Effect of Varied Imperfections on Bracing Demand of Cold-formed Steel Stud Walls

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Abstract

The purpose of this analytical study was to determine the effect of varied out-of-straightness imperfection on the bracing strength and stiffness demand of multiple cold-formed steel stud walls. This study is an extension of previous work performed to develop relationships between the required brace strength and stiffness for bridging of multiple stud walls and the required brace strength and stiffness of a single stud. Eight-foot tall walls with three different imperfections were analyzed using critical buckling analysis. The required cross-sectional area to prevent buckling was determined and the critical brace force and stiffness were calculated for various magnitudes of imperfection. Critical brace strength was found to accumulate directly as a multiple of the number of studs, regardless of stud out-of-straightness. Critical brace stiffness is not directly related to the number of studs, but a relationship was formulated that is independent of stud out-of-straightness. The required brace strength and stiffness of a multiple stud wall with a specified initial imperfection can thus be related to the required brace strength and stiffness of a single stud for any magnitude of imperfection.

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Introduction

Previous research (Green, Sputo, Urala, 2004) was conducted to determine the required bracing strength and stiffness to provide for bracing a single stud against flexural buckling. From a series of tests, the following equations for required brace strength and stiffness were developed for a single stud:

Required Brace Strength: $P_{br,1} = 0.01\ P_n$
Required Brace Stiffness: $\beta_{br,1} = 2(4\text{-}2/n)P_n / L_b$

where:

P_n = nominal strength of stud
L_b = unbraced length of stud
n = number of brace points

The AISI *Specification* (2007) has incorporated these provisions in Section D3.3 (Bracing of Axially Loaded Compression Members)

In a further study (Beery and Sputo, 2006), the required brace strength and stiffness demand of a multiple stud wall was related to the number of studs and the brace strength and stiffness of a single stud. In this analytical study, walls comprised of up to 30 studs were analyzed using MASTAN2, where each of the studs was modeled with an out-of-straightness in the same direction of L/384. 8-foot walls and 12-foot walls were studied using both elastic critical load analysis and second-order elastic analysis and the following equations were recommended:

Required Brace Strength: $P_{br,n} = n_s * P_{br,1}$
Required Brace Stiffness: $\beta_{br,n} = \beta_{br,1}$ for n_s=1
$\beta_{br,n} = \beta_{br,1}\ [0.4\ n_s^2 + 0.5\ n_s]$ for n_s>1

where:

$P_{br,1}$ = required brace strength for a single stud
$\beta_{br,1}$ = required brace stiffness for a single stud
n_s = number of studs (anchored at one end)
= 1/2 the number of studs (anchored at both ends)

The modeled out-of-straightness of L/384 was derived from the ASTM C-955 maximum allowable out-of-straightness of L/384. The intent of the work reported on in this paper was to develop similar relationships for brace strength and stiffness requirements for multiple stud walls with differing imperfections. Imperfections of L/384, L/480, and L/960 were studied. Brace strength and stiffness for these multiple stud walls were related to the number of studs in the wall and the required brace strength and stiffness of a single stud.

Methodology

Models of stud walls were created in MASTAN2 (2002). The studs were eight feet tall, spaced at 24 inches on center, with a single line of horizontal bridging at mid-height. The bridging was modeled as a series of rigid links with pinned ends at the stud connection. One set of models was anchored to a fixed point at one end of the wall as shown in Figure 1. The other set of models was anchored to fixed points at both ends of the wall as shown in Figure 2. Walls comprised of 1,5,10, 15, 20, 25, and 30 studs were analyzed with out-of-straightness of L/384, L/480, and L/960. An axial load of 1 kip was applied to each stud, and a critical buckling analysis was performed, at which the load ratio at failure was noted. The cross sectional area of the bracing was incrementally increased until the wall failed in second mode buckling. The area and brace force were recorded and equations for critical brace strength and stiffness were then formulated. These equations are a function of the number of studs in the wall and the bracing requirements for a single stud with specified out-of-straightness.

Results

The results of the analysis are tabulated in Tables 1 through 18.

Tables 1 and 2 tabulate the relationships between stiffness and brace force for one through thirty studs, anchored on one end, with an out of straightness of L/384, for the critical brace stiffness and two times the critical brace stiffness. Table 3 formulates equations for brace stiffness and brace force as functions of the number of braced studs. Likewise Tables 4 through 6 illustrate this for studs with an out-of-straightness of L/480, and Tables 7 through 9 for studs with an out-of-straightness of L/960. The stiffness ratio versus the number of braced studs for the varied out-of-straightnesses is plotted in Figure 3 and the strength ratio versus the number of braced studs for the varied out-of-straightnesses is plotted in Figure 4. It can be seen that the magnitude of the out-of-straightness plays little role in the accumulation of required brace stiffness and strength.

Tables 10 and 11 tabulate the relationships between stiffness and brace force for one through thirty studs, anchored on both ends, with an out of straightness of L/384, for the critical brace stiffness and two times the critical brace stiffness. Table 12 formulates equations for brace stiffness and brace force as functions of the number of braced studs. Likewise Tables 13 through 15 illustrate this for studs with an out-of-straightness of L/480, and Tables 16 through 18 for studs with an out-of-straightness of L/960. The stiffness ratio versus the number of braced studs for the varied out-of-straightnesses is plotted in Figure 5 and the strength ratio versus the number of braced studs for the varied out-of-straightnesses is plotted in Figure 6. It can be seen that the magnitude of the out-of-straightness plays little role in the accumulation of required brace stiffness and strength.

As a rule, the critical brace strength of a single stud decreases as out-of-straightness is decreased. However, the critical brace strength of multiple studs also decreases, and the relationship remains the same. The critical brace stiffness does not change with different values of stud out-of-straightness. Therefore, the relationships previously derived still hold true.

For the walls anchored on both ends, half of the braces transfer force in tension, while half the braces transfer force in compression. For out-of-straightness of L/384 and L/480, the compressive force in the brace exceeds the buckling capacity of a typical CRC bridging channel in walls with 15 or more studs. These results were obtained in previous research (Beery and Sputo, 2006) and were expected. However, for an out-of-straightness of L/960, the compressive brace force did not exceed the brace's capacity. This result is encouraging, since most studs are manufactured to a tighter tolerance than the ASTM C-955 tolerance of L/384.

Conclusions

The results of this study indicate that the equations for the accumulation of bracing stiffness demand and brace strength are independent of the magnitude of out-of-straightness.

Table 1. Calculated relationships at critical stiffness, L/384, with anchor at one end

Number of Studs	30	25	20	15	10	5	1
A brace (in^2)	0.2576	0.1801	0.1164	0.0666	0.0306	0.0084	0.0007
L brace (in)	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	316.6	221.4	143.1	81.81	37.58	10.35	0.8369
$\beta_{br,n}$ / $\beta_{br,1}$*n	12.61	10.58	8.548	6.517	4.490	2.474	1.000
$P_{br,n}$ /$P_{br,1}$	31.51	26.24	20.97	15.70	10.43	5.167	1.000

Table 2. Calculated relationships at twice critical stiffness, L/384, with anchor at one end

Number of Studs	30	25	20	15	10	5	1
A brace (in^2)	0.2576	0.1801	0.1164	0.0666	0.0306	0.0084	0.0007
L brace (in)	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	316.6	221.4	143.1	81.81	37.58	10.35	0.8369
$\beta_{br,n}$ / $\beta_{br,1}$*n	12.61	10.58	8.548	6.517	4.490	2.474	1.000
$P_{br,n}$ /$P_{br,1}$	30.77	25.63	20.49	15.35	10.22	5.086	1.000

Table 3. Formulated equations, L/384 with anchor at one end

Condition	Stiffness	Brace Force
Beta	y = 0.4056x + 0.4379	y = 1.0538x - 0.1061
2Beta	y = 0.4056x + 0.4379	y = 1.0273x - 0.0531

Table 4. Calculated relationships at critical stiffness, L/480, anchored at one end

Number of Studs	30	25	20	15	10	5	1
A brace	0.2576	0.1801	0.1164	0.0666	0.0306	0.0084	0.0007
L brace	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$	316.6	221.4	143.1	81.81	37.58	10.35	0.8369
$\beta_{br,n}$ / $\beta_{br,1}$*n	12.61	10.58	8.548	6.517	4.490	2.474	1.000
$P_{br,n}$ /$P_{br,1}$	31.50	24.95	20.96	14.77	10.43	5.169	1.000

Table 5. Calculated relationships at twice critical stiffness, L/480 with anchor at one end

Number of Studs	30	25	20	15	10	5	1
A brace	0.2576	0.1801	0.1164	0.0666	0.0306	0.0084	0.0007
L brace	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$	316.6	221.4	143.1	81.81	37.58	10.35	0.8369
$\beta_{br,n}$ / $\beta_{br,1}$*n	12.61	10.58	8.548	6.517	4.490	2.474	1.000
$P_{br,n}$ /$P_{br,1}$	29.63	25.77	20.49	15.20	10.22	4.030	1.000

Table 6. Formulated equations, L/480 with anchor at one end

Condition	Stiffness	Brace Force
Beta	y = 0.4056x + 0.4379	y = 1.0366x - 0.1781
2Beta	y = 0.4056x + 0.4379	y = 1.0282x - 0.4374

Table 7. Calculated relationships at critical stiffness, L/960 with anchor at one end

Number of Studs	30	25	20	15	10	5	1
A brace (in^2)	0.2576	0.1801	0.1164	0.0666	0.0306	0.0084	0.0007
L brace (in)	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	316.6	221.4	143.1	81.81	37.58	10.35	0.8369
$\beta_{br,n}$ / $\beta_{br,1}$*n	12.61	10.58	8.548	6.517	4.490	2.474	1.000
$P_{br,n}$ /$P_{br,1}$	31.48	26.21	20.95	15.68	10.42	5.162	1.000

Table 8. Calculated relationships at twice critical stiffness, L/960 with anchor at one end

Number of Studs	30	25	20	15	10	5	1
A brace (in^2)	0.5152	0.3602	0.2328	0.1331	0.0611	0.0169	0.0136
L brace (in)	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	633.3	442.7	286.2	163.6	75.15	20.71	16.74
$\beta_{br,n}$ / $\beta_{br,1}$*n	1.261	1.058	0.8548	0.6517	0.4490	0.2474	1.000
$P_{br,n}$ /$P_{br,1}$	30.75	25.61	20.48	15.35	10.21	5.083	1.000

Table 9. Formulated equations, L/960 with anchor at one end

Condition	Stiffness	Brace Force
Beta	y = 0.4056x + 0.4379	y = 1.0528x - 0.1065
2Beta	y = 0.4056x + 0.4379	y = 1.0265x - 0.0496

Table 10. Calculated relationships at critical stiffness, L/384 with anchors at both ends

Number of Studs	15	10	5	1
A brace (in^2)	0.0178	0.0084	0.0026	0.0003
L brace (in)	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	21.85	10.36	3.134	0.4199
$\beta_{br,n}$ / $\beta_{br,1}$*n	3.498	2.488	1.505	1.008
$P_{br,n}$ /$P_{br,1}$	7.800	5.168	2.550	0.5009

Table 11 Calculated relationships at twice critical stiffness, L/384 with anchors at both ends

Number of Studs	15	10	5	1
A brace (in^2)	0.0356	0.0169	0.0051	0.0007
L brace (in)	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	43.71	20.73	6.269	0.8398
$\beta_{br,n}$ / $\beta_{br,1}$*n	3.498	2.488	1.505	1.008
$P_{br,n}$ /$P_{br,1}$	7.6551	5.0862	2.5261	0.5006

Table 12. Formulated equations, L/384 with anchors at both ends

Condition	Stiffness	Brace Force
Beta	y = 0.3615x + 0.7242	y = 1.0435x - 0.0388
2Beta	y = 0.3615x + 0.7242	y = 1.0224x - 0.0200

Table 13. Calculated relationships at critical stiffness, L/480 with anchors at both ends

Number of Studs	15	10	5	1
A brace (in^2)	0.0178	0.0084	0.0026	0.0003
L brace (in)	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	21.85	10.36	3.134	0.4199
$\beta_{br,n}/\beta_{br,1}$*n	3.493	2.485	1.503	1.007
$P_{br,n}/P_{br,1}$	7.795	5.418	2.673	0.5251

Table 14. Calculated relationships at twice critical stiffness, L/480 with anchors at both ends

Number of Studs	15	10	5	1
A brace (in^2)	0.0356	0.0169	0.0051	0.0007
L brace (in)	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	43.71	20.73	6.269	0.8398
$\beta_{br,n}/\beta_{br,1}$*n	3.493	2.485	1.503	1.007
$P_{br,n}/P_{br,1}$	7.653	5.086	2.526	0.5005

Table 15. Formulated equations, L/480 with anchors at both ends

Condition	Stiffness	Brace Force
Beta	$y = 0.361x + 0.7232$	$y = 1.044x + 0.0572$
2Beta	$y = 0.361x + 0.7232$	$y = 1.022x - 0.0196$

Table 16. Calculated relationships at critical stiffness, L/960 with anchors at both ends

Num Studs	30	25	20	15	10	5	1
A brace (in^2)	0.0666	0.0469	0.0306	0.0178	0.0084	0.0026	0.0003
L brace (in)	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	81.83	57.59	37.59	21.85	10.36	3.13	0.4199
$\beta_{br,n}/\beta_{br,1}*n$	6.518	5.505	4.491	3.482	2.477	1.498	1.003
$P_{br,}n/Pbr_{,1}$	15.68	13.05	10.42	7.790	5.164	2.547	0.5004

Table 17. Calculated relationships at twice critical stiffness, L/960 with anchors at both ends

Number of Studs	30	25	20	15	10	5	1
A brace (in^2)	0.1331	0.0937	0.0612	0.0356	0.0169	0.0051	0.0007
L brace (in)	720.0	600.0	480.0	360.0	240.0	120.0	24.00
$\beta_{br,n}$ (kips/in)	163.7	115.2	75.18	43.71	20.73	6.269	0.8398
$\beta_{br,n}/\beta_{br,1}*n$	6.518	5.505	4.491	3.482	2.477	1.498	1.003
$P_{br,n}/P_{br,1}$	15.35	12.78	10.21	7.649	5.083	2.524	0.5002

Table 18. Formulated equations, L/960 with anchors at both ends

Condition	Stiffness	Brace Force
Beta	y = 0.3884x + 0.6267	y = 1.0482x - 0.0577
2Beta	y = 0.3884x + 0.6267	y = 1.0249x - 0.0307

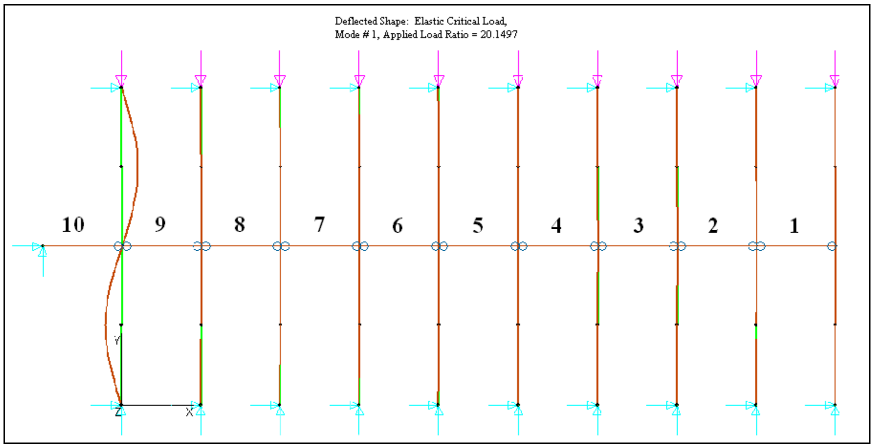

Figure 1. Model of 10-stud wall anchored on one end with 8-foot studs at 24 inches on center

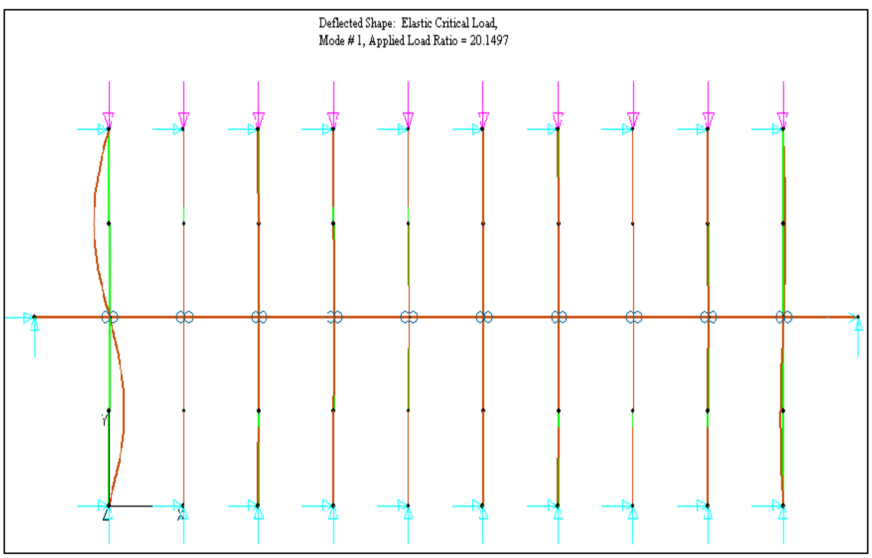

Figure 2. Model of 10-stud wall braced on both ends with 8-foot studs at 24 inches on center.

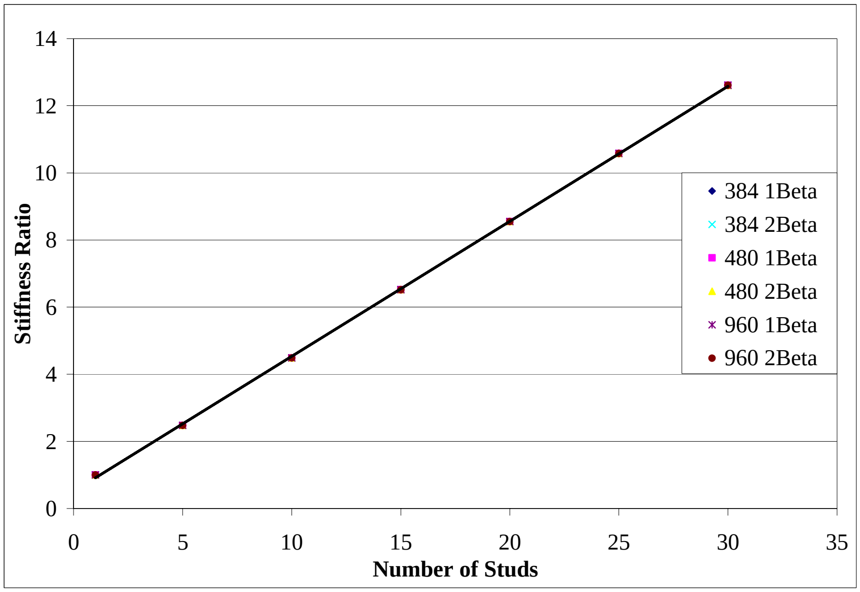

Figure 3. Stiffness ratio vs. number of studs, anchored on one end

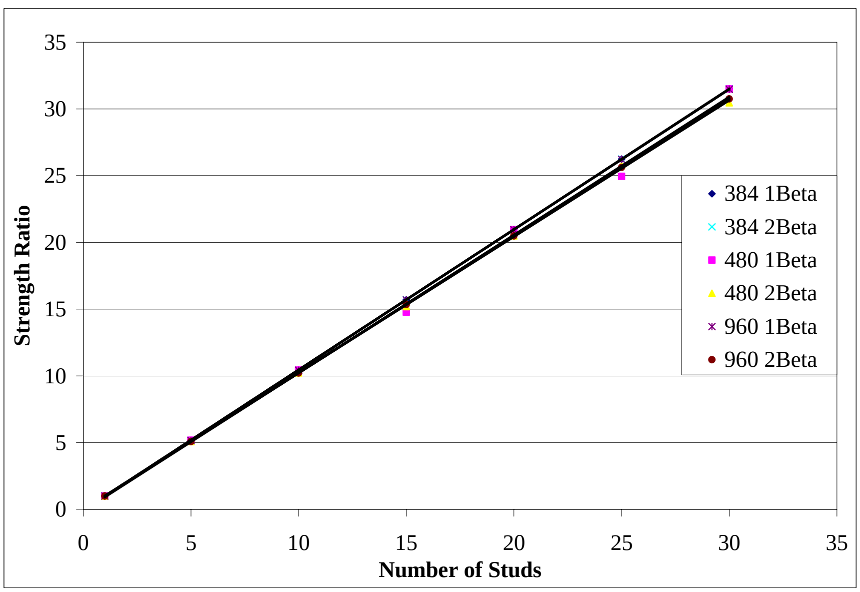

Figure 4. Strength ratio vs. number of studs, anchored at one end

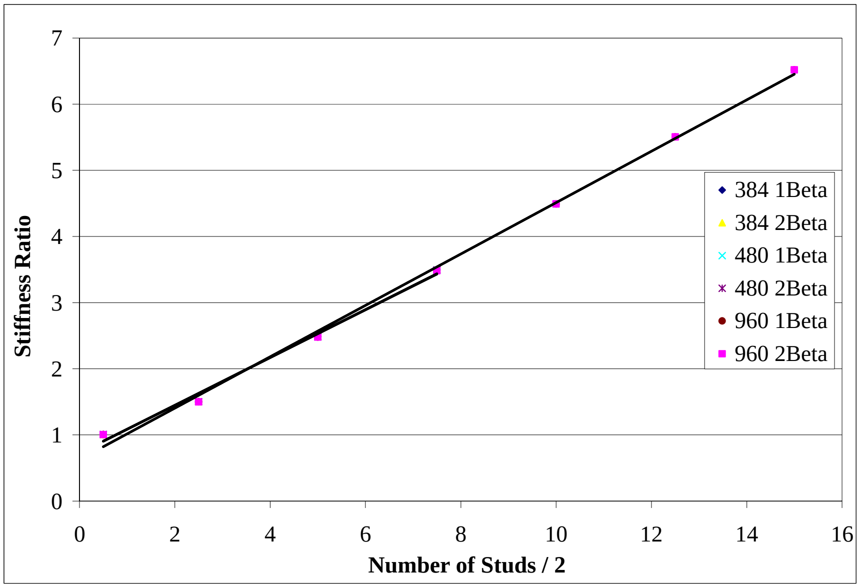

Figure 5. Stiffness ratio vs. number of studs, anchored at both ends

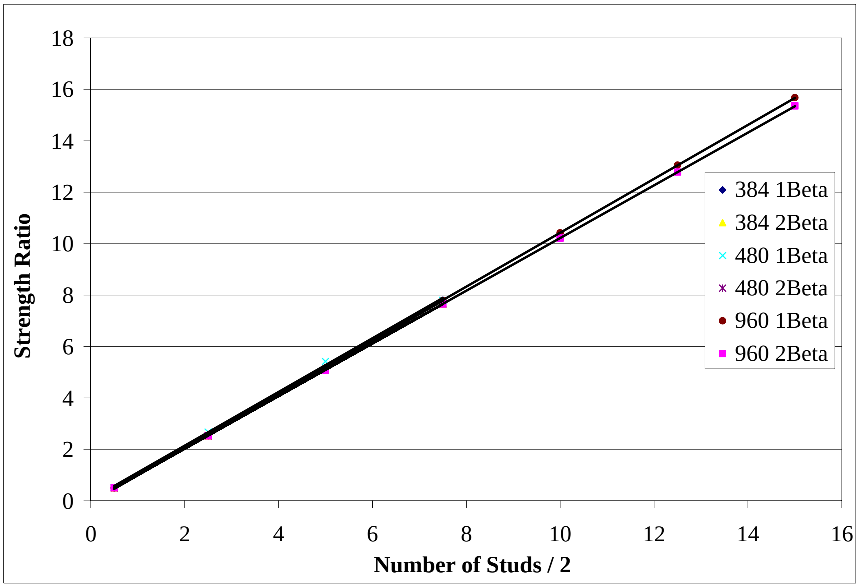

Figure 6. Strength ratio vs. number of studs, anchored at both ends

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