Influence of Bolt-Line Eccentricity on WT Tension Member Capacity

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ABSTRACT

This paper focuses on the influence of connection eccentricity (as defined by the perpendicular distance between the bolt-gage line and the elastic neutral axis) on the capacity of WT sections designed as tension members. A series of eight Grade 50, WT6×7 short tension member specimens (specimens were 36 in. in length) were tested to determine their ultimate load capacity. The experimental tests were performed by loading the specimens through the stem in direct tension. The WTs were fabricated with varying edge distances (4 total nominal edge distances) and with both punched and drilled holes. The experimental failure loads are compared with the design resistance predicted by the AISC *Load and Resistance Factor Design Specification for Structural Steel Buildings*, hereinafter referred to as "the specification" (AISC, 1993). It is shown that sections with small eccentricities perform reasonably well when compared with predicted resistance. However, as the eccentricity is increased, the specification is unconservative in predicting the failure load.

INTRODUCTION AND BACKGROUND

Lateral bracing systems in structures are frequently comprised of single angles, double angles, or WT's with high-strength bolted connections. It is typically not convenient or possible to place the centerline of a given fastener group on the section's centroidal axis. Section J1.8 of the specification states, however, that the eccentricity that arises from the connection geometry may be neglected in the design of tension members (AISC, 1993).

The shear lag coefficient, U, developed by Munse and Chesson (Munse and Chesson, 1963), is intended to account for the reduced net section efficiency of a tension member when it is connected by less than all of the cross section elements. Munse and Chesson performed a series of experimental tests in addition to compiling the results of other available data. They concluded that net section efficiency is influenced by:

- Efficiency coefficient
- Fabrication factor
- Bearing factor
- Shear lag factor
- Ductility factor

Munse and Chesson proposed that the effective net section area, due to the transmission of the axial load through less than all components, may be accounted for using the equation

$$\textit{Effective area} = A_n \left(1.60 - 0.7\frac{A_n}{A_g}\right)\left(1-\frac{\bar{x}}{L}\right) \tag{1}$$

where

A_n = net section area

A_g = gross section area

$\left(1.60 - 0.7\frac{A_n}{A_g}\right)$ = efficiency coefficient

$\left(1-\frac{\bar{x}}{L}\right)$ = shear lag coefficient

$\bar{x}$ = connection eccentricity

L = connection length

Note that the specifications neglect the efficiency coefficient as for most connections this is close to unity (Munse and Chesson, 1963).

In their text, *Design of Steel Structures*, Gaylord et al. (Gaylord, Gaylord, and Stallmeyer, 1992) develop the effective net area as a function of all the parameters cited by Munse and Chesson. This equation is

$$A_{eff} = K_1 \; K_2 \; K_3 \; K_4 \; A_{net} \tag{2}$$

where

K_1 = ductility factor = $0.82 + 0.0032 \quad R \le 1$

where $R = \%$ area reduction in coupon test

K_2 = fabrication factor (0.85 for punched holes, 1.0 for drilled holes)

K_3 = efficiency coefficient $= 1.6 - 0.7\left(A_n/A_g\right)$

K_4 = shear lag factor $= 1 - \frac{\bar{x}}{L}$

The specifications incorporate only coefficients K_2 and K_4. However, K_2 is accounted for not by the 0.85 and 1.0

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Table 1. Specimen Geometry

Specimen Number	No. of Bolts, *n*	Edge Distance[a]	Nominal Ecc., *e*	Specimen Depth, *d*	Web Thickness, t_w	Hole Diameter	Hole Fabrication	Yield Strength	Tensile Strength
1	4	0.915	3.24	5.915	0.195	0.7800	Punched	58.75	75.13
2	4	0.935	3.24	5.935	0.195	0.8210	Drilled	58.75	75.13
3	4	2.430	1.74	5.930	0.195	0.7800	Punched	58.75	75.13
4	4	2.405	1.74	5.905	0.196	0.8180	Drilled	58.75	75.13
5	4	3.430	0.74	5.930	0.192	0.8020	Drilled	58.75	75.13
6	4	3.468	0.74	5.968	0.199	0.7800	Punched	58.75	75.13
7	4	4.145	0.07	5.975	0.195	0.8140	Punched	58.75	75.13
8	4	4.095	0.07	5.925	0.194	0.8140	Drilled	58.75	75.13

[a]All above dimensions are in inches and stresses are in ksi.

coefficients presented above; instead the designer is to add $^1/_{16}$ of an inch to the nominal hole diameter to account for hole damage occurring as a result of punching. The increase in diameter need not be incorporated if the hole is to be drilled. However, as the designer is not generally aware of the hole drilling method that will be used (and as it is generally more cost effective for the fabricator to punch the hole) one typically would add the $^1/_{16}$ in. dimension to the nominal diameter in all cases. The factor K_4 is used directly and is often referred to as "Munse's *U*".

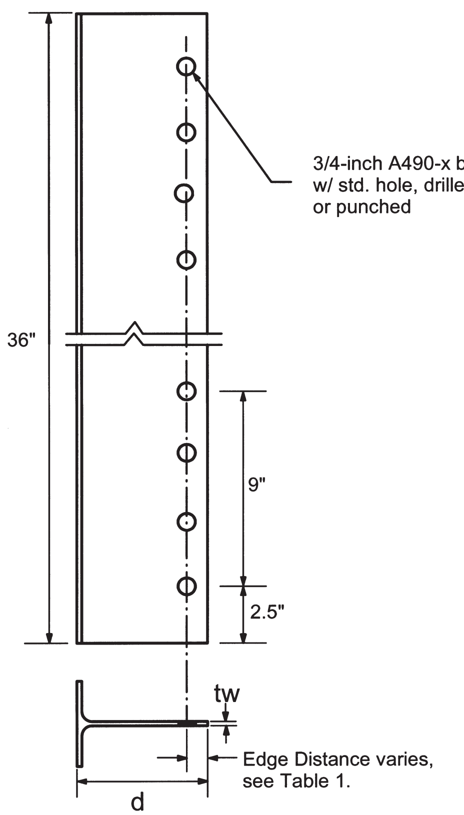

Fig 1. Typical WT 6×7 specimen.

More recently, Kulak and Wu (Kulak and Wu, 1997) conducted tests in an attempt to reduce the work involved in the design of a tension member when shear lag is a concern. In addition, they reevaluated the effective net area equation from Gaylord et al. (1992). The data set examined by Kulak and Wu consists of single and double angles with punched or drilled holes.

Their study indicates that connection length affects a section's efficiency as a function of its influence on the shear lag. A specimen fastened with six bolts and a similar angle fastened with four bolts, having all other connection parameters held constant, exhibited little difference in ultimate strength. However, an angle of similar size fastened with only two bolts had approximately 84 percent of the capacity of the four and six bolt specimens.

From a finite element analysis it was shown that with a connection having four or more bolts in line, an angle is able to develop the average stress in the connected leg equal to the ultimate strength and the average stress in the outstanding leg equal to the yield strength (Kulak and Wu, 1997). However, it was found that in a specimen having three or less bolts the connected leg was able to develop the average of the ultimate stress while the outstanding leg was able to develop less than the average of the yield stress.

Kulak and Wu compared the test data against predicted strength values in an effort to evaluate the shear lag coefficient *U* (Kulak and Wu, 1997). The predicted strength values used were developed on the basis of net section rupture only, calculating the effective net area of the critical cross section based on Equation 2 and the specification's equations.

Using Equation 2 and assuming K_1 and K_3 are both equal to one, resulted in slightly unconservative predictions. This was especially true for connections with fewer than four bolts and for connections with drilled rather than punched holes.

The effective net section area is calculated on the basis of the *U* factor and the $^1/_{16}$ in. increase in the nominal hole diameter to account for punched holes. The *U* factors used in Wu and Kulak's evaluation of code predictions were calculated as specified in Chapter B of the specifications and as allowed for in the Commentary on Chapter B. Comparisons with predictions by the two resulting code equations and test failure values produced very unconservative predictions. In a few instances, the predicted failure load as a function of the Commentary's *U* factor was over fifty percent larger than the actual failure load.

On the basis of the above results Kulak and Wu (Kulak and Wu, 1997) concluded that the calculated *U* value can be unconservative.

CURRENT STUDY

The primary purpose of this study is to evaluate the influence of connection eccentricity on the strength of WT short (36 in.) tension members with bolted connections. The study also evaluates the effect of hole fabrication methods (i.e., punching versus drilling). WT sections were selected as opposed to angles to eliminate the influence of out-of-plane bending.

Eight WT6×7s were tested in tension to failure. Four nominal gage dimensions were specified for the eight specimens. There is a "matched" drilled hole specimen and punched hole specimen for each gage. Specimens were fastened through their webs with ¾-in. A490-X bolts. Bolt holes in the specimens were either drilled or punched to a specified diameter of 13/16 of an inch. The pitch and end distances were held constant for all specimens at 3.0 in. and 2.5 in., respectively. Specimen geometries and material properties can be seen in Table 1 and Figure 1. All specimens were saw-cut from a single length of W12×14. Yield and ultimate strengths shown in Table 1 were obtained from six coupons machined from the web of the wide flange stock.

EXPERIMENTAL TEST SETUP

Tests were performed using a Baldwin 200 kip universal testing machine (UTM). A pair of bar stock grips were bolted to each end of the WT sections. The grips were fabricated from ASTM 1080 cold rolled bar stock, 22-in. by 3-in. by ¾-in. Pairs of grips were used at each end to eliminate out-of-plane eccentricity at the connection. Figure 2 illustrates the bolted connection and Figure 3 shows a specimen in the UTM.

The grips were placed on each side of a WT's web and the bolts tightened to the snug-tight condition. The combined specimen-grip set was then placed in the crossheads

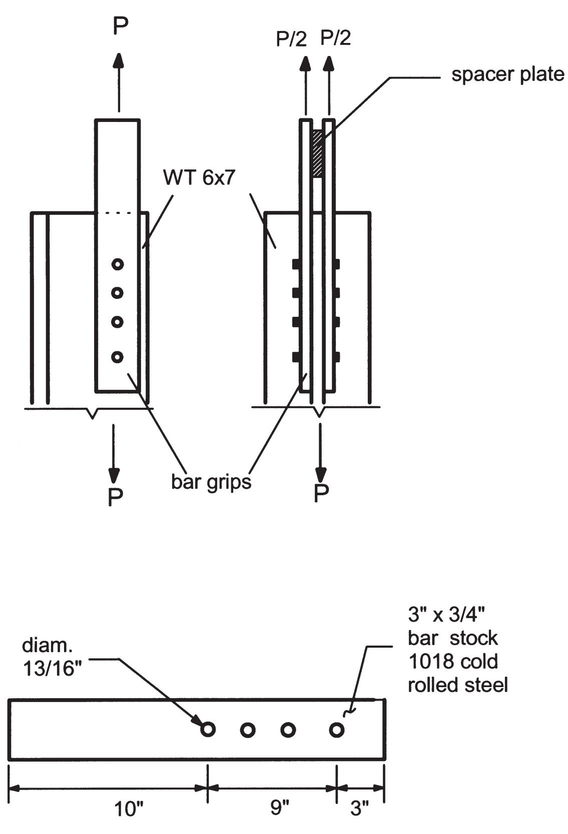

Fig. 2. Bar Stock Grips

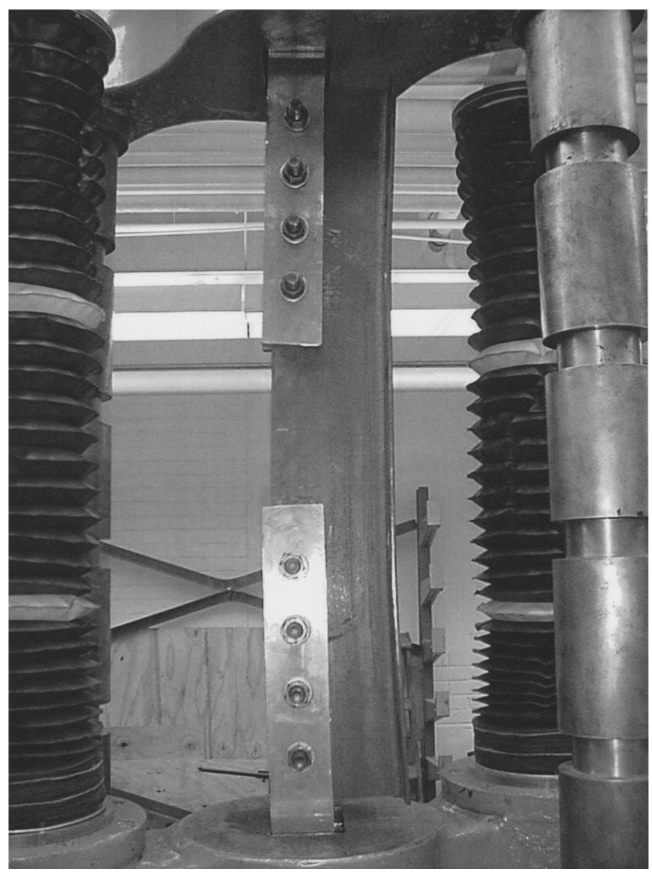

Fig. 3. WT 6×7 in UTM frame (note in-plane bending).

Table 2. Specimen Failure Loads and AISC-LRFD Limit States

Spec. No.	Exp.[a] Load	AISC-LRFD Limit States: Rupture (D1-2) U = Calc[b]	Rupture (D1-2) U =0.85	Yield (D1-1)	Bolt Bearing (J3-1b)[c]	Bolt Shear (J3.6)[d]	Block Shear Capacity[e]	Interaction Eq. (H1-1a)	AISC Predicted Capacity	Prof. Factor P_{exp}/P_{aisc}	F_u*A_{net}	Prof. Factor P_{exp}/F_u*A_{net}
1 (p)	52.8	92.1	122.3	122.2	131.9	264.9	85.6	34.8	85.6	0.62	143.9	0.37
2 (d)	59.5	92.3	122.6	122.2	131.9	264.9	86.5	34.9	86.5	0.69	144.2	0.41
3 (p)	94.3	116.1	122.3	122.2	131.9	264.9	103.0	54.9	103.0	0.92	143.9	0.66
4 (d)	103.5	116.3	122.6	122.2	132.5	264.9	104.0	55.0	104.0	1.00	144.2	0.72
5 (d)	126.0	130.2	123.0	122.2	129.8	264.9	113.9	85.0	113.9	1.11	144.7	0.87
6 (p)	118.2	129.3	122.1	122.2	134.6	264.9	117.3	84.7	117.3	1.01	143.7	0.82
7 (p)	130.0	129.1	121.9	122.2	131.9	264.9	121.6	123.0	121.6	1.07	143.4	0.91
8 (d)	137.2	130.0	122.7	122.2	131.2	264.9	122.3	123.8	122.2	1.12	144.4	0.95

[a]All capacities are shown in kips.
[b]Net section rupture strengths are calculated using U values as determined by Equation (B3-2) and Commentary Section B3.
[c]Bolt bearing is calculated neglecting hole deformation.
[d]Bolts are in double shear.
[e]The controlling block shear equation was J4-3b for all specimens.

of the UTM and secured by wedge grips. Each specimen was loaded with a steadily increasing load until the ultimate load was reached.

EXPERIMENTAL RESULTS AND AISC PREDICTED SECTION CAPACITIES

Yielding of the web material to either side of the innermost bolt on the critical cross section was observed, followed by necking down of the web at this location as the ultimate load was approached. In all test specimens rupture initiated at this bolt hole, and propagated to the outside edge of the web. Specimens 1 through 6 also exhibited significant in-plane bending as a result of their connection eccentricities. Two exceptions to the above failure mode were observed in specimens 7 and 8. Specimen 7 failed in true net section rupture, a simultaneous fracturing through both the web and flange areas. Specimen 8 failed in block shear, with rupture of both the shear and tension block planes. Both specimens 7 and 8 had a bolt line eccentricity of 0.07 in. The only difference between them was the method of hole fabrication. Specimen 7 had punched holes and specimen 8 had drilled holes. Specimens 1, 7 and 8 after testing are shown in Figure 4.

Fig. 4. Specimens 1, 7 and 8 (from right to left) after testing.

Table 2 shows a comparison of experimental failure loads to section strength as predicted by the specifications. Note that the predicted strengths in Table 2 do not include any resistance factors. In the calculation of predicted strength the effective hole diameter as given by the code was only applied to those sections with punched holes. In the calculated U value, limited to 0.90, $\bar{x}$ is measured as the larger distance between the bolt gage line and the centroidal axis specified in the Commentary Section B3 of the specification. In addition to traditional tension member limit states, the section strength is also calculated using a modified form (without resistance factors) of the combined bending and axial load predictions given in Chapter H of the specification. AISC Equation H1-1a applies for all tests. P_n is taken as the net section rupture strength (with $U = 1 - \bar{x} / L$), and M_n is taken from Chapter F, Section F1.2c. The upper limit of $1.5M_y$ governed in all specimens. However, this interaction load strength is not included in determining the professional factor shown in Table 2.

Figure 5 illustrates the experimental results compared with the specification predictions. It can be seen that for sections with small eccentricities, the load strength prediction equations yield good results. However, as the eccentricity increases, the specification prediction becomes unconservative.

INFLUENCE OF CONNECTION ECCENTRICITY AND HOLE FABRICATION ON PREDICTED STRENGTHS

Eccentricity Effects

At eccentricities of approximately 1.50 in. or more, the specification no longer produces conservative results, as seen in Figure 5.

The present AISC net section rupture provisions do not take into account the bending of a member in direct tension due to connection eccentricity, hence the consideration of an interaction equation in this paper. The equation, though providing a more accurate picture of the forces involved in an eccentrically loaded connection, provides an overly conservative estimation of strength. This is especially true for sections with intermediate eccentricities. The primary reason for the conservative predictions is that there is some rotational restraint developed at the bolted connection, which induces a restoring moment that partially counteracts the moment arising from connection eccentricity. The rotational restraint developed at the grips would also develop from the in-plane stiffness of typical gusset plates. Increasing connection lengths would thus be expected to increase the rotational restraint at a connection, as the moment lever arm increases. The rotational restraint is reduced by the bolt-to-hole clearance, and second-order moments due to transverse deflection of the connection will also partially offset the primary moment due to connection eccentricity.

Bolt Hole Fabrication Effects

The average percent difference between failure loads of corresponding drilled and punched hole specimens is 8 percent. However, using an effective hole diameter $^{1}/_{16}$ in. larger than the actual diameter for punched holes results in less than a 1 percent reduction in the net section area. Kulak and Wu (1997) make note of this in their findings. They noted, "for angles of medium and large size, the reduction is usually less than 2 percent." The specified hole diameter increase is insufficient in accounting for the observed reduction in load capacity due to punched holes.

Shear Lag Effects

Shear lag has been reported to limit the stress development in the outstanding leg of an angle to the yield strength (Kulak and Wu, 1997). The specimens examined to support this finding had an eccentricity of about one inch. However, as previously noted, eccentricity not only affects shear lag, but it induces bending too. Specimen 8 had an eccentricity of nearly zero inches and can, according to specification, only develop an average ultimate stress over 90 percent of its net area. However, the specimen failed in block shear, at a failure load exceeding the specification's net section rup-

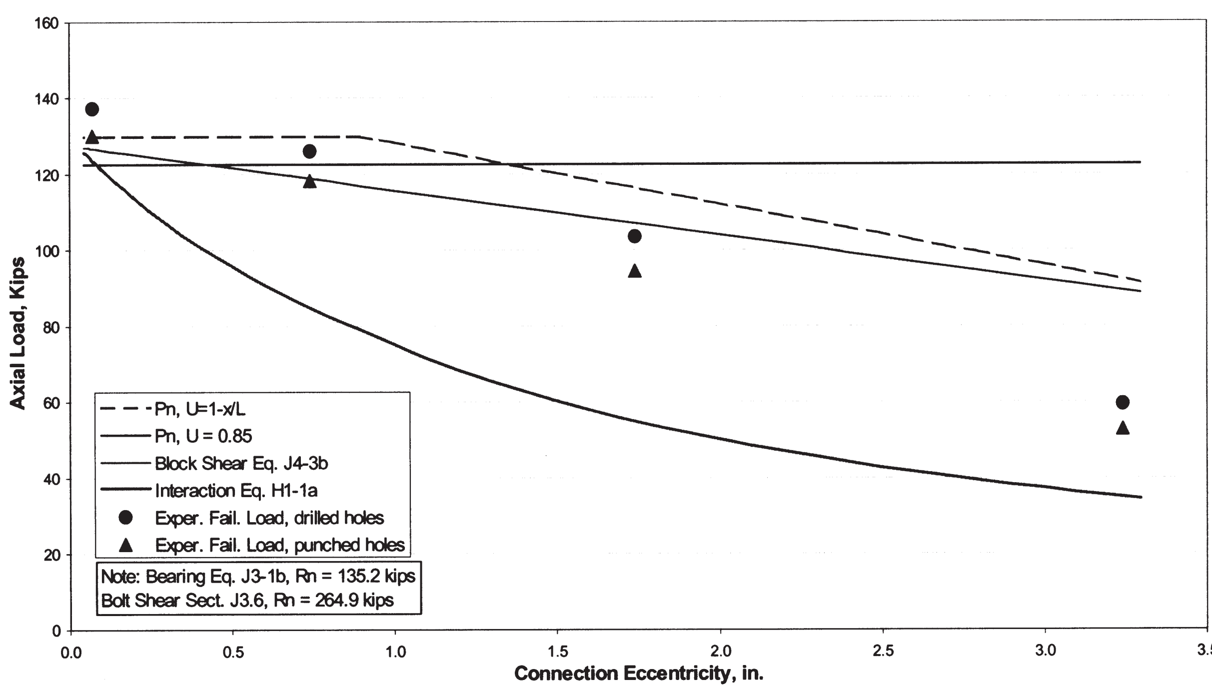

Fig. 5. Graphical presentation of AISC predictions.

ture prediction, at a load of equal to 95 percent of F_uA_{net}. This indicates that the net section rupture of this member exceeds the specification U factor upper bound of 0.90. The specification's upper limit on the U factor might not accurately portray the effects of shear lag in a member with zero or near zero eccentricity. Further, the U factor as presently defined may primarily reflect the reduction in load capacity due to bending rather than shear lag.

Specimen 7's net section rupture could be due to the fact that the holes were punched, reducing the ductility at the innermost bolt hole enough so that net section rupture, not block shear, controlled the failure.

FINAL COMMENTS

Though the designer is explicitly permitted to disregard connection eccentricity in Section J1.8 of the specification, this study suggests that this practice can lead to unconservative strength predictions. Figure 6 illustrates the moment that must be accounted for in strength predictions. The proper consideration of this moment in design is complicated by the partial rotational restraint at the grips, comparable to the in-plane behavior of a gusset plate in a given connection. The restraint in effect provides for a restoring moment to be developed; hence, the discrepancy between the failure loads and the value determined by the interaction equation. The authors note that the second-order moment, beneficial in tension members as it reduces the primary

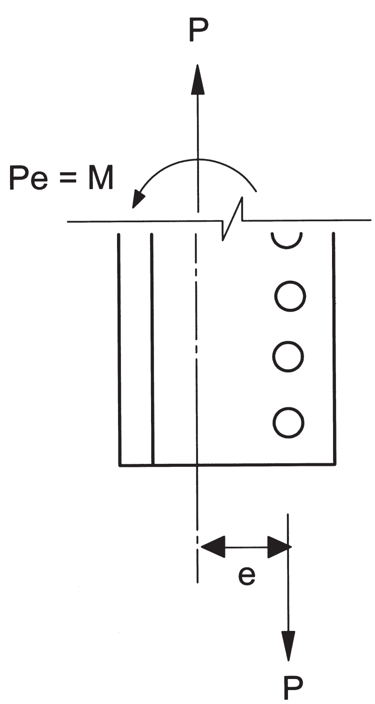

Fig. 6. Moments developed in an axial member because of bolt line eccentricity.

moment, is likely to be very small at the net section, again due to the connection restraint.

Of note is the fact that the tests conducted in the development of the U factor and those conducted by Kulak and Wu had an average eccentricity of approximately 1 in. The U factor in the specifications is inherently calibrated against the interaction of combined tension-flexure occurring in these studies. This leads to the fact that the specified U value cannot accurately be used in the net section strength predictions when the eccentricity becomes significant.

As a result of this work the authors recommend that tension members of WT and similar sections (i.e. single and double angles), with connection eccentricities larger than 1.5 in., be designed using the applicable interaction equation in Chapter H. Additionally, in lieu of the $^1/_{16}$ in. increase in hole diameter, the authors suggest that a factor K_2 be used in net section rupture calculations to account for the deleterious effects of hole punching. Note that Munse and Chesson (Munse and Chesson, 1963) recommended a value of 0.85.

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