths for Composite Slab Push-Out Tests

For other failure modes, the shear strength is defined by

$$P_r = k_t P_{rs} \tag{4.14}$$

where P_r = shear strength of stud

k_t = reduction factor for modes of failure other than SS

For concrete pull-out failure of studs in slabs with one stud per trough, in a central or favorable position, the strength is

$$P_r = k_{cp} P_{rs} \tag{4.15}$$

$$k_{cp} = \frac{\left[\eta_{cp} + \lambda_{cp}\left(1+\lambda_{cp}{}^{2} - \eta_{cp}{}^{2}\right)^{0.5}\right]}{\left(1+\lambda_{cp}{}^{2}\right)} \leq 1.0 \tag{4.16}$$

$$\eta_{cp} = \frac{0.56 v_{tu} h^{2}\left(b_{o} - \frac{h}{4}\right)}{h_{p} N_{r} P_{rs}} \leq 1.0 \tag{4.17}$$

$$\lambda_{cp} = \frac{e_{r} T_{y}}{h_{p} P_{rs}} \tag{4.18}$$

$$T_{y} \cong 0.8 A_{s} f_{u} \tag{4.19}$$

$$v_{tu} = 0.8 f_{cu}{}^{0.5} \leq 5 \tag{4.20}$$

where k_{cp} = reduction factor for CPT failure mode

η_{cp} = non-dimensional group for CPT failure mode

λ_{cp} = non-dimensional group for CPT failure mode

v_{tu} = shear strength of concrete

h = height of stud

b_o = average width of deck trough

h_p = height of steel deck

N_r = number of studs per rib

e_r = distance from center of stud to nearer wall of rib for favorable position studs

T_y = yield tensile strength of stud

f_{cu} = cube strength of concrete

If $h>2h_p$, use $h=2h_p$. If $\eta_{cp}\geq 1.0$, it should be taken as 1.0. This indicates failure type SS rather than CPT.

For rib punching failure of studs placed in the unfavorable position, the strength is

$$P_r = k_{rp} P_{rs} \tag{4.21}$$

$$k_{rp} = \frac{\left[\eta_{rp} + \lambda_{rp}\left(1 + \lambda_{rp}^{\ 2} - \eta_{rp}^{\ 2}\right)^{0.5}\right]}{\left(1 + \lambda_{rp}^{\ 2}\right)} \leq 1.0 \tag{4.22}$$

$$\eta_{rp} = \frac{1.8\left(e_f + h - h_p\right)t f_{yp}}{P_{rs}} \tag{4.23}$$

$$\lambda_{rp} = \frac{e_f T_y}{2 h_p P_{rs}} \tag{4.24}$$

$$T_y \cong 0.8 A_s f_u \tag{4.25}$$

where k_{rp} = reduction factor for RP failure mode

η_{rp} = non-dimensional group for RP failure mode

λ_{rp} = non-dimensional group for RP failure mode

e_f = distance from center of stud to nearer rib wall for unfavorable position studs

t = thickness of steel deck

f_{yp} = yield strength of steel deck

For combined rib punching and concrete pull-out failure of studs in slabs with two studs placed in series or diagonally in a trough, the stud placed on the unfavorable side is assumed to fail by rib punching. The stud placed on the favorable side is assumed to fail by concrete pull-out. The resistances of the two studs are added to get the combined resistance. For the rib punching failure mode, the equations are as follows:

$$P_r = k_u P_{rs} \tag{4.26}$$

$$k_u = \frac{\left[\eta_u + \lambda_u\left(1 + \lambda_u^{\,2} - \eta_u^{\,2}\right)^{0.5}\right]}{\left(1 + \lambda_u^{\,2}\right)} \leq 1.0 \tag{4.27}$$

$$\eta_u = \frac{\left(e + h - h_p\right) t f_{yp}}{P_{rs}} \tag{4.28}$$

$$\lambda_u = \frac{eT_y}{2h_p P_{rs}} \tag{4.29}$$

where k_u = reduction factor for rib punching in RPCP failure mode

η_u = non-dimensional group for rib punching in RPCP failure mode

λ_u = non-dimensional group for rib punching in RPCP failure mode

e = distance from center of stud to nearer wall of rib

For the concrete pull-out failure mode, the equations are as follows:

$$P_r = k_f P_{rs} \tag{4.30}$$

$$k_f = \frac{\left[\eta_f + \lambda_f\left(1 + \lambda_f^{\,2} - \eta_f^{\,2}\right)^{0.5}\right]}{\left(1 + \lambda_f^{\,2}\right)} \leq 1.0 \tag{4.31}$$

$$\eta_f = \frac{0.56 v_{tu} h^2 \left(e + s_t - \dfrac{h}{4}\right)}{h_p P_{rs}} \quad if\ 0.75h \leq \left(e + s_t\right) \tag{4.32}$$

$$\eta_f = \frac{v_{tu}\left(e + s_t\right)^2 \left(0.75h - \dfrac{\left(e + s_t\right)}{3}\right)}{h_p P_{rs}} \quad if\ 0.75h > \left(e + s_t\right) \tag{4.33}$$

$$\lambda_f = \frac{eT_y}{h_p P_{rs}} \tag{4.34}$$

$$T_y \cong 0.8 A_s f_u \tag{4.35}$$

$$\nu_{tu} = 0.8 f_{cu}^{\ 0.5} \leq 5 \tag{4.36}$$

where k_f = reduction factor for concrete pull-out in RPCP failure mode

η_f = non-dimensional group for concrete pull-out in RPCP failure mode

λ_f = non-dimensional group for concrete pull-out in RPCP failure mode

s_t = spacing of studs

When $h>2h_p$, assume $h=2h_p$. If $\eta_f \geq 1.0$, k_f is taken as 1.0 and the failure mode is RPSS.

The Johnson and Yuan predicted strengths are compared to the experimental strengths in Table 4.5 and Fig. 4.5. The equations appear to adequately predict the strengths of both strong and weak position studs. The average ratio of the experimental strength to the predicted strength is 1.01, the minimum is 0.57, and the maximum is 1.60; the standard deviation is 0.23, and the coefficient of variation is 23%. On average, the Johnson and Yuan equations provide good predictions of stud strengths and failure modes. However, the minimum and maximum ratios are not as close to 1.0 as desired. Although based upon a sound understanding of the behavior of studs, the method is tedious and somewhat difficult to use, and the user must first predict the failure mode of the studs so that the appropriate model can be used.

Table 4.5 Johnson and Yuan Ultimate Strength Comparison

Series	Test	Stud Position	Q_e (k)	Actual Failure Mode	$Q_{J\&Y}$ (k)	Predicted Failure Mode	$Q_e/Q_{J\&Y}$
D1	D1	S	9.77	SS/WP	9.37	SS	1.042
D1	D2	S	7.29	SS	9.37	SS	0.778
D1	D3	S	9.23	SS	9.37	SS	0.985
D2	D4	2S	8.95	SS/WP	9.29	CP	0.963
D2	D5	2S	8.76	SS/WP	9.29	CP	0.943
D2	D6	2S	7.16	SS/WP/WF	9.29	CP	0.771
D3	D7	W	6.16	SS/RP/WP	9.35	RP	0.659
D3	D8	W	8.01	SS/RP/SR	9.35	RP	0.856
D3	D9	W	7.44	SS/RP/SR	9.35	RP	0.795
D4	D10	S	12.53	SS/WP	10.58	SS	1.184
D4	D11	S	13.54	SS	10.58	SS	1.280
D4	D12	S	15.55	SS	10.58	SS	1.469
D5	D13	W	15.08	SS/RP	9.92	RP	1.520
D5	D14	W	11.65	SS/RP/SR	9.92	RP	1.174
D5	D15	W	10.90	SS/RP/SR	9.92	RP	1.099
D6	D16	2S	11.87	SS	10.22	CP	1.162
D6	D17	2S	15.42	SS/TR	10.22	CP	1.509
D7	D19	S	8.86	SS	11.63	SS	0.762
D7	D20	S	9.14	SS/WF	11.63	SS	0.786
D7	D21	S	6.63	SS	11.63	SS	0.570
D8	D22	2S	9.23	SS/WP	10.99	CP	0.840
D8	D23	2S	10.30	SS/WF	10.99	CP	0.937
D8	D24	2S	11.46	WF/WP	10.99	CP	1.043
D9	D25	W	9.17	SS/RP/SR	10.74	RP	0.854
D9	D26	W	7.32	SS/RP/SR	10.74	RP	0.681
D9	D27	W	6.88	WF/SR	10.74	RP	0.640
D10	D28	S	20.01	SS	21.97	CP	0.911
D10	D29	S	18.72	SS/WF	21.97	CP	0.852
D10	D30	S	21.80	SS	21.97	CP	0.992
D11	D32	2S	17.49	SS	18.60	CP	0.940
D11	D33	2S	20.89	SS	18.60	CP	1.123

Table 4.5 Johnson and Yuan Ultimate Strength Comparison (cont'd.)

Series	Test	Stud Position	Q_e (k)	Actual Failure Mode	$Q_{J\&Y}$ (k)	Predicted Failure Mode	$Q_e/Q_{J\&Y}$
D12	D34	W	15.05	SS/RP	15.56	RP	0.968
D12	D35	W	12.03	SS/RP/WP	15.56	RP	0.773
D12	D36	W	15.67	SS/RP	15.56	RP	1.007
D13	D37	S	16.18	SS	15.41	SS	1.050
D13	D38	S	17.07	SS	15.41	SS	1.107
D13	D39	S	14.53	SS/WP	15.41	SS	0.943
D14	D40	2S	14.70	SS	13.90	CP	1.058
D14	D41	2S	16.95	SS	13.90	CP	1.219
D14	D42	2S	17.43	SS	13.90	CP	1.254
D15	D43	W	9.12	SS/WP	12.80	RP	0.713
D15	D44	W	11.14	SS/SR/WP	12.80	RP	0.871
D15	D45	W	11.07	SS/SR	12.80	RP	0.865
D16	D46	S	5.89	SS/WF	4.91	SS	1.201
D16	D47	S	5.18	SS	4.91	SS	1.056
D16	D48	S	5.36	SS/WF	4.91	SS	1.093
D18	D52	W	4.05	SS/RP/WF	?	RP	?
D18	D53	W	4.54	SS/WF	?	RP	?
D18	D54	W	4.81	SS/WF	?	RP	?
D20	D58	S	6.03	WF	5.94	SS	1.015
D20	D59	S	8.10	WF	5.94	SS	1.363
D20	D60	S	9.50	WF	5.94	SS	1.599
D22	D64	W	5.40	SS/WF	?	RP	?
D22	D65	W	6.68	RP/WF	?	RP	?
D22	D66	W	6.46	RP/WF	?	RP	?
D26	D77	S	22.54	SS	21.80	CP	1.034
D27	D79	S	23.12	CP	21.80	CP	1.060
D27	D80	S	19.35	CP	21.80	CP	0.887
D27	D81	S	24.39	CP	21.80	CP	1.119
D28	D82	W	13.90	RP/SS	15.37	RP	0.905
D28	D83	W	18.85	RP/SS	15.37	RP	1.227
D28	D84	W	10.10	RP/SS	15.37	RP	0.657
D29	D86	W	20.71	RP/SS	15.37	RP	1.348
D29	D87	W	19.91	RP/SS	15.37	RP	1.296

? Formulas result in imaginary number

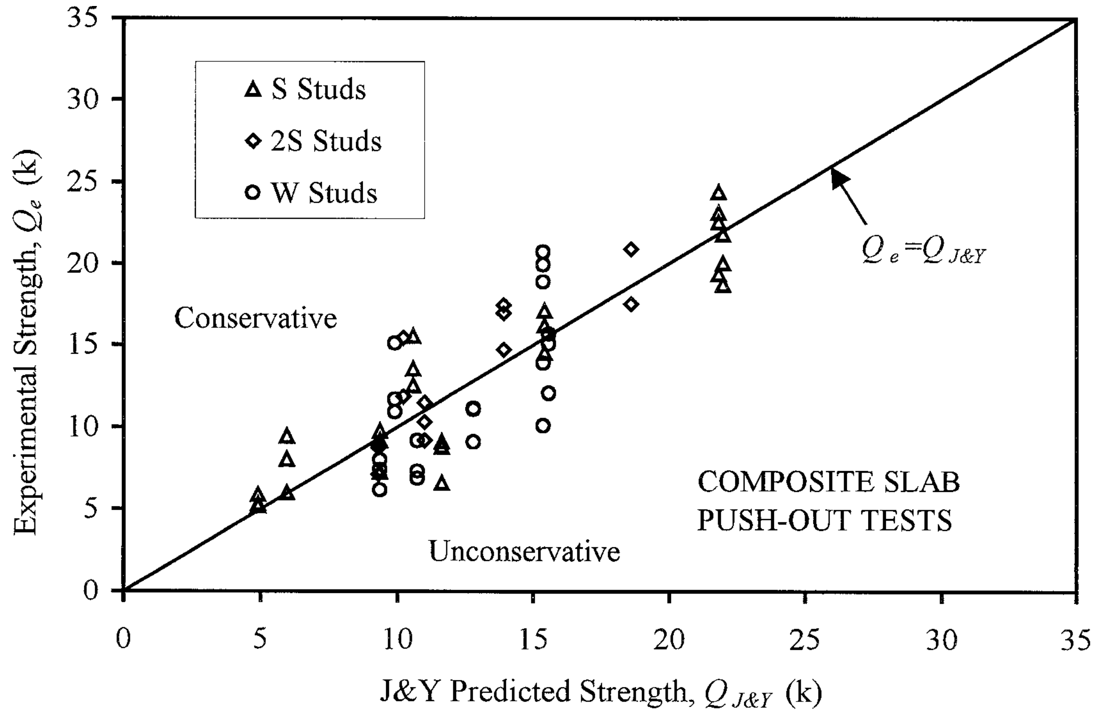

Fig. 4.5 Experimental Strengths vs. Johnson and Yuan Predicted Strengths for Composite Slab Push-Out Tests