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DESIGN OF STAINLESS STEEL SECTIONS AGAINST DISTORTIONAL BUCKLING

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Abstract

Current cold-formed *stainless steel* design codes for distortional buckling, including the Australian/New Zealand Standard AS/NZS 4673 (2001) and the North American ASCE (2002), have been based on cold-formed *carbon steel* codes without the support or corroboration of experimental evidence. As such, an experimental program on the distortional buckling of axially compressed, cold-formed stainless steel simple lipped channels and lipped channels with intermediate stiffeners was conducted. Results show that the effect of stainless steel material non-linearity is partially negated by the strength-enhanced corners, and this becomes evident in the design evaluation. Both the effective width and the "direct strength" (AS/NZS 4600 1996) design approaches are considered. When the enhanced corner properties are ignored, the effective width design evaluation may become unconservative for sections with a corner area less than 10% of the gross area and become overly conservative for sections with a corner area greater than approximately 10% of the gross area. The "direct strength" evaluation provides reasonably conservatively strength predictions for sections with a corner area of at least 10% of the gross area, provided enhanced corners are ignored and the (actual) fixed end conditions are modeled in the elastic buckling analysis.

Introduction

Current design guidelines for the distortional buckling of stainless steel structural members are uncritically based on those for cold-formed carbon steel

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and do not account for stainless steel material characteristics. Stainless steel has a low proportionality stress, inherent stress-strain non-linearity and is capable of pronounced strength enhancements due to cold working. Van den Berg (2000) is credited for proposing the use of a plasticity reduction factor (E_s/E_o or E_t/E_o, where appropriate) with design equations to account for stainless steel nonlinearity, but this leads to iterative calculations and may not be suitable for designers. Stainless material characteristics were investigated in a recent experimental program on the distortional buckling of stainless steel simple lipped channels and lipped channels with intermediate stiffeners (Lecce and Rasmussen 2004). Sections were brake-pressed from austenitic 304, ferritic 430 stainless and ferritic-like 3Cr12 chromium weldable steel sheets. The experimental results are compared to predictions obtained from current design specifications and are used to assess whether or not these design rules, based on those for cold-formed carbon steel, are appropriate for stainless steel.

The stainless steel codes considered in this paper are the Australian/New Zealand AS/NZS 4673 (2001) and the North American ASCE (2002) specifications which use the effective width approach to determine section capacity and which, for section geometries considered here, are essentially identical to those available cold-formed carbon steel design codes including AS/NZS 4600 (1996), and NAS (2001). As section geometries become more complicated, with a combination of edge and intermediate stiffeners, the effective width calculations become cumbersome and unattractive to designers. An alternative design procedure well known as the Direct Strength Method (DSM) has been proposed in recent years by Schafer (2002) for cold-formed carbon steel which uses the gross cross sectional area and a reduced design stress, based on a rational elastic buckling analysis. The "direct strength" evaluation (i.e., DSM) for the design against distortional buckling was included in the AS/NZS 4600 (1996) standard for cold-formed carbon steel and is appreciably straightforward and designer-friendly. Both the effective width approach and DSM are herein compared with experimental results (Lecce and Rasmussen 2004) and the influence of stress-strain nonlinearity and enhanced corner properties on the design evaluations are discussed.

Distortional Buckling Test Results

The complete set of mechanical properties for brake-pressed austenitic 304, ferritic 430 and ferritic-like 3Cr12 chromium weldable steel, as used for the experimental program, are reported in Lecce and Rasmussen (2004). The material test results show that significant strength enhancement was achieved by the work-hardening of the corners. For example, the corner 0.2% proof stress, $f_{y,c}$, of the austenitic 304 material was 2.33 times greater than the flat material 0.2% proof stress, $f_{y,f}$. Section dimensions and testing procedures are given in Lecce and Rasmussen (2004). All columns were tested under axial compression with fixed end conditions and failed by distortional buckling. Results showed that the mean ultimate stress was greater than $f_{y,f}$, suggesting that failures occurred in the nonlinear range of the stress-strain curve. For simple lipped channels, E_t/E_0 ranged from 0.29 to 0.47 and E_s/E_0 ranged from 0.71 to 0.88, showing a significant loss of stiffness at ultimate capacity. The loss was greater for lipped channels with intermediate stiffeners where E_t/E_0 ranged from 0.13 to 0.26 and E_s/E_0 ranged from 0.47 to 0.73. However, as will be shown in following sections, gradual yielding is partially counteracted by enhanced corner properties and this contributes to the distortional buckling strength. Therefore, enhanced corner strength properties cannot be ignored in the design code evaluation.

Effective Width Design Approach

As mentioned in the introduction, the stainless steel codes in the past have uncritically followed suit with those for carbon steel and therefore comparison with the current cold formed carbon steel design guidelines is important. Reference is given to the respective codes for detailed design procedures and some important aspects of the calculations are highlighted here.

The effective width approach used in North American and Australian/New Zealand standards determines strength based on local plate instability with allowance for post-buckling strength development. For partially stiffened flange elements, subject to distortional buckling, the lip effective width is reduced according to a ratio of $I_s/I_a \leq 1.0$ where I_s is the moment of inertia of the lip and I_a is the adequate moment of inertia required for the flange element to behave as an adequately stiffened element. The procedures for finding effective widths of lipped channels with *partially stiffened* flanges are given in clauses 2.4.2 (ASCE 2002), 2.4.3 (AS/NZS 4673 2001 and AS/NZS 4600 1996) and B4.2 (NAS 2001) and are essentially identical for the section geometries considered herein. For the *adequately* edge-stiffened flanges with an intermediate stiffener the ASCE (2002), AS/NZS 4673 (2001) and AS/NZS (1996) differ from NAS (2001) and this will be discussed further in the following pages. Results are presented first for the design of simple lipped channels in Table 1, followed by results for lipped channels with intermediate stiffeners in Table 2.

In Tables 1 and 2, the code-predicted load (using a resistance and safety factor of 1.0) is denoted by the symbol P_d where the subscript "d" represents design. If enhanced corner properties are *excluded* from the calculation as is current practice in the Australian/New Zealand and North American standards;

$$P_d = P_{d,f} = (A_{e,f} + A_c) f_{y,f} \tag{1}$$

where, $A_{e,f}$ is the effective area of the flats, A_c is the corner area and $f_{y,f}$ is the proof stress of the flat (virgin) material. If enhanced corner properties are *included*;

$$P_d = P_{d,fc} = A_{e,f} f_{y,f} + A_c f_{y,c} \tag{2}$$

where $f_{y,c}$ is the corner proof stress. Note in Eqs.1 and 2, A_c is replaced by $A_{c,r}$ if the corner area is reduced in the calculations due to ineffectiveness intermediate stiffeners (see Table 2).

Table 1. Effective area approach for simple lipped channels

Experimental Data							ASCE (2002), AS/NZS 4673 (2001), NAS (2001), AS/NZS 4600 (1996)				
								Without enhanced corner properties		**With** enhanced corner properties	
Specimen ID	P_u	$f_{y,f}$	$f_{y,c}$	A_g	A_c	A_c/A_g	$A_{e,f}$	$P_{d,f}$	$P_u/P_{d,f}$	$P_{d,fc}$	$P_u/P_{d,fc}$
	kN	MPa	MPa	mm^2	mm^2	%	mm^2	kN		kN	
304D1a	102	242	565	565	61	10.8	356	101	1.01	121	0.84
304D1b	101	242	565	565	61	10.8	355	101	1.00	120	0.84
304D2a	104	242	565	565	61	10.8	356	101	1.03	121	0.86
304D2b	104	242	565	565	61	10.8	356	101	1.03	121	0.86
430D1a	39	271	452	211	21	10.0	121	39	1.00	42	0.91
430D1b	39	271	452	211	22	10.4	123	39	0.99	43	0.90
430D2	45	271	452	215	22	10.1	129	41	1.10	45	1.00
430D3a	40	271	452	188	22	11.6	119	38	1.04	42	0.94
430D3b	39	271	452	188	22	11.6	119	38	1.01	42	0.92
3Cr12D1a	138	339	606	555	62	11.2	345	138	1.00	155	0.89
3Cr12D1b	139	339	606	555	62	11.2	346	138	1.01	155	0.90
Statistical evaluation								**mean**	**1.02**		**0.90**
								STDV	**0.0304**		**0.0476**
								COV	**0.030**		**0.053**
Notes: 1 in = 25.4 mm; 1 kip = 4.45 kN; 1 ksi = 6.89 MPa											

Referring to Table 1, one can see that the North American and Australian/New Zealand standards give a reasonable strength prediction with a mean tested to predicted ratio, $P_u/P_{d,f}$ of 1.02 and a coefficient of variation (COV) of 0.030, provided enhanced corner properties are ignored. If one considers the effects of the enhanced corner properties, the code-predicted values become unconservative with a mean $P_u/P_{d,fc}$ of 0.90. For sections with a corner area of 10.0-11.6% of the gross area, the codes used in Table 1 give reasonable capacity predictions provided enhanced corners are not included. Furthermore, one can conclude that effects of enhanced corner properties partially negate the effects of stress-strain nonlinearity and to clearly define the effects of early loss of stiffness, the enhanced corner properties cannot be ignored in strength evaluation.

Table 2 shows the strength predictions for sections with lips and intermediate stiffeners. Evidently the North American and Australian/New Zealand standards offer a conservative design approach with a mean $P_u/P_{d,f}$ = 1.12, if corner strength properties are excluded, but unconservative if they are included ($P_u/P_{d,f}$ = 0.99).

Table 2. Effective area approach for lipped channels with intermediate stiffeners

Experimental Data							ASCE (2002), AS/NZS 4673 (2001), AS/NZS 4600 (1996), NAS (2001)					
									Without enhanced corner properties		**With** enhanced corner properties	
Specimen ID	P_u	$f_{y,f}$	$f_{y,c}$	A_g	A_c	A_c/A_g	$A_{c,r}$	$A_{e,f}$	$P_{d,f}$	$P_u/P_{d,f}$	$P_{d,fc}$	$P_u/P_{d,fc}$
	kN	MPa	MPa	mm^2	mm^2	%	mm^2	mm^2	kN		kN	
304DS1a	132	242	565	634	123	19.3	74	433	123	1.08	146	0.90
304DS1b	134	242	565	634	123	19.3	74	433	123	1.09	146	0.92
430DS1	60	271	452	269	54	20.2	33	157	52	1.16	57	1.04
430DS2	62	271	452	269	54	20.2	33	157	52	1.20	57	1.08
430DS3	64	271	452	278	54	19.6	33	176	57	1.12	63	1.02
430DS4	73	271	452	278	54	19.6	33	176	57	1.27	63	1.15
3Cr12DS1a	163	339	606	565	124	22.0	74	388	157	1.04	177	0.92
3Cr12DS1b	161	339	606	565	124	22.0	74	388	157	1.03	177	0.91
Statistical evaluation									**mean**	**1.12**		**0.99**
									STDV	**0.0813**		**0.0914**
									COV	**0.072**		**0.092**
Notes: 1 in = 25.4 mm; 1 kip = 4.45 kN; 1 ksi = 6.89 MPa												

For the section geometry considered here, design calculations indicate that the edge stiffener provides partial stiffness only (i.e., $I_s<I_a$ and k<4). As such, the flange intermediate stiffener is completely ignored in calculations and the flange element is designed as a simple edge-stiffened element per clause B4.2 (NAS 2001) and equivalently clause 2.4.2 (ASCE 2002) and clause 2.4.3 (AS/NZS 4673 2001, AS/NZS 4600 1996). The justification for ignoring the intermediate stiffener in cases where k<4 was given by research which suggested that the distortional buckling stress is altered by less than ±10% for sections with flanges that have both intermediate and edge stiffeners compared to those with just edge stiffeners (NAS Commentary 2002). However, this conclusion is unsupported by the research presented herein since these rules lead to over-conservative results as shown in Table 2 (excluding corner strength properties).

For cases where the flange edge stiffener *is* adequate ($I_s>I_a$ and k=4), as determined by clause B4.2 (NAS 2001), the NAS allows the designer to take advantage of the added strength given by the intermediate stiffener as outlined in clause B5.1 (NAS 2001). Clause B5.1 evaluates the effective width for local sub-element buckling and distortional buckling of the intermediate stiffener and uses the governing buckling mode (local or distortional) to determine the element strength. This differs from procedures outlined in clause 2.5 (ASCE 2002, AS/NZS 4673 2001, AS/NZS 4600 1996) where, if the intermediate stiffener satisfies the minimum moment of inertia, an equivalent flange thickness is found and the effective width is determined by plate local buckling rules (again, provided that the flange is adequately stiffened by the edge stiffener). None of the section geometries considered in this program are adequately edge-stiffened and therefore these rules could not be tested against experimental results and further examination is warranted.

Direct Strength Method

The AS/NZS 4600 (1996) has a separate design check for distortional buckling in clause 3.4.6, akin to the Direct Strength Method (DSM), which eliminates the need to determine effective widths and is based the research of Hancock et. al (1994). The equations for the critical buckling design stress, f_n, takes into account the effects of yielding in the following form;

$$f_n=\left[1-\frac{f_y}{4f_{od}}\right]f_y \qquad for \quad f_{od}>\frac{f_y}{2} \qquad (3a)$$

$$f_n = \left[0.055\left(\sqrt{\frac{f_y}{4f_{od}}}-3.6\right)^2 + 0.237\right] f_y \qquad \mathit{for} \quad \frac{f_y}{13} \le f_{od} \le \frac{f_y}{2} \qquad (3b)$$

The critical elastic buckling stress, f_{od}, used in the equations of clause 3.4.6 can be determined from a rational elastic buckling analysis such as finite strip, Thin Wall (Papangelis and Hancock 1995), or spline finite strip ($f_{od,TW}$ or $f_{od,s}$, respectively). The most significant difference between the two analyses is the prescribed end conditions; Thin Wall finite strip analysis assumes simply supported ends whereas the spline finite strip analysis incorporates fixed end conditions, representing the true end conditions of the experimental tests. As shown in Lecce and Rasmussen (2004), the distortional buckling stress is higher for fixed end conditions. The critical inelastic buckling stress, f_n, is then multiplied by the gross area, A_g, to determine the strength. This is the same procedure as in the DSM and the calculations will be referred to as such. Tables 3 and 4 show the predicted loads for simple lipped channels and lipped channels with intermediate stiffeners, respectively. Henceforth, any reference to DSM calculations using Thin Wall (TW) or spline rational buckling analysis will be given the abbreviation DSM/TW or DSM/spline. The code-predicted strength is given as;

$$P_d = P_{d,f} = A_g f_{n,f} \qquad (4)$$

or

$$P_d = P_{d,avg} = A_g f_{n,avg} \qquad (5)$$

where $f_{n,f}$ in Eq.(4) ignores enhanced corners ($f_y = f_{y,f}$ in Eq. 3a/b) and $f_{n,avg}$ in Eq.(5) includes enhanced corners ($f_y = f_{y,avg}$ in Eq. 3a/b). The weighted average of proof stress, $f_{y,avg}$, is calculated as follows;

$$f_{y,avg} = \frac{(A_g - A_c) f_{y,f} + A_c f_{y,c}}{A_g} \qquad (6)$$

Referring to Table 3, the simple lipped channels tested have a corner area ranging between 10.0% and 11.6% of the gross area. Using a DSM/TW analysis and virgin material properties results in a conservative strength prediction, with a mean $P_u/P_{d,f}$=1.13 and $P_u/P_{d,avg}$=1.08 if the enhanced corner properties are included. By comparison, the DSM/spline evaluation results in a less conservative mean $P_u/P_{d,f}$=1.00 and unconservative $P_u/P_{d,avg}$=0.94. Referring to Table 4, lipped channels with intermediate stiffeners tested have a greater corner area ranging between 19.3% and 22.0% of the gross area, approximately twice that of the simple lipped channels. The DSM/TW evaluation with virgin material properties, results in a $P_u/P_{d,f}$=1.28, which is considerably higher than that obtained for sections with 10.0% to 11.6% corner area. By comparison, the DSM/spline evaluation results in a mean ratio of $P_u/P_{d,f}$=1.07 which is reasonably conservative. If corner properties are considered, the DSM/TW gives a $P_u/P_{d,avg}$=1.19 whereas DSM/spline gives $P_u/P_{d,avg}$=0.95.

For all the DSM evaluations provided in Tables 3 and 4, the calculations most representative of the actual tests performed are those of DSM/spline with enhanced corner properties. The spline finite strip analysis provides a critical *elastic* buckling analysis and by accounting for fixed end conditions and enhanced corner strength, the effects of stress strain non-linearity can be isolated. Since the mean test to predicted strength ratio $P_u/P_{d,avg} < 1$, one can conclude that the material inelasticity is not adequately accounted for. However, as long as the corner area accounts for at least 10% of the gross area, and the enhanced corner properties due to cold working are ignored, the elastic material model of DSM/spline, provides reasonable results.

Table 3. AS/NZS 4600 (1996) Direct strength method for simple lipped channels

Experimental Data								f_{od} from **Thin Wall finite strip**, $f_{od}=f_{od,TW}$							f_{od} from **spline finite strip**, $f_{od}=f_{od,s}$						
									Without enhanced corner properties			**With** enhanced corner properties				**Without** enhanced corner properties			**With** enhanced corner properties		
Specimen ID	P_u	$f_{y,f}$	$f_{y,c}$	$f_{y,avg}$	A_g	A_c	A_c/A_g	$f_{od,TW}$	$f_{n,f}$	$P_{d,f}$	$P_u/P_{d,f}$	$f_{n,avg}$	$P_{d,avg}$	$P_u/P_{d,avg}$	$f_{od,s}$	$f_{n,f}$	$P_{d,f}$	$P_u/P_{d,f}$	$f_{n,avg}$	$P_{d,avg}$	$P_u/P_{d,avg}$
	kN	MPa	MPa	MPa	mm^2	mm^2	%	MPa	MPa	kN		MPa	kN		MPa	MPa	kN		MPa	kN	
304D1a	102	242	565	277	565	61	10.8	179	160	91	1.13	170	96	1.06	261	186	105	0.97	203	115	0.89
304D1b	101	242	565	277	565	61	10.8	179	160	91	1.12	170	96	1.05	261	186	105	0.96	203	115	0.88
304D2a	104	242	565	277	565	61	10.8	179	160	91	1.15	170	96	1.08	283	190	107	0.97	209	118	0.88
304D2b	104	242	565	277	565	61	10.8	179	160	91	1.15	170	96	1.08	283	190	107	0.97	209	118	0.88
430D1a	39	271	452	289	211	21	10.0	177	167	35	1.09	171	36	1.07	225	189	40	0.96	196	41	0.93
430D1b	39	271	452	290	211	22	10.4	177	167	35	1.11	171	36	1.08	225	189	40	0.98	196	41	0.94
430D2	45	271	452	289	215	22	10.1	203	181	39	1.16	186	40	1.12	264	202	43	1.04	210	45	1.00
430D3a	40	271	452	292	188	22	11.6	198	178	34	1.18	184	35	1.14	237	194	36	1.09	202	38	1.04
430D3b	39	271	452	292	188	22	11.6	198	178	34	1.15	184	35	1.12	237	194	36	1.06	202	38	1.02
3Cr12D1a	138	339	606	369	555	62	11.2	264	230	128	1.08	240	133	1.04	332	252	140	0.99	266	148	0.93
3Cr12D1b	139	339	606	369	555	62	11.2	264	230	128	1.09	240	133	1.04	332	252	140	0.99	266	148	0.94
Statistical evaluation										**mean**	**1.13**			**1.08**				**1.00**			**0.94**
										STDV	**0.0334**			**0.0339**				**0.0445**			**0.0581**
										COV	**0.030**			**0.031**				**0.045**			**0.062**
Notes: 1 in = 25.4 mm; 1 kip = 4.45 kN; 1 ksi = 6.89 MPa																					

Table 4. AS/NZS 4600 (1996) Direct strength method for lipped channels with intermediate stiffeners

Experimental Data								f_{od} from **Thin Wall finite strip,** $f_{od}=f_{od,TW}$							f_{od} from **spline finite strip,** $f_{od}=f_{od,s}$						
									Without enhanced corner properties			**With** enhanced corner properties				**Without** enhanced corner properties			**With** enhanced corner properties		
Specimen ID	P_u	$f_{y,f}$	$f_{y,c}$	$f_{y,avg}$	A_g	A_c	A_c/A_g	$f_{od.TW}$	$f_{n,f}$	$P_{d,f}$	$P_u/P_{d,f}$	$f_{n,avg}$	$P_{d,avg}$	$P_u/P_{d,avg}$	$f_{od,s}$	$f_{n,f}$	$P_{d,f}$	$P_u/P_{d,f}$	$f_{n,avg}$	$P_{d,avg}$	$P_u/P_{d,avg}$
	kN	MPa	MPa	MPa	Mm^2	mm^2	%	MPa	MPa	kN		MPa	kN		MPa	MPa	kN		MPa	kN	
304DS1a	132	242	565	304	634	123	19.3	223	176	112	1.18	201	127	1.04	342	199	126	1.05	237	150	0.88
304DS1b	134	242	565	304	634	123	19.3	223	176	112	1.20	201	127	1.05	342	199	126	1.06	237	150	0.89
430DS1	60	271	452	308	269	54	20.2	164	159	43	1.39	163	44	1.36	262	201	54	1.10	217	58	1.02
430DS2	62	271	452	308	269	54	20.2	164	159	43	1.44	163	44	1.41	350	219	59	1.05	240	65	0.96
430DS3	64	271	452	306	278	54	19.6	192	175	49	1.30	184	51	1.24	333	216	60	1.06	236	66	0.97
430DS4	73	271	452	306	278	54	19.6	192	175	49	1.47	184	51	1.40	509	235	65	1.10	260	72	0.99
3Cr12DS1a	163	339	606	398	565	124	22.0	342	255	144	1.13	282	159	1.02	398	267	151	1.08	298	169	0.97
3Cr12DS1b	161	339	606	398	565	124	22.0	342	255	144	1.12	282	159	1.01	398	267	151	1.07	298	169	0.96
Statistical evaluation										**mean**	**1.28**			**1.19**				**1.07**			**0.95**
										STDV	**0.1423**			**0.1785**				**0.0212**			**0.0467**
										COV	**0.111**			**0.150**				**0.020**			**0.049**
Notes: 1 in = 25.4 mm; 1 kip = 4.45 kN; 1 ksi = 6.89 MPa																					

Conclusions

A total of 19 distortional buckling tests of stainless steel lipped channels and lipped channels with intermediate stiffeners under axial compression have been compared to the strength predictions of current design guidelines for cold-formed stainless steel including AS/NZS 4673 (2001) and ASCE (2002) and cold formed steel design guidelines AS/NZS 4600 (1996) and NAS (2001). The design rules of these specifications are adequate for simple lipped channels, with a corner area between 10% and 11.6% of the gross area, as is typical for most cold-formed stainless steel channels, but become over-conservative for sections with intermediate stiffeners having a corner area from 19-20% of the gross area. The DSM offers a simple, designer-friendly approach and gives adequate strength predictions provided that correct boundary conditions are considered and enhanced corner properties are ignored. There is now enough evidence to show that neglecting the adverse effects of stainless steel material non-linearity and early loss of stiffness may lead to unconservative strength predictions if the corner area is less than about 10% of the gross area, while overly conservative predictions result when the corner area exceeds about 10% of the gross area.

Appendix – Notation

A_g	gross area
A_c	corner area
$A_{c,r}$	reduced corner area
$A_{e,f}$	effective area of flats
COV	coefficient of variation
E_t	tangent modulus
E_s	secant modulus
E_o	initial elastic modulus
f_n	reduced critical stress based on f_{od}, and f_y [AS/NZS 4600 (1996) Clause 3.4.6]
f_{od}	critical elastic buckling stress [AS/NZS 4600 (1996) Clause 3.4.6]
$f_{od,TW}$	critical elastic buckling stress from Thin Wall finite strip analysis
$f_{od,s}$	critical elastic buckling stress from spline finite strip analysis
$f_{n,f}$	reduced critical stress based on f_{od} and $f_{y,f}$
$f_{n,avg}$	reduced critical stress based on f_{od} and $f_{y,avg}$
f_y	0.2% proof stress
$f_{y,c}$	0.2% proof stress of corner (cold-worked) material
$f_{y,f}$	0.2% proof stress of flat (virgin) material

$f_{y,avg}$	weighted average of corner and flat yield 0.2% proof stresses
P_d	design load (resistance/safety factor=1.0)
$P_{d,avg}$	design load based design stress $f_{n,avg}$
$P_{d,f}$	design load based on flat material properties
$P_{d,fc}$	design load based on flat and corner material properties
P_u	test ultimate load
STDV	standard deviation

Appendix – References

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