TREATMENT OF SHEAR OF REINFORCED CONCRETE SLENDER BEAMS WITH WEB REINFORCEMENT IN WELL-KNOWN STRUCTURAL INTERNATIONAL CODES

Thaar Saud Al-Gasham
College of Engineering
University of Wassit

Abstract

Structural standards and codes of practice are reviewed continuously and improvements are implemented as research findings reveal more accurate method of design. Design for shear unlike design for bending and axial forces, which have been perfected over the years, because of its behavior is difficult to predicate accurately. In spite of many decades of experimental research and the use of highly sophisticated analytical tools, it is not yet fully understood.

This paper reviews the provisions of the current standards in relation to shear of reinforced concrete beams, highlights their weaknesses and strengths and compares their predictions with 122 test beams failing in shear (from existing tests). It was found that five codes [ACI, BS, NZ, EUR, NOR] lead to some, unsafe strength predictions. In other cases these methods could lead to excessively conservative predictions. To examine the accuracy of the existing methods, statistical analysis [Mean ($\bar{X}$), Standard Deviation (*SD*), and Coefficient of Variation (*COV*)] of shear failure strength to predicted design value are used.

Keywords: Shear, reinforced concrete, slender beams, stirrups, international codes.

معادلة القص للعتبات الخرسانية المسلحة النحيفة في المدونات العالمية الإنشائية

ثائر سعود الغشام
كلية الهندسة
جامعة واسط

الخلاصة

تراجع المدونات الإنشائية العملية بصورة مستمرة وتشهد إضافة تحسينات كلما كان هناك اكتشاف لطرق تصميم أكثر دقة من قبل الباحثين. إن تصميم القص مختلف عن تصميم الانحناء والقوى المحورية وذلك لان هناك صعوبة في تحديد سلوكه بدقة رغم إجراء التجارب العديدة واستخدام طرق تحليل متطورة إلا انه لحد الآن يعتبر غير مفهوم .

ان هذا البحث يراجع تلك المدونات في ما يتعلق بموضوع القص في العتبات الخرسانية المسلحة ويسلط الضوء على مناطق ضعفها و قوتها ,ومقارنة نتائجها مع ١٢٢ عتبة(مسلحة للقص بالاطواق) وهذه العتبات مأخوذة من بحوث سابقة . وقد تبين من خلال هذا البحث ان المدونات الخمسة وهي الامريكية و البريطانية و الاوربية و نيوزلاندية و النرويجية تؤدي في بعض الحالات الى تحديد مقاومة القص بصورة غير امينه وفي حالات اخرى متحفظة جدا.

لفحص دقة الطرق المتوفرة والمقارنة في مابينها استخدمت تحليلات احصائية { المعدل) $\bar{X}$ (، الانحراف المعياري (SD) و معامل التغاير(COV) } للمقاومة الفعلية والتصميمة للقص .

Introduction

The shear strength of reinforced concrete beams with stirrups has been a highly controversial matter since Morsh (10) proposed the first truss models. Since then, different analytical models have been discussed, such as truss models with concrete contribution, shear/compression theories, truss models with variable angle of inclination, and compression field theories. However, some of these models were too complex to be implemented in a code of practice and they had to be simplified. As Regan (13) has pointed out, for simpler models the problem is mostly that of the need to neglect some factors, considered secondary. However, what is secondary in one case may be primary in another. Dealing with shear in today`s codes of practice is very primitive and need to more elaborate technique. Predications of current standards for ultimate shear capacity of R.C beams are found to be either too conservative or slightly risky for certain compressive strength of concrete, ratio of tension reinforcement, ratio of web reinforcement, and ratio of shear span to effective depth.

In order to have a closer view to the above mentioned. This paper firstly presents a brief review of the provisions of well-known international standards in relation to the design of reinforced concrete beams against shear. The chosen standards are from United States (ACI 318-2005) (1), Britain (BS 8110) (5), Europe (European Standards, Euro code 2) (8), New Zealand (NZS 3101) (14) and Norwegian (NS 3473 E) (11). Secondly, the accuracy of the standards in predicting the ultimate shear of R.C beams is examined by comparing their predictions against experimental studies available in the literature.

Treatment Of Shear In The Standards

Provisions for shear design of reinforced concrete members appear in majority of international standards of concrete design. In all Standards, the shear strength is based on an average shear stress on the full effective cross section ($b_w.d$). In member without shear reinforcement, shear is assumed to be carried by the concrete web (Vc). In member with shear reinforcement, a portion of the shear strength is assumed to be provided by the concrete (Vc) and the remainder by the shear reinforcement (Vs).

The shear strength provided by concrete is assumed to be same for beams with and without shear reinforcement and is taken as the shear causing significantly inclined cracking.

These assumptions are similar for most Standards but there are differences in the manners of calculating (Vs and Vc) that produce different results. Provisions of some of more well-known standards are reviewed here in this section.

1. ACI Standard

A: shear strength provided by concrete

$$Vc = \left(0.16\sqrt{f_c^{'}}+17\,\rho_w\,\frac{V\,d}{M}\right)b_w d \le 0.29\sqrt{f_c^{'}}\,b_w d \qquad (1)$$

But $\frac{V\,d}{M} \le 1$, $f_c^{'} \le 70MPa$

It can be seen that the term $\left(\frac{Vd}{M}\right)$ may be substituted by the term $\left(\frac{d}{a}\right)$ due to alternative formula which is $(M = aV)$.

B: shear strength provided by shear reinforcement

$$Vs = \frac{A_v . f_{yv} . d}{S} = \rho_v . f_{yv} . b_w . d \tag{2}$$

However, V_s should not be taken greater than $0.66\sqrt{f'_c}\, b_w .d$

where f'_c is the design compressive cylinder strength of concrete at 28 days (MPa), b_w is web width(mm), d is the effective depth of beams (mm), ρ_w is the ratio of tension reinforcement, A_v is the area of shear reinforcement within a distance S (mm^2), f_{yv} is the yield strength of shear reinforcement(MPa) , S is the spacing of shear reinforcement (mm) , ρ_v is the ratio of vertical shear reinforcement , a is the shear span(distance between concentrated load and face of support ,mm), V is applied shear force (N) and M is applied bending moment that occurs simultaneously with V at section considered(N.mm).

2. British Standard

A: shear strength provided by concrete

$$Vc = 0.79\left(100\rho_W\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f'_c}{20}\right)^{1/3} b_w .d \tag{3}$$

$$3\% \geq \rho_w \geq 0.15\% \quad , \quad \frac{400}{d} \geq 1 \quad , \quad 32MPa \geq f'_c \geq 20MPa$$

Where Eq. (3) substitutes $1.25f'_c$ for f_{cu}-the latter being concrete cube strength.

B: shear strength provided by shear reinforcement

$$V_s = \rho_v . f_{yv} . b_w . d \tag{4}$$

3. European Standard

Europe code neglects the concrete contribution to shear strength, therefore, the nominal shear strength for R.C beams with web reinforcement in accordance with Euro code 2 is:

$$Vn = Vs = 0.9\,\rho_v\, f_{yv}\, b_w\, d \cot\theta \leq 0.9 b_w\, d\, v\, f'_c \frac{\cot\theta}{1+\cot\theta^2} \tag{5}$$

where θ is the angle of the inclined struts and v is a coefficient that takes into account the increase of fragility and the reduction of shear transfer by aggregate interlock with the increase of the compressive concrete strength. It may be taken to be 0.6 for $f'_c \leq 60MPa$, and $0.9 - f'_c/200 \geq 0.5$ for high strength concrete beams (HSC).

The recommended limiting value for $\cot\theta$ are given by $1 \leq \cot\theta \leq 2.5$

4. New Zealand Standard

A: shear strength provided by concrete

$$Vc = \left(0.07 + 10\rho_w\right)\sqrt{f_c'}\, b_w\, d \leq 0.2\sqrt{f_c'}\, b_w\, d \tag{6}$$

B: shear strength provided by shear reinforcement

$$Vs = \rho_v \, f_{yv} \, b_w \, d \tag{7}$$

5. Norwegian Standard

A: shear strength provided by concrete

$$V_c = 0.33(f_{tn} + 100\rho_w)(1.5 - d).b_w.d \leq 0.66 f_{tn}(1.5 - d).b_w.d \tag{8}$$

$$1.4 \geq (1.5 - d) \geq 1$$

B: shear strength provided by shear reinforcement

$$Vs = \rho_v \, f_{yv} \, b_w \, d \tag{9}$$

Where f_{tn} is the tensile strength and d in meter . Norwegian – code reported **Table 1** for f_{tn} and f_c`.

Comparison Of The Standards Predictions With Test Results

In order to investigate the accuracy of codes` provisions for shear, they are compared with 122 experimental results in this section. Appendix contains the chosen test beams extracted from different sources [Adebar and Collins(2), Ahmad, Khalloo, and Poveda(3), Angelakos, Bentzand Collins(4), Cladera, and Mari(6,7), Kong, and Rangan(9), Ozcebe,Ersoy, and Tankut(12), Tan, Kang, Teng, and Weng(15), Yoon, Cook, and Mitchell(16), and Zararis(17)]. All these beams were reported to have failed in shear. These beams were simply supported and loaded with one or two point loads. The longitudinal reinforcement was constant along the beam. The shear span to depth ratio (*a/d*) for all these beam specimens was greater than 2.49, this means that all beams were slender beams (a/d >2). Beams are identified using the notations used in the original papers. The ranges of the different variables in these beams are summaries in **Table 2**.

The results of the shear strength of the beams predicted by different codes and the corresponding strength obtained from the test are presented in Appendix. Ratio of RSSV (***Relative Shear Strength Value of the ratio V_{fail}/V_{pred}***) are calculated from these and recorded in Appendix, then the values of $\bar{X}$,*SD* and *COV* are also calculated for each codes and listed in Table(3).

Table 3 shows that European code (EUR) has higher values of $\bar{X}$,SD and COV than other codes in which this values are 1.64 , 0.53 , and 32.19% respectively. This means that EUR-code has lower representation of shear strength than other codes.

Norwegian code (NOR) has lower values of statistical results than others. However, it has higher number of unsafe values of RSSV (**V_{fail}/V_{pred}**) less than one, which are 41. These numbers of failing beams are due to the lower values of $\bar{X}$, which is 1.06. The values of SD and COV are 0.22 and 21.02% respectively.

New Zealand code (NZ) has statistical results ($\bar{X}$, SD and COV) which are equal to 1.22, 0.29 and 23.85% respectively.

American code (ACI) and British code (BS) have nearest values of $\bar{X}$,SD and COV, but BS-code has lower values of $\bar{X}$, and unsafe values of RSSV (less than one), which are 1.26 , and 13 respectively than ACI-code.

It is clear from **Table 2** that, British code (BS) and ACI-code are more safety than other codes used in this paper because they have lower values of failing beams (RSSV <1.0). The values of Mean ($\bar{X}$) for ACI and BS codes are 1.29 and 1.26, respectively. This means that they have acceptable conservatism in comparison with other three codes. Therefore, using ACI and BS codes in shear design is recommended.

Factors Affecting Shear Strength

The same previous 122 beam test results are used to investigate the reasons behind the weak representation of code design equations for the shear strength. to do so, a series of graphs [**Fig. 1-4**] were plotted using the main factors affecting shear strength (f_c',ρ_w,,a/d, $\rho_v f_{yv}$) as X-axis and the value of RSSV [V_{fail}/V_{pred}] as Y-axis the predications of code equations.

The horizontal line at $V_{fail}/V_{pred}=1.0$ represents a reference point where the actual shear strength V_{fail} equals the shear strength predicted using different design equations V_{pred}. Data points that fall below this line represent beams that had a measured shear strength that was less than that predicted by design equation. The line of average and conservative of RSSV values (dispersion line) for each code observed in these **Figures**.

The maximum average of RSSV is an indictor of dispersion. The positive slope (average RSSV increase with increasing the factor that plotted RSSV with it) means that rise of safety (underestimate) values will be obtained with increasing this factor. The negative slope (average RSSV decrease with increasing the factor that plotted RSSV with it) means that drop of safety values will be obtained with increasing this factor.

A nearly horizontal line with less rise or drop in the slope indicates better representation.

1 Effect of Compressive Strength of Concrete (f_c')

Fig. 1, shows that existing codes of shear design lead to large spread of the RSSV values for tested members. The unsafe values of RSSV ($V_{fail}/V_{pred}<1$) are clear in the **Figures**.

The line of average and conservative values for 122 test results with f_c' values are plotted and the statistical equations of effect f_c' on RSSV for all five codes are shown below.

$$RSSV_{ACI} = 1.215 + 0.00125 f_c'$$

$$RSSV_{BS} = 0.923 + 0.00577 f_c'$$

$$RSSV_{EUR} = 1.837 - 0.00339 f_c'$$

$$RSSV_{NZ} = 1.25 - 0.0005 f_c'$$

$$RSSV_{NOR} = 0.97 + 0.0015 f_c'$$

Positive slopes with increasing f_c' indicate a rise in safety (conservative) with f_c'. Negative slopes indicate lower safety with rising f_c'.

Maximum average value is 1.837 for EUR- code, this mean that this code is much more conservative than others. The minimum average value is 0.923 for BS- code, that indicating the unsafe values of RSSV ($V_{fail}<V_{pred}$) in normal strength concrete (NSC).

Figure 1, shows that ACI-code has high dispersion and this dispersion increases from 1.241-1.371 for f_c' values from 21-125.2 MPa at an average rise of 0.13% for each 1 MPa. This means that this dispersion will increase with increasing f_c'.

The BS-code has unsafe values especially for normal strength concrete. It gives an average value of 1.044 at f_c' of 21 MPa and this value increases at average rise rate equals to 0.58% for each 1 MPa to give an average value of 1.645 for f_c' equals to 125.2 MPa. This means that BS-code gives safe values and much dispersion with increasing f_c'.

EUR and NZ codes have negative slope with increasing f_c' (a drop in conservatism with increases f_c'). These codes have RSSV drop from 1.766 to 1.413 and 1.24 to 1.187 at an average drop of 0.34 % and 0.05% respectively, **Figure 1**.

The ratio of RSSV for NOR-code increases from 1.002 to 1.158 with f_c' of 21 MPa and 125.2 MPa respectively at an average rise of 0.15% [**Figure 1**].

2 Effect of Ratio of Tension Reinforcement (ρw)

The nominal strength results of the 122 test beams are plotted with rising ρ_w. The effect of ρ_w on the different design codes will be shown in **Figure 2**. The statistical equations of the effect of ρ_w on RSSV for existing codes are shown below:-

$$RSSV_{ACI} = 0.919 + 0.131\rho_w$$

$$RSSV_{BS} = 0.936 + 0.115\rho_w$$

$$RSSV_{EUR} = 1.568 + 0.025\rho_w$$

$$RSSV_{NZ} = 0.95 + 0.095\rho_w$$

$$RSSV_{NOR} = 0.813 + 0.087\rho_w$$

From above equations, maximum average rise is 13.1% for ACI methods, where its RSSV rises from 1.019 to 1.679 for ρ_w of 0.76% to 5.8% respectively. Minimum average rise for code equations is 2.5% for EUR method, but this method has maximum average value (1.568) from others. Its RSSV rises from 1.587 to 1.713 for ρ_w ranging from 0.76% to 5.8% respectively.

BS and NZ methods have nearest values of average of RSSV equal to 0.936 and 0.95 respectively. BS code has RSSV rises from 1.023 to 1.603 for ρ_w of 0.76% and 5.8% respectively at an average rise of 11.5% while NZ code has RSSV rises from 1.022 to 1.501 for ρ_w of 0.76% and 5.8% respectively at an average rise of 9.5%.

NOR method has minimum average value of RSSV equals to 0.813. This ratio rises from 0.879 to 1.318 with ρ_w ranging from 0.76% to 5.8% respectively at an average rise rate equals to 8.7%.

3 Effect of a/d

RSSV results of the 122 test beams are plotted with rising *a/d.* The effect of *a/d* on the different methods will be discussed in **Figure 3**. The statistical equations of the effect *a/d* on RSSV for all five methods are shown below:-

$$RSSV_{ACI} = 1.454 - 0.052\ a/d$$

$$RSSV_{BS} = 1.717 - 0.145\ a/d$$

$$RSSV_{EUR} = 1.662 - 0.007\ a/d$$

$$RSSV_{NZ} = 1.442 - 0.071\ a/d$$

$$RSSV_{NOR} = 1.254 - 0.062\ a/d$$

Figure 3, shows that RSSV for all methods drop with increasing *a/d* . Maximum average drop is 14.5% for BS method and minimum average drop is 0.7% for EUR method.

ACI and NZ methods have average drops 5.2% and 7.1% for each 1 of *a/d* respectively. With respect to NOR method, the ratio of RSSV drops from 1.1 to 0.944 with *a/d* of 2.49 and 5 respectively at an average drop of 6.2%.

4 Effect of $\rho_v f_{yv}$

RSSV results of all the 122 test beams are plotted with rising $\rho_v f_{yv}$. the effect of $\rho_v f_{yv}$ on the different methods will be discussed in **Figure 4**. The statistical equations of the effect of $\rho_v f_{yv}$ on RSSV for all five methods are shown below:-

$$RSSV_{ACI} = 1.514 - 0.229\ \rho_v f_{yv}$$

$$RSSV_{BS} = 1.443 - 0.185\ \rho_v f_{yv}$$

$$RSSV_{EUR} = 2.043 - 0.412\ \rho_v f_{yv}$$
$$RSSV_{NZ} = 1.433 - 0.218\ \rho_v f_{yv}$$
$$RSSV_{NOR} = 1.214 - 0.159\ \rho_v f_{yv}$$

From above equations, all methods decrease with increasing $\rho_v f_{yv}$.

Maximum average value is 2.043 for EUR code. This indicator that this method gives much more conservative than others. At the same time, it has maximum average slope is 41.2%, where its RSSV drops from 1.915 to 0.387 for $\rho_v f_{yv}$ of 0.3096 MPa to 4.0183 MPa respectively .

The NOR method has minimum average value, which is 1.214. Its RSSV values drop from 1.165 to 0.575 for $\rho_v f_{yv}$ of 0.3096 MPa to 4.0183 MPa respectively, at an average drop 15.9% for each 1 MPa of $\rho_v f_{yv}$.

ACI code has average value of RSSV equals to 1.514 and this ratio drops from 1.443 to 0.594 for $\rho_v f_{yv}$ ranging 0.3096-4.018 MPa respectively at an average drop 22.9%

BS and NZ codes have close average values of RSSV equal to 1.443 and 1.433 respectively. However, BS method has lesser slope value, which is 18.5% for each 1 MPa of $\rho_v f_{yv}$. This method drops from 1.386 to 0.7 for $\rho_v f_{yv}$ of 0.3096 to 4.018 MPa.

Conclusions

The main conclusions to be drawn from this paper are:

1. None of the codes were successful in predicting the ultimate shear accurately for all beams. For some beams, codes` predictions were too conservative and for some too risky (unsafe design) especially for beams with high shear reinforcement (stirrups) , high shear span to depth ratio (*a/d*), low longitudinal steel ratio (ρ_w),and low strength of concrete.
2. Design by Norwegian code leads to the largest percentage of unsafe design that equals to 33.6% , while design by British and European codes lead to the least percentage of unsafe design that equals to 10.66 for each code.
3. For all 122-test result of beams taken from the literature, accurate, safe and simple representations are proposed for predicting the nominal shear strength in normal rectangular beams.
4. BS and ACI codes are more safety than other codes used in this paper, at the same time, they have acceptable statistical values ($\bar{X}$, SD and COV) in comparison with others. These values are 1.22, 0.29, and 23.85% respectively for BS-code and 1.29, 0.31, and 24.35% respectively, for ACI-code.

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Table (1) Concrete Strength in MPa

f_c`	12	20	28	36	44	54	64	74	84	94
f_{tn}	1.0	1.4	1.7	2.00	2.25	2.5	2.6	2.7	2.7	2.7

Table (2) Range of Parameter in the Database

Parameter	d(mm)	ρ_w%	$P_v f_y$ (MPa)	f_c` (MPa)	a/d	V_{fail} (KN)
Minimum	95	0.76	0.3096	21	2.49	15.6
Maximum	1200	5.8	4.0183	125.2	5	1172.2

Table (3) Comparison between V_{fail} and V_{pred} for 122 Beams

Code	$\bar{X}$	SD	COV%	NO.<1	Max. value	Min. value
American code (ACI)	1.29	0.31	24.35	17	2.58	0.20
British code (BS)	1.26	0.31	24.94	13	2.64	0.20
European code (EUR)	1.64	0.53	32.19	13	3.69	0.70
New Zealand code (NZ)	1.22	0.29	23.85	18	2.43	0.21
Norwegian code (NOR)	1.06	0.22	21.02	41	1.99	0.20

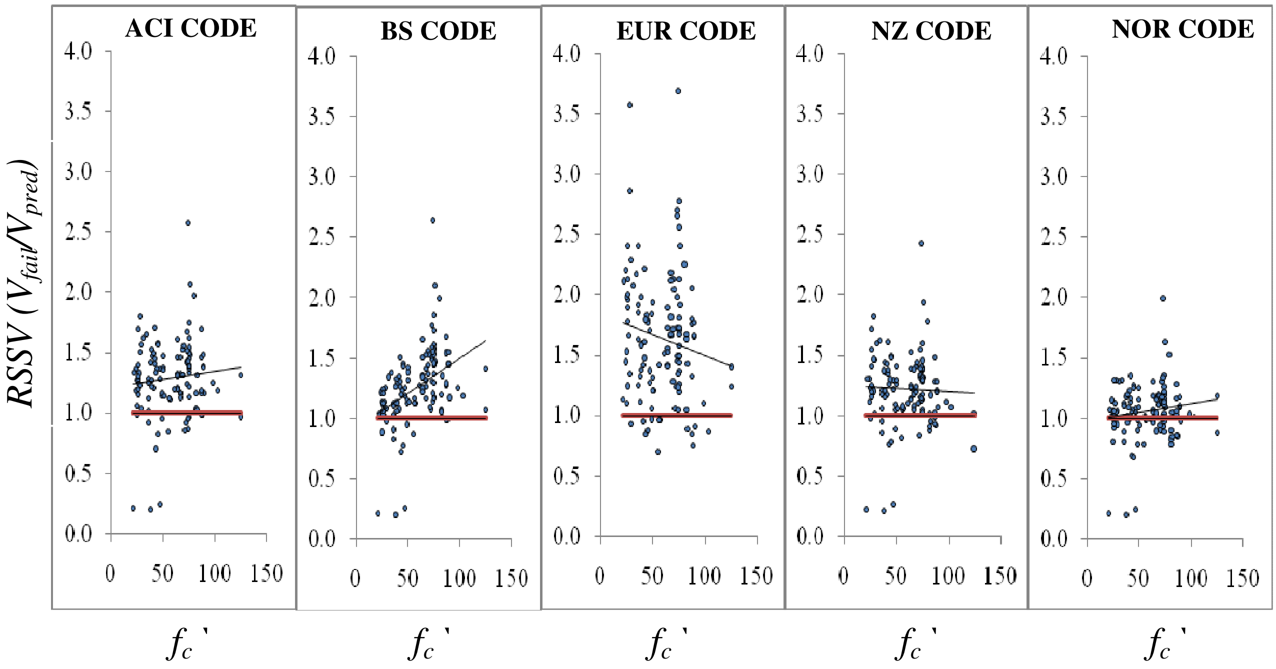
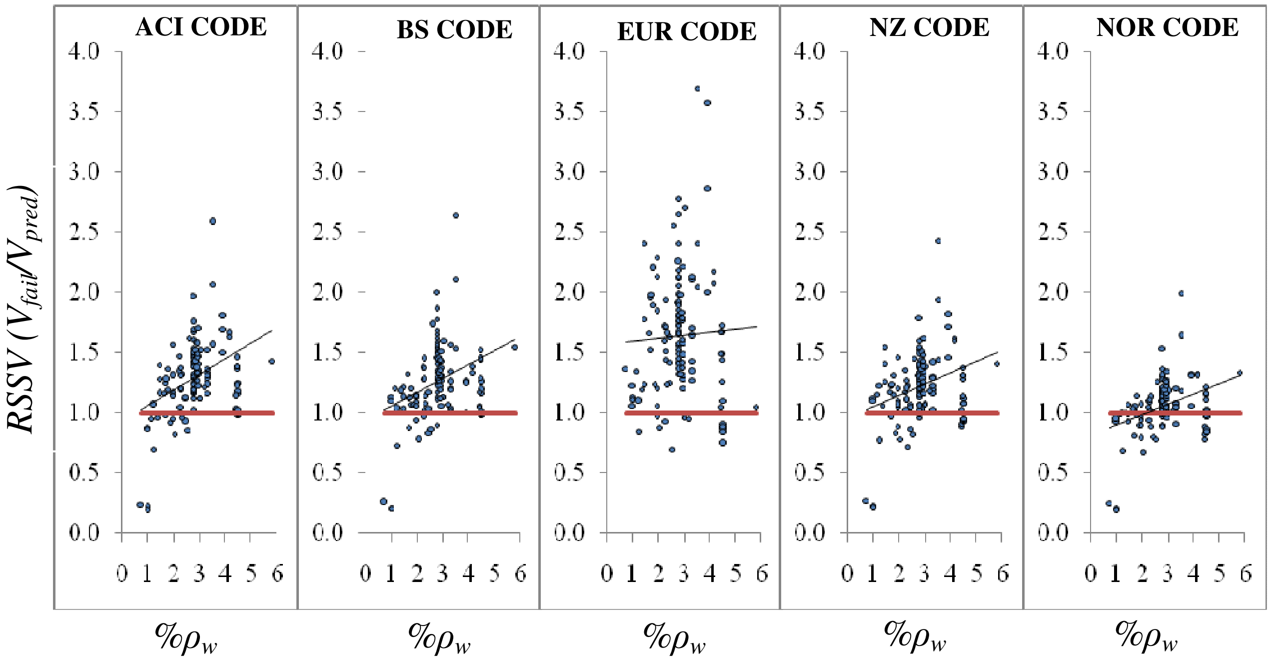
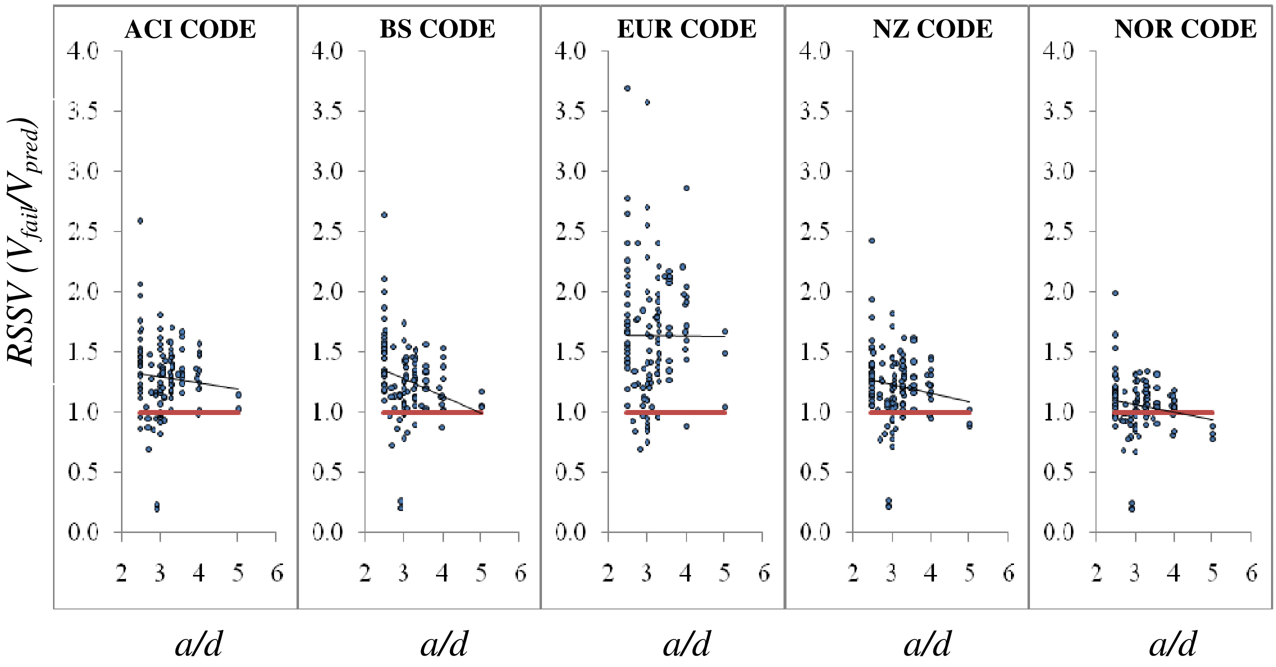


Figure (1) f_c` versus the relative shear strength predictions



Figure(2) % ρ_w versus the relative shear strength predictions



Figure(3) a/d versus the relative shear strength predictions

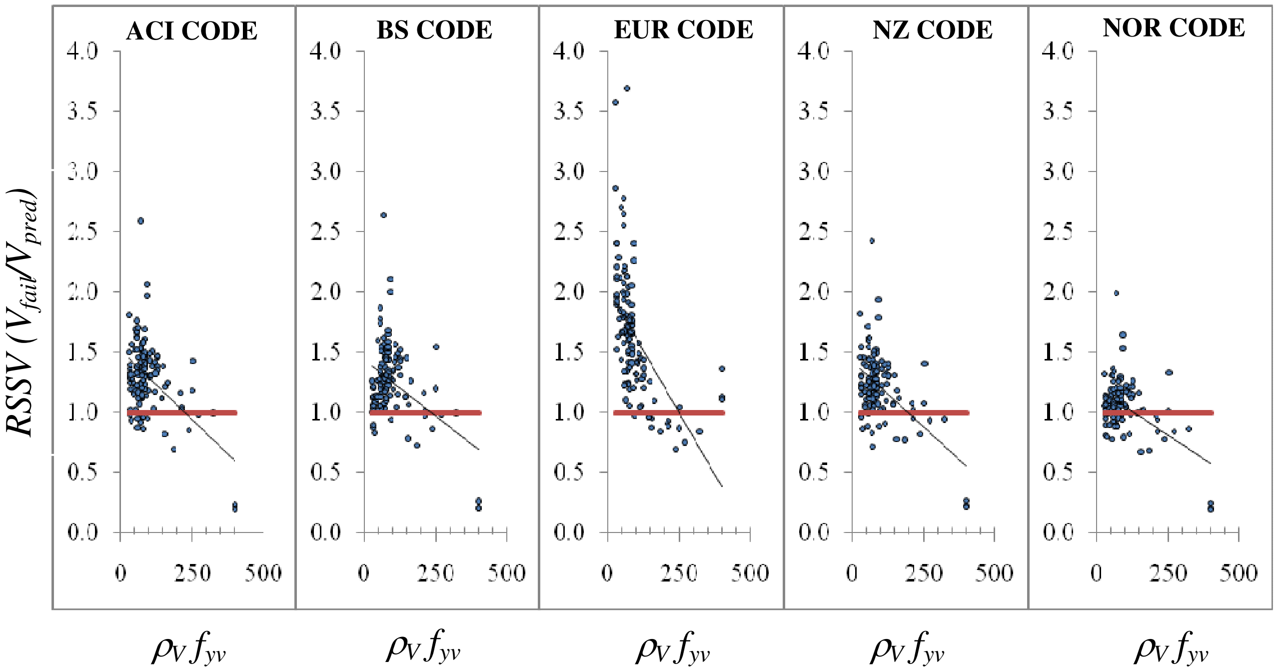


Figure (4) $\rho_v f_{yv}$ versus the relative shear strength predictions

Appendix Details of Experimental Beams

Ref.	Beam name	b, mm	d, mm	f_c', MPa	ρ_w ,%	ρ_v %	f_{yv} MPa	a/d	V_{fail} KN	V_{ACI} KN	V_{fail}/V_{ACI}	V_{ES} KN	V_{fail}/V_{ES}	V_{EUR} KN	V_{fail}/V_{EUR}	V_{NZ} KN	V_{fail}/V_{NZ}	V_{NOR} KN	V_{fail}/V_{NOR}
2	ST4	290	278	49	1.95	0.11	430	2.88	158	138	1.15	140	1.13	86	1.84	151	1.05	176	0.90
2	ST5	290	278	49	1.95	0.18	536	2.88	169	177	0.95	180	0.94	175	0.97	191	0.89	215	0.78
2	ST6	290	278	49	1.95	0.28	430	2.88	230	197	1.17	199	1.16	218	1.06	210	1.10	235	0.98
2	ST19	290	278	51	1.95	0.214	430	2.88	201	176	1.14	176	1.14	167	1.20	189	1.06	213	0.94
3	LNW-3	127	216	45	2.07	0.378	421	3	63	76	0.83	81	0.77	72	0.88	80	0.78	93	0.68
3	LHW-3a	127	198	88	4.54	0.65	421	3	107	109	0.98	109	0.98	144	0.74	116	0.92	127	0.84
3	LHW-3b	127	198	87	4.54	0.78	421	3	121	123	0.99	123	0.99	143	0.85	129	0.93	141	0.86
3	LHW-4	127	198	83	4.54	0.51	421	4	95	93	1.03	94	1.01	107	0.89	100	0.95	112	0.85
4	SE100B-M	295	920	75	1.36	0.16	500	2.5	583	606	0.96	495	1.18	489	1.19	553	1.05	580	1.01
4	SE50A-M	169	459	74	1.03	0.13	500	2.72	139	159	0.87	123	1.13	113	1.23	124	1.12	149	0.93
4	SE50B-M	169	459	74	1.16	0.13	500	2.72	152	160	0.95	126	1.21	113	1.35	132	1.15	153	0.99
4	SE100A-M-	295	920	71	1.03	0.16	500	2.5	516	599	0.86	470	1.10	489	1.06	469	1.10	546	0.94
4	DB120M	300	925	21	1.01	0.791	508	2.92	282	1335	0.21	1339	0.21	250	1.13	1252	0.23	1344	0.21
4	DB140M	300	925	38	1.01	0.791	508	2.92	277	1405	0.20	1372	0.20	250	1.11	1300	0.21	1394	0.20
4	BM100	300	925	47	0.76	0.791	508	2.92	342	1432	0.24	1349	0.25	250	1.37	1273	0.27	1390	0.25
6	A36	200	260	26	1.47	0.12	267	2.77	89	64	1.40	73	1.21	37	2.41	57	1.55	84	1.06
6	A48	200	260	26	1.47	0.16	269	2.77	89	69	1.28	79	1.12	50	1.78	63	1.41	89	0.99
6	A72	200	260	26	1.47	0.25	256	2.77	93	80	1.16	90	1.03	75	1.24	74	1.25	100	0.93
6	B90	200	260	26	1.96	0.13	262	3.46	85	65	1.30	80	1.06	40	2.13	71	1.20	89	0.95
6	HN-V3	200	303	42	2.99	0.166	530	3.3	177	125	1.41	140	1.27	120	1.48	132	1.34	155	1.14
6	HN-V4	200	303	42	2.99	0.118	530	3.3	188	110	1.71	124	1.51	85	2.21	116	1.61	140	1.34
6	V13HC	199	307	38	2.9	0.21	500	3.25	190	134	1.42	150	1.27	144	1.32	139	1.36	162	1.17
6	V17HC	199	306	39	2.92	0.16	500	3.27	151	119	1.27	135	1.12	110	1.37	125	1.21	148	1.02
6	V24HC	195	306	39	2.99	0.12	500	3.27	128	105	1.22	121	1.06	81	1.58	110	1.16	133	0.96
6	V17HCS	200	312	45	2.86	0.16	500	3.21	200	126	1.58	137	1.46	112	1.79	134	1.50	158	1.27
6	V24HCS	200	302	44	2.95	0.12	500	3.3	150	110	1.37	122	1.23	82	1.83	116	1.29	140	1.07
6	V17HR	200	306	42	2.91	0.16	500	3.27	177	122	1.45	135	1.31	110	1.61	128	1.38	152	1.17
6	V24HR	201	306	39	2.9	0.12	500	3.27	164	108	1.52	124	1.33	83	1.98	114	1.44	137	1.20
6	V13HRS	199	305	41	2.93	0.21	500	3.28	202	135	1.49	150	1.35	143	1.41	141	1.43	165	1.23
6	V17HRS	199	305	45	2.93	0.16	500	3.28	193	123	1.57	134	1.44	109	1.77	130	1.48	154	1.25
6	V24HRS	199	307	43	2.91	0.12	500	3.25	147	110	1.34	123	1.20	82	1.79	117	1.26	140	1.05

Ref.	Beam name	b, mm	d, mm	f_c', MPa	ρ_w ,%	ρ_v %	f_y MPa	a/d	V_{fail} KN	V_{ACI} KN	V_{fail}/V_{ACI}	V_{BS} KN	V_{fail}/V_{BS}	V_{EUR} KN	V_{fail}/V_{EUR}	V_{NZ} KN	V_{fail}/V_{NZ}	V_{NOR} KN	V_{fail}/V_{NOR}
7	H50/2	200	353	50	2.28	0.109	530	3.06	178	130	1.37	129	1.38	92	1.93	141	1.27	163	1.09
7	H50/4	200	351	50	2.99	0.239	540	3.08	246	182	1.35	187	1.31	204	1.21	190	1.30	213	1.15
7	H60/2	200	353	61	2.28	0.141	530	3.06	180	150	1.20	141	1.27	119	1.51	163	1.10	180	1.00
7	H75/2	200	353	69	2.28	0.141	530	3.06	204	156	1.31	141	1.44	119	1.71	170	1.20	184	1.11
7	H75/4	200	351	69	2.99	0.239	530	3.08	255	194	1.32	185	1.37	200	1.28	206	1.24	228	1.12
7	H100/4	200	351	50	2.99	0.239	540	3.08	267	182	1.47	187	1.43	204	1.31	190	1.41	213	1.25
9	S1-1	250	292	64	2.8	0.157	569	2.5	228	173	1.32	168	1.36	147	1.55	182	1.25	213	1.07
9	S1-2	250	292	64	2.8	0.157	569	2.5	208	173	1.21	168	1.24	147	1.41	182	1.14	213	0.98
9	S1-3	250	292	64	2.8	0.157	569	2.5	206	173	1.19	168	1.23	147	1.40	182	1.13	213	0.97
9	S1-4	250	292	64	2.8	0.157	569	2.5	278	173	1.61	168	1.65	147	1.89	182	1.53	213	1.30
9	S1-5	250	292	64	2.8	0.157	569	2.5	253	173	1.47	168	1.51	147	1.72	182	1.39	213	1.19
9	S1-6	250	292	64	2.8	0.157	569	2.5	224	173	1.30	168	1.33	147	1.52	182	1.23	213	1.05
9	S2-1	250	292	73	2.8	0.105	569	2.5	260	155	1.67	146	1.78	98	2.65	168	1.54	199	1.31
9	S2-2	250	292	73	2.8	0.126	569	2.5	233	164	1.42	155	1.50	118	1.97	177	1.32	208	1.12
9	S2-3	250	292	73	2.8	0.157	569	2.5	253	177	1.43	168	1.51	147	1.72	190	1.33	221	1.15
9	S2-4	250	292	73	2.8	0.157	569	2.5	219	177	1.24	168	1.30	147	1.49	190	1.15	221	0.99
9	S2-5	250	292	73	2.8	0.209	569	2.5	282	198	1.42	190	1.49	195	1.45	212	1.33	242	1.16
9	S3-2	250	297	67	1.65	0.101	632	2.49	178	153	1.16	135	1.32	107	1.66	152	1.17	172	1.03
9	S3-3	250	293	67	2.79	0.101	632	2.49	229	157	1.46	150	1.53	105	2.18	167	1.37	198	1.16
9	S3-4	250	293	67	2.79	0.101	632	2.49	175	157	1.12	150	1.17	105	1.67	167	1.05	198	0.88
9	S4-4	250	292	87	2.8	0.157	569	2.5	258	177	1.46	168	1.54	147	1.76	201	1.28	222	1.16
9	S4-6	250	198	87	2.78	0.157	569	2.53	203	120	1.70	121	1.68	99	2.05	137	1.49	159	1.28
9	S5-1	250	292	89	2.8	0.157	569	3.01	242	174	1.39	168	1.44	147	1.65	203	1.19	222	1.09
9	S5-2	250	292	89	2.8	0.157	569	2.74	260	176	1.48	168	1.55	147	1.77	203	1.28	222	1.17
9	S5-3	250	292	89	2.8	0.157	569	2.5	244	177	1.38	168	1.45	147	1.66	203	1.20	222	1.10
9	S7-2	250	294	75	4.46	0.126	569	3.3	205	168	1.22	158	1.29	119	1.72	180	1.14	210	0.98
9	S7-3	250	294	75	4.46	0.157	569	3.3	247	181	1.37	171	1.44	148	1.67	193	1.28	223	1.11
9	S7-4	250	294	75	4.46	0.196	569	3.3	274	197	1.39	188	1.46	184	1.49	209	1.31	239	1.15
9	S7-5	250	294	75	4.46	0.224	569	3.3	304	209	1.45	199	1.52	211	1.44	221	1.38	251	1.21
9	S7-6	250	294	75	4.46	0.262	569	3.3	311	225	1.38	215	1.44	247	1.26	237	1.31	267	1.17
9	S8-1	250	292	75	2.8	0.105	569	2.5	272	155	1.75	146	1.86	98	2.78	170	1.60	200	1.36

Ref.	*Beam name*	*b, mm*	*d, mm*	*fc`, MPa*	ρ_w ,%	ρ_v %	f_y *MPa*	*a/d*	V_{fail} *KN*	V_{ACI} *KN*	V_{fail}/V_{ACI}	V_{BS} *KN*	V_{fail}/V_{BS}	V_{EUR} *KN*	V_{fail}/V_{EUR}	V_{NZ} *KN*	V_{fail}/V_{NZ}	V_{NOR} *KN*	V_{fail}/V_{NOR}
9	S8-2	250	292	75	2.8	0.126	569	2.5	251	164	1.53	155	1.62	118	2.13	179	1.40	209	1.20
9	S8-4	250	292	75	2.8	0.157	569	2.5	266	177	1.50	168	1.58	147	1.81	192	1.39	222	1.20
9	S8-5	250	292	75	2.8	0.196	569	2.5	289	193	1.50	184	1.57	183	1.58	208	1.39	238	1.22
9	S8-6	250	292	75	2.8	0.224	569	2.5	284	205	1.39	196	1.45	209	1.36	219	1.29	249	1.14
12	TS36	150	310	75	2.59	0.23	255	3	156	96	1.62	90	1.73	61	2.56	108	1.45	124	1.26
12	TH39	150	310	73	3.08	0.2	255	3	143	94	1.52	90	1.59	53	2.70	103	1.39	121	1.18
12	ACI59	150	310	82	4.43	0.13	425	5	97	95	1.02	92	1.06	58	1.67	110	0.88	124	0.78
12	TH59	150	310	75	4.43	0.18	425	5	119	105	1.14	102	1.17	80	1.49	116	1.02	134	0.89
12	TS59	150	310	82	4.43	0.27	425	5	125	123	1.02	119	1.05	120	1.04	138	0.91	152	0.83
15	2-58/0.25	110	443	55	2.58	0.48	499	2.82	155	182	0.85	178	0.87	223	0.70	189	0.82	198	0.78
15	4-80/2.50	110	398	74	5.8	0.48	538	3.14	265	185	1.43	171	1.55	254	1.04	188	1.41	199	1.33
15	G-2.70-5.38	110	463	43	1.23	0.333	555	2.7	105	152	0.69	145	0.73	125	0.84	138	0.76	153	0.69
16	N1-N	375	655	36	2.8	0.08	430	3.28	457	356	1.28	404	1.13	190	2.41	379	1.21	407	1.12
16	N2-S	375	655	36	2.8	0.08	430	3.28	363	356	1.02	404	0.90	190	1.91	379	0.96	407	0.89
16	N2-N	375	655	36	2.8	0.11	430	3.28	483	388	1.25	436	1.11	261	1.85	411	1.18	438	1.10
16	M2-S	375	655	67	2.8	0.11	430	3.28	552	474	1.17	436	1.27	261	2.11	518	1.07	536	1.03
16	M2-N	375	655	67	2.8	0.16	430	3.28	689	526	1.31	489	1.41	380	1.81	571	1.21	589	1.17
16	H2-S	375	655	87	2.8	0.14	430	3.28	598	512	1.17	468	1.28	333	1.80	606	0.99	584	1.02
16	H2-N	375	655	87	2.8	0.23	430	3.28	721	607	1.19	563	1.28	547	1.32	701	1.03	679	1.06
17	A-1	307	466	24	1.8	0.1	330	3.92	233	171	1.37	193	1.21	106	2.20	178	1.31	204	1.14
17	CRA-1	305	460	25	1.69	0.1	350	3.98	168	171	0.98	191	0.88	110	1.53	173	0.97	208	0.81
17	CRB-1	229	457	24	2.28	0.15	340	4.01	173	146	1.19	169	1.02	120	1.44	156	1.11	169	1.02
17	1WCRA-1	305	457	26	1.71	0.1	350	4.01	215	173	1.25	192	1.12	110	1.95	175	1.23	210	1.02
17	1WCA-1	305	462	25	1.76	0.1	350	3.95	220	173	1.27	194	1.13	111	1.98	178	1.23	208	1.06
17	1WCB-1	231	460	27	2.34	0.15	340	3.97	202	153	1.32	177	1.14	122	1.66	165	1.23	180	1.13
17	3WCA-1	305	460	26	1.77	0.1	350	3.97	208	174	1.19	195	1.06	110	1.89	181	1.15	211	0.98
17	B45	240	1200	25	1.26	0.15	440	3	468	441	1.06	455	1.03	428	1.09	382	1.23	466	1.00
17	R12	152	272	34	4.16	0.21	276	3.6	117	71	1.66	85	1.38	54	2.17	72	1.62	89	1.32
17	R25	152	272	31	4.16	0.21	276	3.6	112	69	1.63	84	1.33	54	2.07	70	1.60	86	1.30
17	C3	76	95	29	1.97	0.16	275	3	16	10	1.57	15	1.08	7	2.29	11	1.46	15	1.06
17	C3	76	132	28	3.95	0.12	258	3	25	14	1.81	20	1.25	7	3.57	14	1.82	19	1.32

Ref.	Beam name	b, mm	d, mm	f_c', MPa	ρ_w ,%	ρ_v %	f_y MPa	a/d	V_{fail} KN	V_{ACI} KN	V_{fail}/V_{ACI}	V_{BS} KN	V_{fail}/V_{BS}	V_{EUR} KN	V_{fail}/V_{EUR}	V_{NZ} KN	V_{fail}/V_{NZ}	V_{NOR} KN	V_{fail}/V_{NOR}
17	Z3	76	132	26	3.95	0.34	179	3	28	17	1.69	23	1.24	14	2.00	16	1.71	21	1.31
17	04	76	132	28	3.95	0.12	258	4	20	13	1.51	20	1.00	7	2.86	14	1.46	19	1.05
17	B50-3-3	152	298	22	3.36	0.12	292	3.6	76	57	1.33	73	1.04	36	2.11	58	1.30	71	1.07
17	B100-3-3	152	298	28	3.36	0.26	269	3.6	95	77	1.23	94	1.01	71	1.34	80	1.19	95	1.00
17	B100-7-3	152	298	47	3.36	0.26	269	3.6	121	89	1.37	97	1.25	71	1.70	94	1.29	112	1.08
17	B100-11-3	152	298	69	3.36	0.26	269	3.6	151	99	1.52	97	1.56	71	2.13	107	1.41	126	1.20
17	B100-15-3	152	298	82	3.36	0.26	269	3.6	116	100	1.17	97	1.20	71	1.63	114	1.02	128	0.90
17	B150-7-3	152	298	47	3.36	0.38	271	3.6	133	104	1.28	112	1.19	105	1.27	109	1.22	127	1.05
17	B150-15-3	152	298	83	3.36	0.38	271	3.6	150	114	1.31	112	1.34	105	1.43	129	1.16	143	1.05
17	1	305	539	36	2.49	0.14	525	3.1	338	301	1.12	327	1.03	271	1.25	318	1.06	336	1.00
17	2	305	539	36	2.49	0.07	525	3.1	222	241	0.92	266	0.83	136	1.63	258	0.86	276	0.80
17	5	305	539	56	2.49	0.14	525	3.1	383	340	1.13	327	1.17	271	1.41	367	1.04	383	1.00
17	W1	406	345	29	2.31	0.39	549	2.65	460	441	1.04	472	0.98	494	0.93	451	1.02	490	0.94
17	Russell23 23 7	457	871	72	1.88	0.16	445	3	788	859	0.92	737	1.07	638	1.24	942	0.84	880	0.90
17	9	457	762	125	2.35	0.16	483	3	749	782	0.96	697	1.07	606	1.24	1048	0.71	848	0.88
17	10	457	762	125	2.89	0.23	464	3	1172	895	1.31	830	1.41	837	1.40	1150	1.02	989	1.18
17	AL2-N	180	233	40	2.23	0.09	844	4	115	78	1.47	90	1.28	72	1.60	85	1.35	105	1.09
17	AL2-H	180	233	75	2.23	0.09	844	4	123	92	1.34	90	1.37	72	1.71	104	1.18	118	1.04
17	BL2-H	180	233	76	2.81	0.09	844	4	138	93	1.48	94	1.46	72	1.92	105	1.31	126	1.09
17	CL2-H	180	233	70	3.5	0.09	844	4	147	94	1.56	96	1.53	72	2.04	102	1.44	124	1.18
17	BS4-H	180	233	80	2.81	0.18	543	2.5	207	105	1.97	104	2.00	92	2.25	116	1.78	135	1.53
17	CS3-H	180	233	74	3.5	0.13	543	2.5	247	96	2.58	94	2.64	67	3.69	102	2.43	124	1.99
17	CS4-H	180	233	76	3.5	0.18	543	2.5	221	107	2.06	105	2.11	92	2.40	114	1.94	135	1.63
17	NNW-3	127	203	41	3.2	0.49	322	3	87	72	1.21	81	1.07	92	0.95	74	1.18	87	1.00
17	NHW-3	127	198	98	4.54	0.51	324	3	102	82	1.25	82	1.25	93	1.10	91	1.12	100	1.02
17	NHW-3a	127	198	90	4.54	0.65	323	3	108	93	1.16	93	1.16	119	0.91	101	1.07	111	0.97
17	NHW-3b	127	198	103	4.54	0.78	324	3	123	104	1.19	103	1.19	143	0.86	115	1.07	122	1.01
17	BUIS-3	203	419	57	3.03	0.34	426	3.27	267	239	1.12	237	1.13	277	0.96	252	1.06	271	0.99
17	EUIS-3	203	419	56	3.03	0.34	426	3.27	267	238	1.12	237	1.13	277	0.96	250	1.07	270	0.99