Assessment of Strut-and-Tie Methods to Estimate Ultimate Strength of RC Deep Beams

Adrija D[1], Indu Geevar[2], Devdas Menon[3], A Meher Prasad[4]

Reinforced concrete (RC) deep beams are structural members characterized by relatively small shear span to depth (a/d) ratios. Sectional analysis as well as design procedures are not valid for these members due to the complex interaction of flexure and shear. The strut-and-tie method (STM) has been widely accepted and used as a rational approach for the design of such disturbed regions (D regions) of reinforced concrete members, where traditional flexure theory cannot be used. The flow of stress is idealized as a truss consisting of compressive struts (concrete) and tension ties (reinforcing steel) transmitting the loads to the supports. Usually, STM considers only equilibrium. Hence, there is no unique solution for a given system, as one can find more than a single truss geometry admissible for a given force field. Therefore, the model which gives the maximum capacity can be considered as the most appropriate one. This paper attempts to predict the ultimate strength of deep beams failing in diagonal compression as well as tension, from the experimental database available in literature based on STM. A modified approach has been used, considering the crushing and splitting failures of the diagonal strut separately. Crushing failure of the diagonal strut has been predicted using a plastic Strut-and-tie model with varying compression zone depth. A localized STM has been considered to predict the splitting failure of the diagonal strut.

Index Terms— Crushing, Deep beams, Disturbed, Splitting, Strut and tie

I. Introduction

Reinforced concrete deep beams find wide applications as transfer members in high rise buildings. These are characterized with shear span to depth ratios less than 2, making the behaviour shear dominated. According to St. Venant's principle, also supported by an elastic stress analysis, the localized effect of a concentrated load or geometric discontinuity will attenuate about one member depth away from the discontinuity. These regions, known as 'D' regions (‘D’ stands for discontinuity/disturbed) are assumed to extend one member depth from the loading point or geometric discontinuity. Therefore, the entire region of a deep beam can be considered to be disturbed.

Schlaich (1987) developed the Strut-and-tie method (STM) to primarily design ‘D’ (discontinuity or disturbed) regions, where the strain distribution is nonlinear. STM is a versatile tool for the analysis of these regions, where sectional analysis and design procedures are not valid. It is an intuitively rational method which considers actual flow of forces with in the member.

Strut-and-Tie method is based on the lower bound theorem of plasticity which states that any statically admissible stress field that is in equilibrium with the applied forces and in which stress levels are within the material yield surface constitutes a lower bound solution. Therefore, the capacity obtained from a strut-and-tie model is always less than the actual capacity.

The work presented in this paper is a modification to the existing Strut-and-tie methods, aimed at predicting the crushing as well as splitting failures of diagonal strut for reinforced concrete deep beams. A simple equilibrium based plastic STM is used to predict the crushing failure of the diagonal strut. A localized STM for diagonal strut is used to predict the splitting failure. This paper compares the equilibrium based plastic STM (considering splitting, with the proposed parameters) and conventional elastic STM for strength prediction of deep beams using the results from experiments conducted by Clark, A.P. (1951), Mathey, R.G., and Waststein, D. (1963), Yang, K.H., Chung, H.S., Lee, E.T., and Eun, H.C (2003), Birrcher et.al. (2009), and Ray Kai Leung Su and Daniel Ting Wee Looi (2016).

II. Strut and Tie Method

Strut-and-tie method idealizes the force flow with in the member as a hypothetical truss consisting of compression struts and tension ties joined together at regions referred to as nodes. Struts, ties and nodes are proportioned to resist the externally applied forces. Fig. 1 shows a typical Strut-and-Tie model for a reinforced concrete beam subject to symmetric two point loading.

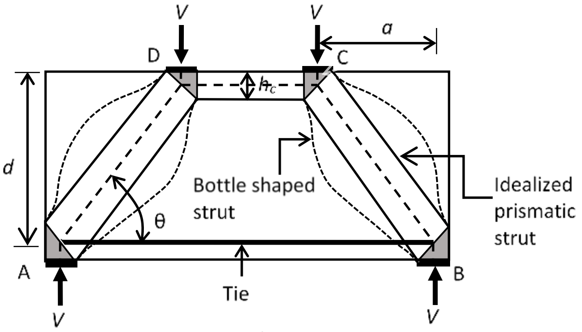

Fig. 1. Typical STM for RC deep beam

It is preferable to use a determinate truss models over indeterminate models so that equilibrium conditions are sufficient to determine the forces on struts and ties. However, there is always more than one truss geometry which is in equilibrium with the external loads. Therefore it is important to choose the right model for strength

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prediction. Since the strut-and-tie method is based on lower bound theorem of plasticity, the truss geometry which gives the maximum capacity is selected.

Struts can be classified as ‘prismatic’ ‘bottle shaped’, or ‘fan shaped’, based on the shape of the stress trajectories in the strut. Prismatic struts are assumed to have uniform cross-sections throughout (Strut CD in Figure 1). Bottle shaped struts take the shape of a bottle and have lateral spread due to orthogonal tension. Crack control reinforcement is required to take care of the tension. For analysis and design purposes, bottle shaped struts are generally idealized as prismatic.

Nodes are the intersection areas of strut and tie in a STM which is similar to joints in trusses. These are highly stressed regions of a structural member and hence it is necessary to check the stresses at the face of the node. For equilibrium, at least three forces are required to act at a node. Based on the number of ties anchored, nodes are generally classified as CCC, CCT, and CTT. As the names suggest, CCC nodes have compressive forces acting on all the three faces, CCT nodes have one tie anchored and CTT node has more than one tie anchored. Limiting stresses at struts and nodes are specified by codes based on the strut and node type respectively. For the present study, a modified equilibrium based strut and tie model (determinate truss model) for deep beams has been considered. This model is capable of predicting all possible failure modes in the member. The codal recommendations from ACI 318-14 has been followed as given in section III.

III. ACI 318-14 Recommendations

ACI code recommends the design of struts, ties and nodes based on the following criteria.

$$\phi F_{ns} \geq F_{us} . \quad (1)$$

$$\phi F_{nn} \geq F_{un} . \quad (2)$$

$$\phi F_{nt} \geq F_{ut} . \quad (3)$$

where F_{ns}, F_{nn} and F_{nt} represent the nominal strength of strut, face of node, and tie respectively (Table I and Equation 4). F_{us}, F_{un} and F_{ut} are the factored force on the strut, face of the node and tie respectively. Φ is the strength reduction factor which is taken as 0.75. For comparison with experimental specimens in the present study, the strength reduction factor, Φ is not considered.

TABLE I

NODAL AND STRUT STRESS LIMITS

Strength of struts	**Strength of nodes**
$F_{ns} = f_{ce}A_{cs}$	$F_{nn} = f_{ce}A_{nz}$
f_{ce}= 0.85$\beta_s f_c$’	f_{ce}= 0.85$\beta_n f_c$’
A_{cs} = Cross sectional area of the strut. β_s = 1.0 (prismatic struts) = 0.75 (bottle shaped with crack control reinforcement as per Eq.5) = 0.6 (bottle shaped without crack control reinforcement as per Eq 5)	A_{ns} = Area of the face of the nodal zone f_c’= cylinder compressive strength of concrete β_n=1.0 (CCC node) = 0.8 (CCT node) = 0.6 (CTT node)

The nominal strength of tie, F_{nt} is given as:

$$F_{nt} = f_y A_{st} . \quad (4)$$

where f_y and A_{st} are yield strength and area of tie reinforcement respectively. Crack control reinforcement as per ACI 318-14 should satisfy the following criteria.

$$\sum \frac{A_{si}}{bs_i} \sin \alpha_i > 0.003 . \quad (5)$$

where A_{si} is the total area of surface reinforcement at spacing s_i in the i^{th} layer of reinforcement crossing a strut at an angle α_i to the axis of the strut

IV. EQUILIBRIUM BASED STM FOR DEEP BEAMS

It has been observed that a single panel STM which assumes direct transfer of loads to supports is the dominant mechanism for beams with a/d ratios less than 2. (Birrcher et.al., 2009). Therefore the model shown in Fig.1 is chosen for the present study. The component forces in the STM can be calculated as:

$$F_{AB} = \frac{V}{\tan\theta} \text{ (tension)} . \quad (6)$$

$$F_{CD} = \frac{V}{\tan\theta} \text{ (compression)} . \quad (7)$$

$$F_{AD} = F_{BC} = \frac{V}{\sin\theta} \text{ (compression)} . \quad (8)$$

where θ is inclination of diagonal struts (AD & BC) with the horizontal.

The STM can be developed based on elastic (Elastic STM) as well as plastic (Plastic STM) theories. The former is developed based on the elastic trajectories. However the solution obtained from such a model may be highly conservative. Plastic STM is based on the truss geometry at ultimate limit state. However, Schlaich (1987) recommends the deviation of the developed STM not greater than 15 degrees from the elastic STM.

A. ELASTIC STM

In this model, the vertical positions of nodes C and D are fixed based on elastic analysis assuming linear strain and stress distribution. Therefore, the height of the compression zone (with uniform stress), $h_{c,e}$ is given by,

$$h_{c,e} = 2\frac{kd}{3} . \quad (9)$$

$$\text{where } kd = \left[\sqrt{2\rho m + (\rho m)^2} - \rho m\right] d . \quad (10)$$

Here, kd is the depth of neutral axis from the extreme compression fibre, ρ is the tie reinforcement ratio (= A_{st}/bd) and m is the modular ratio (=E_s/E_c where E_s and E_c are the moduli of elasticity of steel and concrete respectively). E_s is taken as 200000 MPa and E_c is determined as $5000\sqrt{f_{ck}}$ where f_{ck} = 1.25f_c’.

The tie, strut and nodal strengths are directly based on ACI codal recommendations. The failure load is determined based on the minimum of tie strength, node strength and strut strength. However this model is found to give highly conservative values of collapse load.

B. PLASTIC STM

RC beams with shear span to depth ratios less than 2 are observed to exhibit two types of failure modes namely diagonal crushing and diagonal splitting. Two different strut and tie models are considered to predict these modes separately. The collapse load is determined as the minimum of the loads obtained from these models.

B.1 RESISTANCE AGAINST CRUSHING

Crushing strength of the diagonal strut is computed based on the ACI recommendations, considering a plastic strut-and-tie model. The height of the compression zone is considered as a variable to obtain the optimum truss configuration which gives the maximum capacity. The effect of CCT node width on diagonal strut size has been ignored as per the studies conducted by Birrcher et.al. It is also proposed to consider the enhancement in area at top face of nodes C and D to consider the spread of forces. The diagonal strut width is computed based on ACI recommendations as shown in Fig.2.

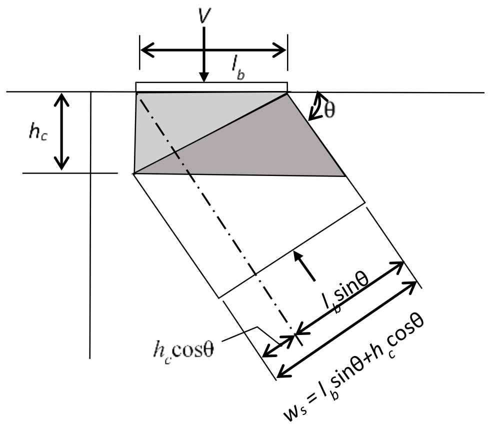

Fig. 2. Nodal zone at typical CCC node

h_c can be evaluated as the maximum width required to avoid the crushing failure of struts as well as nodes (C & D).

$$h_c = \max\left\{ \frac{w_{s,\lim} - l_b \sin\theta}{\cos\theta}, \frac{F_{CD}}{0.85 f_c' b} \right\} . \qquad 11$$

where $$w_{s,\lim} = \frac{F_{BC}}{0.85 \beta_s f_c' b} . \qquad 12$$

Once the node positions are fixed, the diagonal strut inclination, θ can be evaluated as,

$$\theta = \tan^{-1} \frac{d - h_c/2}{a} \qquad 13$$

This is achieved using a simple iterative procedure in MATLAB. The diagonal strut is assumed to be prismatic (β_s = 1), since the splitting failure of the strut is considered separately. It is important to note that, for over-reinforced beams, ties do not reach their capacity. Fig.3 shows the solution algorithm followed. The ultimate load is estimated as the load at which either the tie reinforcement yields (under-reinforced) or the height of the compression zone (based on Eq.11) reaches its maximum limit possible (over-reinforced).

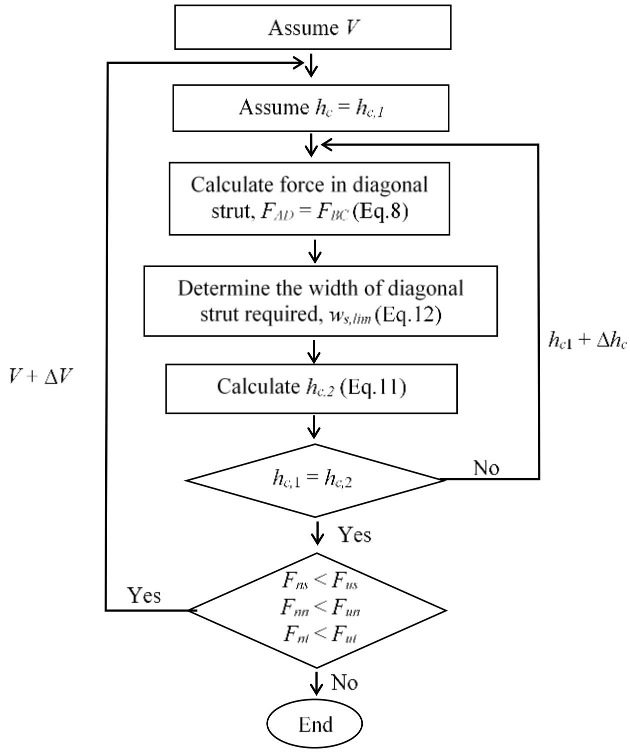

Fig. 3. Solution algorithm for crushing failure

B.2 RESISTANCE AGAINST SPLITTING

Splitting failure of deep beams is characterized by wide opening of diagonal cracks due to the orthogonal tension in the diagonal struts. In the original model recommended by ACI, the reduction in strut strength due to diagonal tension is taken into effect by considering a reduced value of strut efficiency factor β_s, which depends on the amount of crack control reinforcement provided. However, a local strut-and – tie model can be used to predict the resistance of diagonal strut against splitting failure. In the present study, a strut and tie model (EN 1992-1-1) as shown in Fig.4 is used to evaluate the splitting strength of the diagonal strut.

Once the tie in the local strut-and-tie model yields, equilibrium of the model cannot be maintained. Therefore, the resistance of the beam against diagonal splitting can be evaluated as a function of the tensile capacity T of the local STM. In the case of reinforced concrete deep beams without web reinforcement, the direct tensile strength of the concrete determines the capacity of the tie in the local STM. The local tie is assumed to yield once it reaches the splitting tensile strength of concrete. In the case of reinforced concrete deep beams with sufficient web reinforcement, the component of the web reinforcement orthogonal to the diagonal strut is assumed to provide the splitting resistance. The yielding of local tie occurs when the web reinforcement crossing the strut yields.

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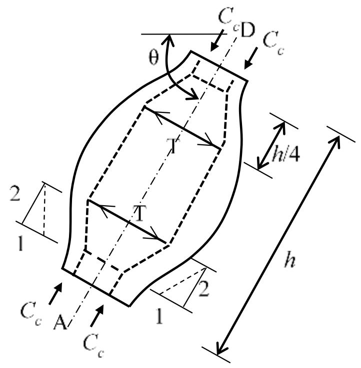

Fig. 4. Local strut-and-tie model for strut BC to calculate splitting tension (EN 1992-1-1)

From the strut geometry, the tensile force on the tie, T can be evaluated as:

$$T = \frac{C_c}{2} \qquad 14$$

For the truss geometry as shown in Fig.1, force, Cc can be determined as:

$$C_c = \frac{V}{2\,\mathrm{Sin}\,\theta} \qquad 15$$

Substituting this in Eq.14, the strength of the deep beam against splitting failure, V_T can be calculated as

$$V_T = 4T\sin\theta\,. \qquad 16$$

For deep beams without web reinforcement, tensile capacity T is obtained as:

$$T = f_{ct}A_{cs}\,. \qquad 17$$

Where f_{ct} is the splitting tensile strength of the concrete. The area of the diagonal strut (A_{cs}) is given by:

$$A_{cs} = w_{s,\max} \times b \qquad 18$$

where $w_{s,max}$ is width of the diagonal strut at maximum spread.

For deep beams with web reinforcement, the maximum tensile capacity T orthogonal to the diagonal strut is the function of areas of horizontal and vertical web reinforcements (A_{sh} and A_{sv}). Therefore T is estimated as

$$T = f_{yv}A_{sv}\cos\theta + f_{yh}A_{sh}\sin\theta\,. \qquad 19$$

where f_{yv} and f_{yh} are the yield strengths of vertical and horizontal web reinforcements respectively. The tensile contribution of concrete is negligible compared to that of reinforcement and hence can be neglected. To estimate θ, height of the compression zone of the model has been fixed as per elastic analysis assuming linear strain and stress distribution.

V. CONCLUSION

From the comparative study the following conclusions are drawn:

- Elastic STM which considers the determinate strut-and-tie model based on elasticity theory is overly conservative. Although it is the simplest method, it is not recommended for practical design.
- Plastic STM with the proposed parameters could predict the failure load with about much less conservatism. The variation with in the results were also found to be less as compared to elastic STM.

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TABLE II

VALIDATION OF EXPERIMENTAL DATA FROM LITERATURE

Author	Specimen	a/d	f'_c MPa	f_y MPa	A_{st} mm^2	A_{sv} mm^2	A_{sh} mm^2	V_{TEST} kN	STM, ELASTIC $\frac{V_{TEST}}{V_{STM}}$	STM, PLASTIC $\frac{V_{TEST}}{V_{STM}}$
Mathey, R.G., and Waststein, D.	I-1	1.51	25.40	267	2495	0	0	310	1.85	1.61
	I-2	1.51	23.00	267	2495	0	0	305	1.99	1.69
	II-3	1.51	21.90	465	1538	0	0	259	1.92	1.68
	II-4	1.51	26.40	465	1538	0	0	309	1.93	1.49
	III-5	1.51	25.70	489	1513	0	0	285	1.84	1.48
	III-6	1.51	25.60	489	1513	0	0	285	1.84	1.47
	IV-7	1.51	24.20	446	1522	0	0	285	1.94	1.50
	IV-8	1.51	24.90	446	1522	0	0	298	1.97	1.58
	V-9	1.51	23.10	694	949	0	0	222	1.71	1.27
	V-10	1.51	27.00	694	949	0	0	267	1.78	1.32
	VI-11	1.51	25.10	694	957	0	0	222	1.58	1.24
	VI-12	1.51	25.70	694	957	0	0	268	1.87	1.39
	V-13	1.51	22.40	711	614	0	0	220	1.89	1.30
	V-14	1.51	26.70	711	614	0	0	221	1.61	0.88
	VI-15	1.51	25.50	711	614	0	0	178	1.35	1.01
	VI-16	1.51	22.80	711	614	0	0	186	1.57	1.04
Clark, A.P.	D0-1	1.16	25.86	370	784	0	0	223	1.29	0.97
	D0-2	1.16	26.20	370	784	0	0	262	1.50	1.14
	D0-3	1.16	25.96	370	784	0	0	225	1.30	0.98
	C0-1	1.55	24.68	370	784	0	0	176	1.37	1.03
	C0-2	1.55	23.48	370	784	0	0	179	1.45	1.05
	C0-3	1.55	23.58	370	784	0	0	168	1.36	0.99
	B0-1	1.94	23.58	370	784	0	0	122	1.23	0.89
	B0-2	1.94	23.91	370	784	0	0	95	0.95	0.72
	B0-3	1.94	23.51	370	784	0	0	129	1.30	0.95
Yang,K.H., Chung,H.S.,Lee,E.T., and Eun,H.C	L5-40	0.56	31.40	804	568	0	0	447	1.80	1.59
	L5-60	0.54	31.40	804	870	0	0	535	1.88	1.80
	L5-75	0.55	31.40	804	1096	0	0	597	1.95	1.89
	L5-100	0.53	31.40	606	1346	0	0	582	1.73	1.89
	L10-40R	1.13	31.40	804	568	0	0	312	1.86	1.22
	L10-60	1.08	31.40	804	870	0	0	376	1.78	1.45
	L10-75R	1.09	31.40	804	1096	0	0	330	1.40	1.27
	L10-100	1.07	31.40	606	1346	0	0	545	2.02	2.03
	UH5-40	0.56	78.50	804	568	0	0	733	1.23	0.96
	UH5-60	0.54	78.50	804	870	0	0	823	1.22	1.11
	UH5-75	0.55	78.50	804	1096	0	0	1011	1.40	1.77
	UH5-100	0.53	78.50	606	1346	0	0	1029	1.29	1.37
	UH10-40	1.13	78.50	804	568	0	0	499	1.35	1.31
	UH10-60	1.08	78.50	804	870	0	0	574	1.17	0.94
	UH10-75R	1.09	78.50	804	1096	0	0	361	0.66	1.06
	UH10-100	1.07	78.50	606	1346	0	0	769	1.21	1.05

Author	Specimen	a/d	f'_c MPa	f_y MPa	A_{st} mm^2	A_{sv} mm^2	A_{sh} mm^2	V_{TEST} kN	STM, ELASTIC $\frac{V_{TEST}}{V_{STM}}$	STM, PLASTIC $\frac{V_{TEST}}{V_{STM}}$
Su, Ray Kai Leung and Looi, Daniel Ting Wee	C30-1.7	1.59	27.60	289	378	0	0	137	2.23	2.12
	C60-1.7	1.59	53.90	592	646	0	0	295	1.85	1.38
	C90-1.7	1.59	78.30	592	971	0	0	377	1.58	1.17
	C30-1.0	0.80	28.20	602	540	0	0	341	1.99	1.41
	C60-1.0	0.80	55.00	592	964	0	0	652	1.91	1.38
	C90-1.0	0.80	85.20	587	1144	0	0	854	1.62	1.16
	C30-0.5	0.45	27.40	602	540	0	0	322	1.41	1.12
	C60-0.5	0.43	54.40	592	667	0	0	700	1.53	1.19
	C90-0.5	0.45	81.10	592	964	0	0	947	1.39	0.93
	C60-0.5	0.43	54.40	592	667	0	0	700	1.53	1.19
	C90-0.5	0.45	81.10	592	964	0	0	947	1.39	0.93
Birrcher et.al.	I-03-2	1.84	36.13	503	11945	2783	1645	2531	1.16	0.99
	I-03-4	1.84	36.75	503	11945	2879	1645	2922	1.31	1.11
	I-02-2	1.84	27.23	503	11945	1920	997	2019	1.53	1.18
	I-02-4	1.84	28.68	503	11945	2016	997	2348	1.63	1.23
	II-03-CCC2021	1.84	22.68	441	12081	2983	2249	2224	2.44	1.28
	II-03-CCC1007	1.84	23.99	441	12081	2983	2249	2126	3.20	1.83
	II-02-CCC1007	1.84	21.65	476	12081	1925	950	1490	2.49	1.40
	II-02-CCC1021	1.84	31.85	476	12081	1925	950	1463	1.40	0.93
	II-03-CCT1021	1.84	30.41	455	12081	2983	2249	2829	2.32	1.27
	II-03-CCT0507	1.84	29.03	455	12081	2983	2249	2660	5.98	1.23
	II-02-CCT0507	1.84	21.51	476	12081	1925	950	1784	5.43	1.11
	II-02-CCT0521	1.84	32.68	476	12081	1925	950	2527	2.95	1.50
	III-1.85-00	1.84	21.86	455	12081	0	0	1624	1.85	0.98
	III-1.85-02	1.84	28.27	476	12081	1925	950	2171	1.91	1.35
	III-1.85-025	1.84	28.27	476	12081	2309	700	2295	2.02	1.25
	III-1.85-03	1.84	34.40	476	12081	2791	1449	1833	1.09	0.77
	III-1.85-01	1.84	34.54	476	12081	962	700	1214	0.87	1.34
	III-1.85-03b	1.84	22.75	476	12081	2983	1449	2095	1.89	1.20
	III-1.85-02b	1.84	22.75	476	12081	1925	950	2082	2.27	1.33
	III-1.2-02	1.2	28.27	455	12081	1255	994	3763	2.12	1.77
	III-1.2-03	1.2	29.10	455	12081	1945	1517	3688	1.66	1.36
	IV-2175-1.85-02	1.85	33.99	469	22124	3627	1711	3394	1.78	1.09
	IV-2175-1.85-03	1.85	33.99	469	22124	5354	2612	3745	1.60	0.85
	IV-2175-1.2-02	1.2	34.54	469	22124	2352	1711	4995	1.75	1.65
	IV-2123-1.85-03	1.85	28.68	455	6129	1466	732	1463	1.21	1.35
	IV-2123-1.85-02	1.85	29.10	455	6129	978	415	1544	1.47	1.53
	M-03-4-CCC2436	1.85	28.27	462	27221	5328	2401	5018	1.41	1.22
	M-03-4-CCC0812	1.85	20.68	448	27221	5328	2401	4137	5.36	2.92
	M-09-4-CCC2436	1.85	28.27	462	27221	14781	2401	6294	1.76	1.51
	M-02-4-CCC2436	1.85	19.31	448	27221	3781	1957	4902	2.40	1.67
	M-03-2-CCC2436	1.85	33.78	469	27221	5328	2401	4875	1.14	1.16
								Avg	**1.82**	**1.28**
								COV†	**0.41**	**0.27**

† Coefficient of variation