Eccentric Compression Test of WT Shape Steel Braces

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ABSTRACT

It is a common practice to provide lateral strength for open steel structures using braces with WT shapes. The construction procedure consists in connecting the brace to the frame using a gusset plate attached to the WT flange with bolts or welding. This connection has an initial eccentricity which is the distance from the WT centroid to the center of the gusset plate thickness, where the loads are transmitted to the brace. The eccentricity is not constant; it depends on the load and the respective deflection, producing a non-linear relationship between the load, the deflection, and the stress distribution. This paper present the test results of two braces submitted to eccentric compression. The braces have 15'0" long and the cross section is WT5x11. The loads are applied using a hollow hydraulic jack that stretches a strand and transmits the load to connector devices attached to the WT flange at each end point of the brace. Two spreadsheets showing the theoretical calculations are developed following the current AISC code and a non-linear analysis using the step-by-step method. The test results compares well with the theoretical calculations.

Keywords: WT shape, flexo-compression, beam-column

RESUMEN

Es práctica común proveer resistencia lateral a las estructuras abiertas de acero usando riostras de sección WT. El procedimiento constructivo consiste en unir la riostra al pórtico con una placa conectada al ala de la sección WT usando pernos ó soldadura. Esta conexión tiene una excentricidad inicial, la cual es la distancia del centroide de la sección WT al centro del espesor de la placa, donde las cargas se transmiten a la riostra. La excentricidad no es constante, depende de la carga y de la deflexión respectiva, produciendo una relación no lineal entre la carga, la deflexión y la distribución de esfuerzos. Este manuscrito presenta los resultados del ensayo de dos riostras sometidas a compresión excéntrica. Las riostras tienen 15'0" de longitud y la sección transversal es WT5x11. Las cargas son aplicadas usando un gato hidráulico hueco el cual estira un cable y transmite la carga a unos conectores unidos al ala de la sección WT en cada punto terminal de la riostra. Los cómputos teóricos se muestran en dos hojas de cálculo desarrollados de acuerdo al actual código AISC y al análisis no-lineal usando el método paso-a-paso. Los resultados de los ensayos comparan bien con los resultados teóricos.

Palabras claves: sección WT, flexo-compresión, viga-columna.

1. INTRODUCTION

WT shapes are commonly used for open steel structures because their maintenance and installation is easier than other shapes. Typically, the WT brace is attached to the gusset plate through the flange with bolts or welding. This constructive advantage produces an initial eccentricity, because the load transmitted by the gusset plate is eccentric respect to the centroid of the WT shape. The initial eccentricity is the distance between the center of the gusset plate and the centroid of the WT shape, which produces an initial bending moment, deflects the brace, and also increases the eccentricity. During loading, there is a P-δ effect which is a non-linear relationship between the compression load, the end moments, the deflection, and the stress distribution.

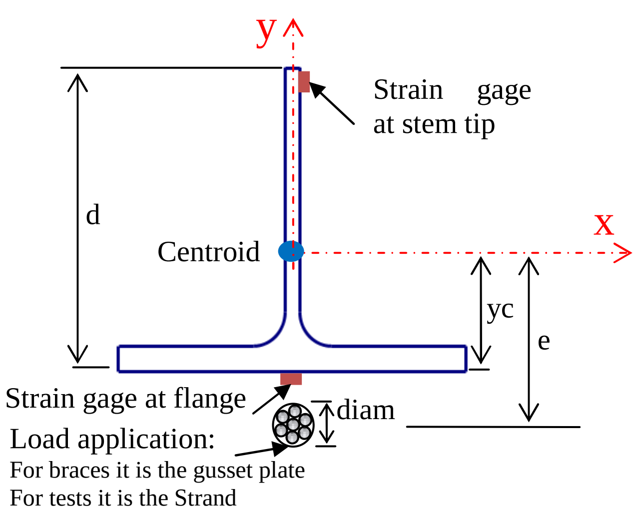
2. Review of Literature

Gordon presents a calculation procedure to obtain the design capacity of a horizontal WT brace under an eccentric compression load following the norms indicated in the AISC Steel Construction Manual (AISC, 2005) to consider the P-δ effect (Gordon, 2010). The procedure considers flexural buckling about the strong and weak axis, torsional buckling, flexural-torsional buckling of members with slender elements, self-weight, local buckling, and the interaction between compression and flexion. For this project, the theoretical calculations are developed using the spreadsheet from Microsoft Office (MS Excel, 2010).

3. Theoretical Calculations with Spreadsheets

The procedure used by Gordon and the current specifications (AISC, 2010) are used to develop the spreadsheet "UHD-WT-Brace" which is able to verify the capacity of WT braces under eccentric compression load. This spreadsheet permits the inclusion of testing loads, and modifications to the nominal geometry. The spreadsheet permits calculate the compression capacity which is defined as the load producing a stress ratio of 1. The stress ratio is defined as the sum of the actual stress divided by the design stress, considering the compression and flexural solicitations due the eccentric load. Figure 1 shows the cross section used for calculations, and Figure 2 shows the main page of the spreadsheet.

The spreadsheet permits to change the eccentricity, observing that for zero-eccentricity the load capacity may be duplicated, which is totally unsafe for an eccentric connection.



Legend:

A:	Cross Section Area
d:	Depth of WT
yc:	Distance from top of flange to centroid
Ix:	Moment of inertia respect to centroidal x-axis
Sx:	Elastic section modulus for stem tip
Sxc:	Elastic section modulus for flange
rx :	radius of gyration about x-axis
Zx:	Plastic section modulus about x-axis
Iy:	Moment of inertia respect to y-axis
rx:	Radius of gyration J: Torsional constant
ro:	Polar radius of gyration about shear center.
H:	Flexural constant
e:	Eccentricity between the force application (strand) and the centroid of the WT shape

Figure 1. Cross Section of WT Brace and Legend for Spreadsheets

The spreadsheet "UHD-Test-WT-Brace" is used to compute the deflections of a WT brace under an eccentric compression load. This spreadsheet considers the P-δ effect, a second-order analysis consisting in the increase of the end-moments due to the deflection. The calculations are done step-by-step with small load increments. The eccentric load produces end moments calculated as the product of the load by its eccentricity with respect to the centroid of the WT-shape.

The first step considers the end moments as the product of the initial eccentricity times the initial compression force, permitting to compute the initial deflection and, therefore, a new eccentricity that is used for the following step to compute the new deflection and eccentricity. Before yielding the deflections are computed with the modulus of elasticity of steel (Es) and after yielding, the spreadsheet considers a zero-modulus of elasticity and the program stops. Figure 3 shows the data used, the first steps of this non-linear analysis, and the chart load vs. deflection for the brace B1. The following equations are used for the step-by-step calculations:

eo = yc + diam/2 + camber (eq. 1)

$P_i = P_{i-1} + \Delta P$ before yielding, or $P = P_{i-1}$ after yielding (eq. 2)

$e_i = eo + \delta_{i-1}$ (eq. 3)

$M_i = P_i \,.\, e_i$ (eq. 4)

$E = Es$ before yielding, or $E = 0$ after yielding (eq. 5)

$\Delta M_i = M_i - M_{i-1}$ (eq. 6)

$\Delta\delta_i = \Delta M_i\, L^2 / (8\, E\, Ix)$ (eq. 7)

$\delta_i = \delta_{i-1} + \Delta\delta_I$ (eq. 8)

$\sigma_{top} = M \,.\, Sx$ (eq. 9)

$\sigma_{bott} = M \,.\, Sxc$ (eq. 10)

$\varepsilon_{top} = \sigma_{top} / E$ (eq. 11)

$\varepsilon_{bott} = \sigma_{bott} / E$ (eq. 12)

Where:

ΔP: Load increment for the step-by-step method (kip)

eo: Initial eccentricity (in)

P_i: Load used for the calculations of step i (kip).

e_i : Eccentricity for calculations of step i (in)

M_i : End moment for calculations of step i (kip-in)

$\Delta\delta_i$: Increment of deflection at step I (in)

δ_i : Deflection at step I (in)

E: Modulus of elasticity for step i.

Es: 29000 ksi

σ_{top} : Stress at stem tip (ksi)

σ_{bott} : Stress at flange (ksi)

ε_{top} : Strain at stem tip

ε_{bott} : Strain at flange

4. TEST SETUP AND RESULTS

Two braces, B1 and B2, consisting of WT5x11 shapes with 15'0" length are tested under eccentric compression according to the setup shown in Figure 4. Both WT shapes are obtained cutting a W10x22 along its web center line and therefore they have same steel properties and slightly different geometric properties. Table 1 shows the nominal and average dimensions obtained after measurements of the cross section at every 1'0". The correction factor is used to modify the nominal geometric properties.

Table 1 Dimensions and Geometric Properties of WT5x11 Tested

Element	**Area (in^2)**	**d (in)**	**yc (in)**	**d-yc (in)**	**Ix (in^4)**	**Sx (in^3)**	**Sxc (in^3)**	**rx (in)**	**Zx (in^3)**	**Iy (in^4)**	**ry (in)**	**J (in^4)**	**ro (in)**	**H**
Nominal	3.24	5.09	1.07	4.02	6.88	1.72	6.11	1.46	3.02	5.71	1.33	0.119	2.16	0.830
B1	3.40	5.06	1.04	4.02	6.94	1.72	6.64	1.42	3.03	6.07	1.33	0.145	2.13	0.844
C.F.	1.05	0.99	0.97	1.00	1.01	1.00	1.09	0.98	1.00	1.06	1.00	1.220	0.98	1.020
B2	3.49	5.08	1.04	4.03	6.99	1.76	6.82	1.43	3.10	6.45	1.36	0.153	2.14	0.847
C.F.	1.08	1.00	0.97	1.00	1.02	1.02	1.12	0.98	1.03	1.13	1.02	1.290	0.99	1.020

Note: C.F. is the correction factor for the geometric properties.
Other legends are shown in Figure 1

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DESIGN BY: Jorge Tito DATE: June 4, 2011 SUBJECT: SHEET N° OF

CHKD. BY: DATE: **Brace B2** JOB N°

FILE: I:\PAPERS\Paper-LACCEI-13\[UHD-WT-Brace.xlsm]WT-Test-B2 REVISION N°

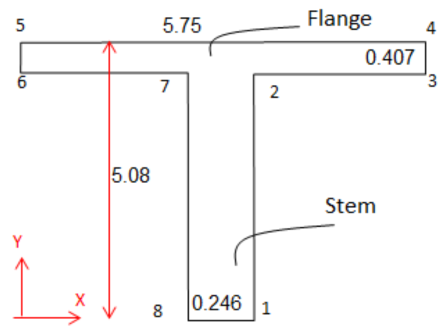
Program Name: **UHD-WT-Brace**

Reference: ANSI / AISC 360 -10, Tables for Eccentrically Loaded by Mark Gordon

Consider self-weight? Yes 1

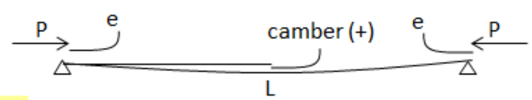
Angle of Bracing with hrzt = 180 deg

	T-Section	**Factor**	**Modified Property**
	WT5X11		
W =	11 lb / ft	1.08	-11.88 =ROUND(11*1.08*COS(RADIANS(180)), 3) =
Ag =	3.24 in^2	1.08	3.49
d =	5.09 in	1.00	5.08
tw =	0.24 in	1.03	0.246
bf =	5.75 in	1.00	5.75
tf =	0.36 in	1.13	0.407
Ix =	6.88 in^4	1.02	6.99 in^4
Sx =	1.72 in^3	1.02	1.76
rx =	1.46 in	0.98	1.43
yc =	1.07 in	0.97	1.04 in
Zx =	3.02 in^3	1.03	3.10
Iy =	5.71 in^4	1.13	6.45 in^4
ry =	1.33 in	1.02	1.36
Qs =	0.834	1.00	0.834
J =	0.119 in^4	1.29	0.153
ro =	2.16 in	0.99	2.14
H =	0.83 in	1.02	0.847
Sxc =	6.43 in^3	1.12	7.17
k =	0.94 in	Using kdet, for detailing	



Point	X	Y
1	5.00	2.00
2a	5.00	6.14
2b	5.53	6.67
3	7.75	6.67
4	7.75	7.08
5	2.00	7.08
6	2.00	6.67
7a	4.22	6.67
7b	4.75	6.14
8	4.75	2.00

Radius at 2 and 7= 0.53



DATA

Length of the element, L = 15 ft

Effective length factor, K = 1

Allowed axial force, Pa = 22.5 kip ASD Positive is compression

Ultimate axial force, Pu = 26.2 kip LRFD Positive is compression

Camber: 5/8 in

Thickness of gusset plate, tgp = 1/2 in

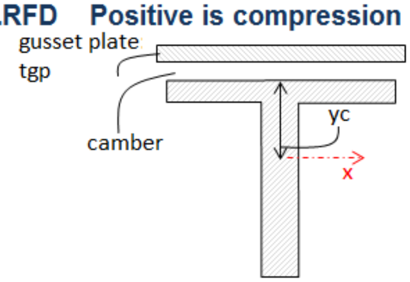
Then, the eccentricity is, ecc = yc + camber + tgp / 2 = 1.92 in

Modulus of elasticity of steel, Es = 29000 ksi

Modulus of Poisson = ν = 0.29

Shear modulus of Steel, Gs = =Es / 2 / (1+nu) = 11240 ksi

Yielding strength of steel, Fy = 62 ksi



Moments about X-X:

Moment due Self-Weight at center-span, M_{Dsw} = -4.01 k-in

Additional moment due dead loads, M_D = 0.00 k-in Load factor dead load = 1.00

Moment due live load at center-span, M_L = 0.00 k-in Load factor live load = 1.00

Service Additional Moment, Moa: =Mdsw + AddMd + AddML = -4.01 k-in

Ultimate Additional Moment, Mou: =Mdsw*LFdead + AddMd*LFdead + AddML*LFlive = -4.01 k-in

Safety Factor for compression, Ωc = 1.00

Safety Factor for bending, Ωb = 1.00

Reduction factor for compression, ϕc = 1.00

Reduction factor for bending, ϕb = 1.00

		STRESS RATIO	**w/o ecc**
Pr / (Pn/SFc) + Mr / (Mn / SFf) =	**=0.4622 + 0.0003 =**	**1.000 Section is OK**	**0.46**
Pru / (fc Pn) + Mru / (fc Mn) =	**=0.5389 + 0.0002 =**	**1.000 Section is OK**	**0.54**

Figure 2: Main Page of the Spreadsheet "UHD-WT Brace", Verifies a WT Brace under Eccentric Compression Load.

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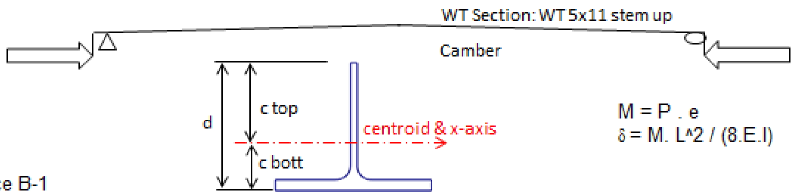
DESIGN BY:	J. Tito	DATE: June 6 - 2011	SUBJECT:	SHEET N° OF
CHKD. BY:		DATE:	**BRACE B1**	JOB N°
FILE: H:\PAPERS\Paper-LACCEI-13\[WT-TEST-6.24.2011-rev2.xlsm]NonLinearCalc-B1				REVISION N°
Program Name:			**UHD-TEST-WT-BRACE**	



Brace B-1
Steel: ASTM A992
Fy = 62 ksi
E = 29000 ksi

Geometry of WT Shape:

	A (in^2)	d (in)	Yc (in)	Ix (in^4)	c top (in)	c bott (in)	Observations
Nominal	3.32	5.09	1.07	6.88			From AISC Manual
Factor	105%	99%	97%	101%			Average after lab measurements
Test	3.49	5.06	1.04	6.94	4.02	1.04	Dimensions used for calculations

Pre-Test conditions

Length, L=	15 ft =	180 in	
Strand diameter:	1/2 in		
Diam/2 =	0.25 in		
Camber	5/8 in		
Initial eccentricity, e=	1.92 in		Initial eccentricity, e =Yc + Diam/2 + Camber

P-δ Effect Inc-P 0.2 kip

P kip	e in	M kip-in	E ksi	Inc-Disp in	Disp in	P kip	σ top ksi	σ bott ksi	ε top x 10^-6	ε bott x 10^-6
0	1.92	0.00	29000	0.0000	0.000	0.00	0.00	0.00	0	0
0.2	1.92	0.38	29000	0.0077	0.008	0.20	0.16	-0.11	6	-4
0.4	1.92	0.77	29000	0.0078	0.015	0.40	0.33	-0.23	11	-8
0.6	1.93	1.16	29000	0.0078	0.023	0.60	0.50	-0.35	17	-12
0.8	1.94	1.55	29000	0.0079	0.031	0.80	0.67	-0.46	23	-16
1	1.95	1.95	29000	0.0080	0.039	1.00	0.84	-0.58	29	-20

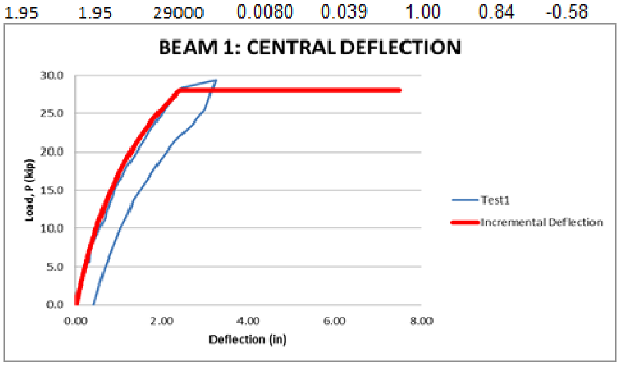


Figure 3: Non-Linear Analysis of an Eccentric Load using the Spreadsheet "UHD-Test-WT-Brace".

A connector device is designed and constructed using welded steel plates with the objective to permit stretching the strand using a hollow jack. Figure 5 shows the detail of the connector device observing that the hole for the strand is at top of the WT flange. This device is designed to support and transmit the jacking load to the WT shape through the welded plates and 4 bolts working in single shear, simulating a typical gusset plate connection.

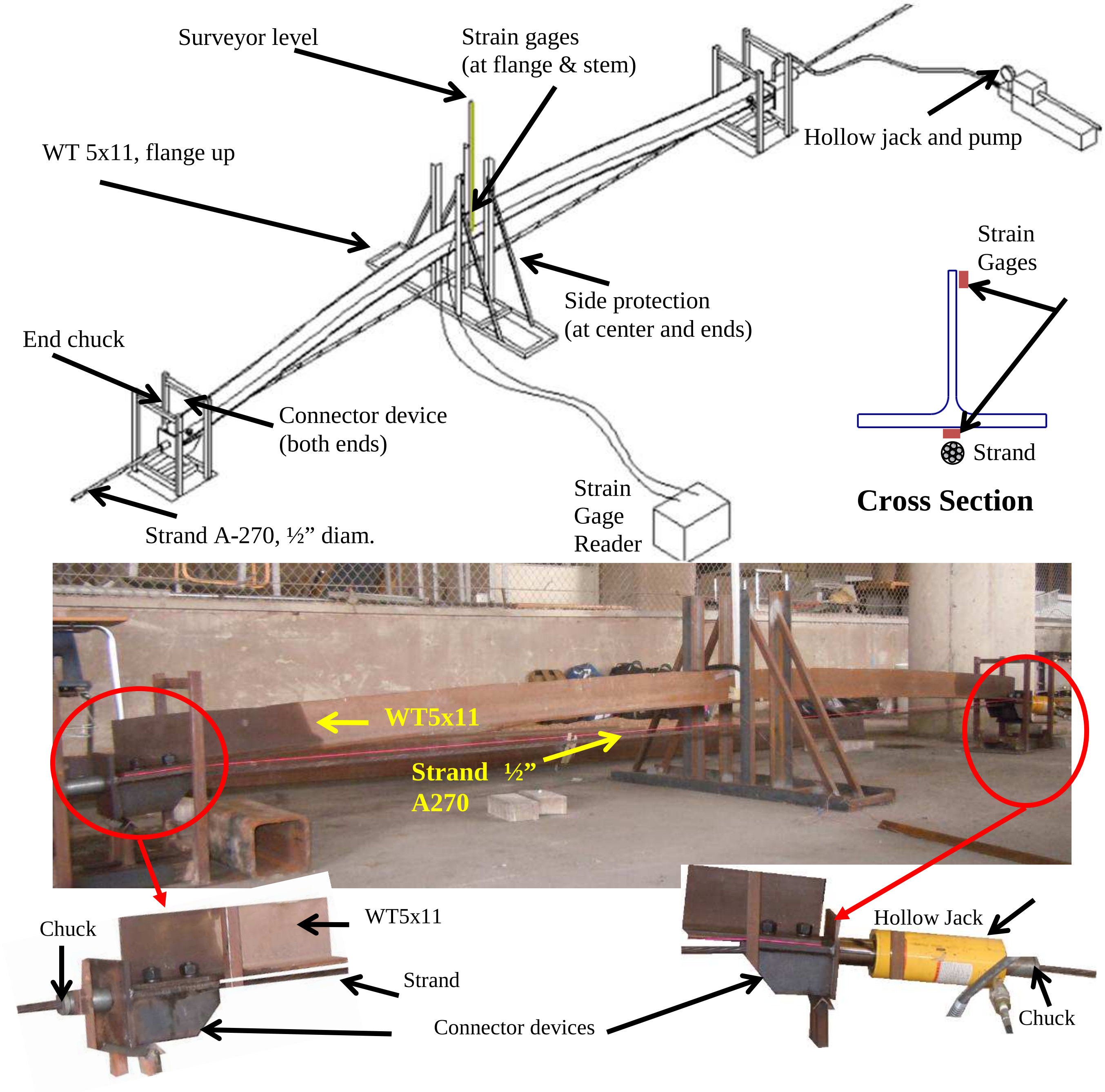
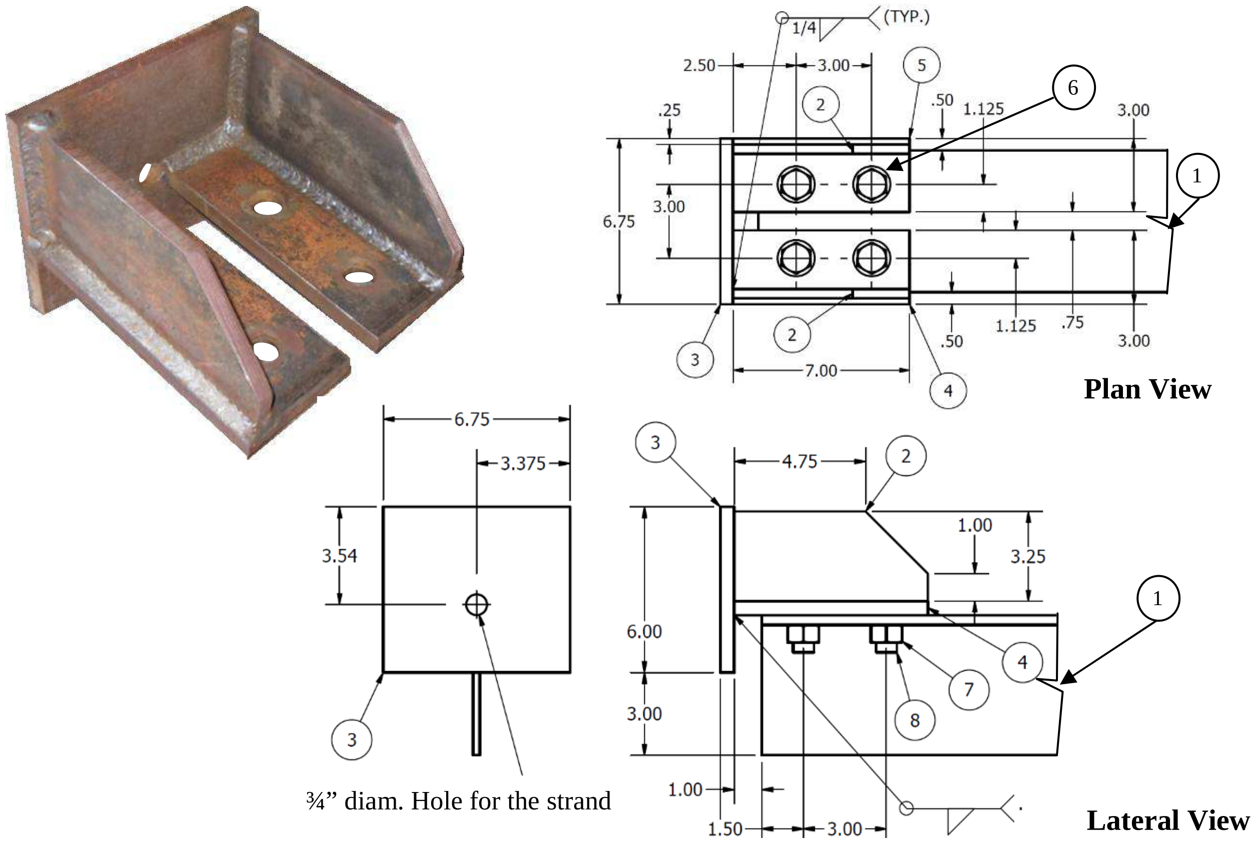


Figure 4: Setup for Eccentric Compression Test of a WT Brace.

The load is applied at one end with a 20 ton hollow hydraulic jack (Enerpac RCH-206) reacting against the connector device and a chuck attached to the ½" diameter strand grade 270. At the other end there is a chuck reacting against the connector device. This loading system permits the application of eccentric loads from 0 to 30 kips, limited by the strand capacity. The central deflection of the WT brace is measured with a surveyor level with precision of 3/64". A strain gage indicator (P3 from Vishay) is used to read two strain gages attached to the central section of the WT brace, one at top of flange and other close to the stem tip.



Legend

1: WT5x11
2: 4 Plates 3/8” x $3\frac{1}{4}$” x 7”
3: 2 Plates ½” x $6\frac{3}{4}$” x 6”
4: 2 Plates ½” x 3” x 7” (right)
5: 2 Plates ½” x 3” x 7” (left)
6: 8 Washers, ¾” diameter
7: 8 Nuts A325, ¾” diameter
8: 8 Bolts A325, ¾” diameter

Figure 5: Assembly of End Connector Used to Apply the Eccentric Load

As shown in Figure 6, the brace B1 receives four cycle of loading-unloading during the first lab session and an additional cycle after yielding, applied during a second lab session. The load #1 consists of a loading from 0 to 24.1 kips without permanent deflection after unloading. The load #2 is a loading from 0 to 12.8 kips. The load #3 consists of loading from 0 to 28.4 kips with 2.6” deflection, the unloading is until 5.7 kips. The next load #4 starts from 5.7 kips ending at 29.3 kips with 3.3” deflection, after unloading there is a permanent deflection of 0.42” because the steel yields. The load #5 is applied to the deformed brace loading until 29.3 kips with 7.5” deflection; after unloading, the permanent deflection is 2.95”.

During the tests, the flange strains are negative because it is in compression and the stem strains are positive because it is in tension. Both strains have a non-linear behavior inside the elastic range, observing that the stem tip reaches tension yielding stress at 27.4 kips, and after this load the slope of the curves decreases significantly. The flange reaches yielding after large deflections of the brace, sustaining the maximum load of 29.3 kips; unfortunately, the strain at this load level is not read.

Figure 6 also shows the deformation and strains of brace B2 which is loaded and unloaded just one cycle. The loading is from 0 to 29.3 kips; presenting yielding after approximately 27.4 kips with 2.3” deflection. The maximum deflection is 7.5” at 29.3 kips, and the permanent deflection is 3.3” after unloading. The flange shows compression strains and the stem has tension strains. Both of them present non-linear behavior for the elastic range. The strain gage located at stem tip failed at the early load of 10 kips, not permitting appreciate yielding.

The flange reaches yielding after large deflections of the brace, sustaining the maximum load of 29.3 kips; unfortunately, the strain at this load level is not read. In general, both braces have similar behavior.

5. DISCUSSION OF RESULTS

The deflection at center of the specimen and the strains from the flange and the stem tip of the central section are compared with the theoretical results from the spreadsheets explained before. The properties used for calculations are obtained from the specifications for the steel ASTM A-992 as it is usual for W shapes (ASTM 2011). The specification indicates the yielding stress, Fy, is between 50 ksi and 65 ksi; and the modulus of elasticity, Es, is 29000 ksi. After evaluation of the brace B1results it is decided to continue the calculations using Fy as 62 ksi, which is inside the specified limits.

The spreadsheet "UHD-WT-Brace" permits estimating the maximum load that the brace can resist. After inputting the setup values and using a reliability factor of 1.0, the maximum estimated compression load is 26.2 kips, that is close to the 27.4 kips that produce yielding in both tests.

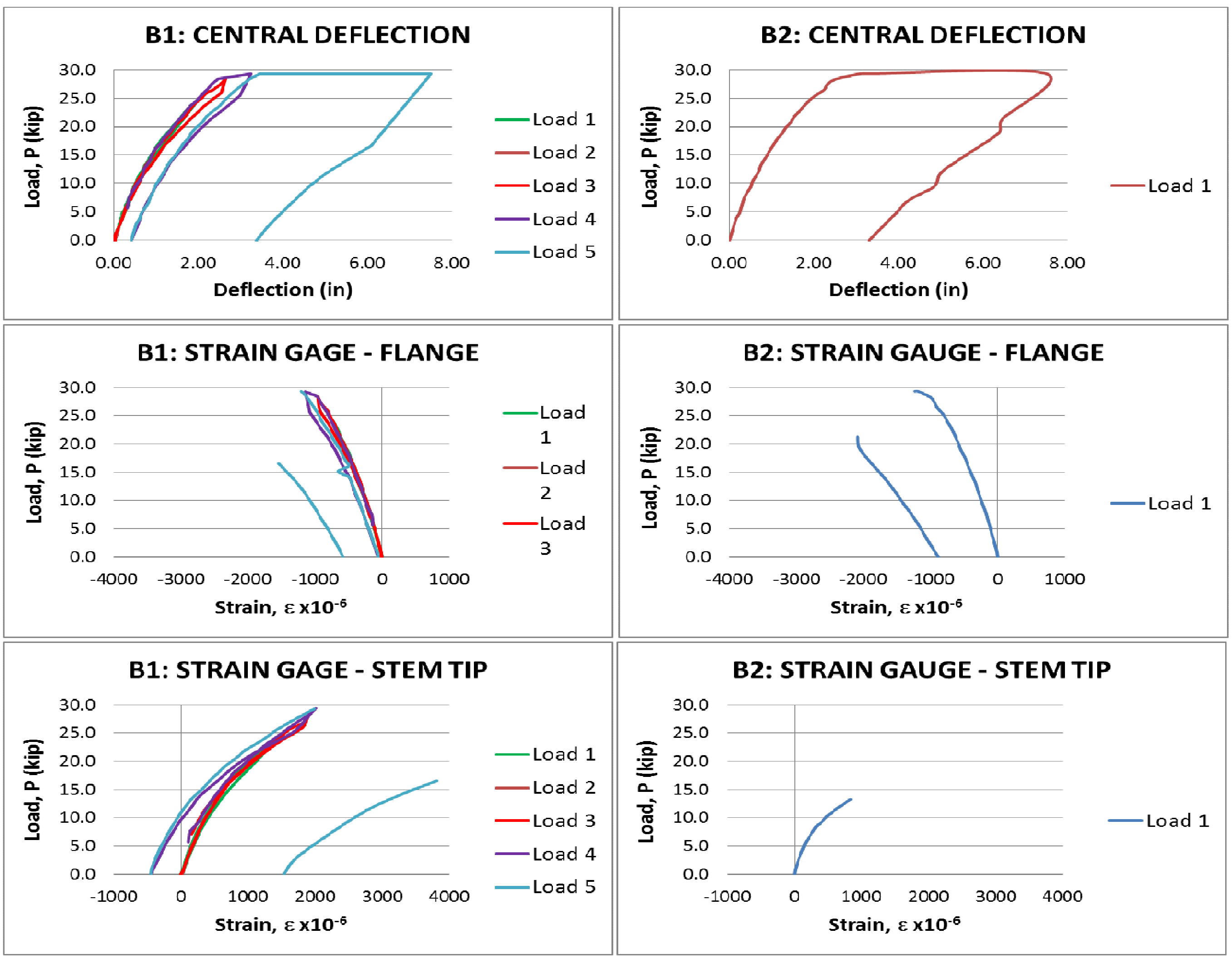


Figure 6: Deflection and Strain Gage from Tests on Braces B1 and B2

Figure 7 shows the comparison between the calculations using the spreadsheet "UHD-WT-Test-Brace" and the test results. The spreadsheet uses the setup values for the initial eccentricity and also considers the self-weight of the brace. The theoretical curves for deflections and strains agree very well with the results from the tests. For brace B1, the load #3 is used for comparison and in case of brace B2, there is only one loading.

The spreadsheets use the correction factors of the geometric properties shown in Table 1, and also the initial camber of the WT shapes. The location of the strand center-line respect to the flange is defined by the hole of the connector plate, as shown in Figure 5; note that for the spreadsheet this dimension is equivalent to half of the gusset plate thickness. The initial eccentricity is given by the sum of the centroid (yc), camber, and the distance from the strand center-line to the flange. The eccentricity changes with the deflection of the brace and therefore the end moments also change. The load applied according to the setup indicated in Figure 4 produces upward deflections.

The brace self-weight is considered by the spreadsheets as negative because the setup uses the WT-section with the flange down, meaning that the self-weight deflect the brace downward.

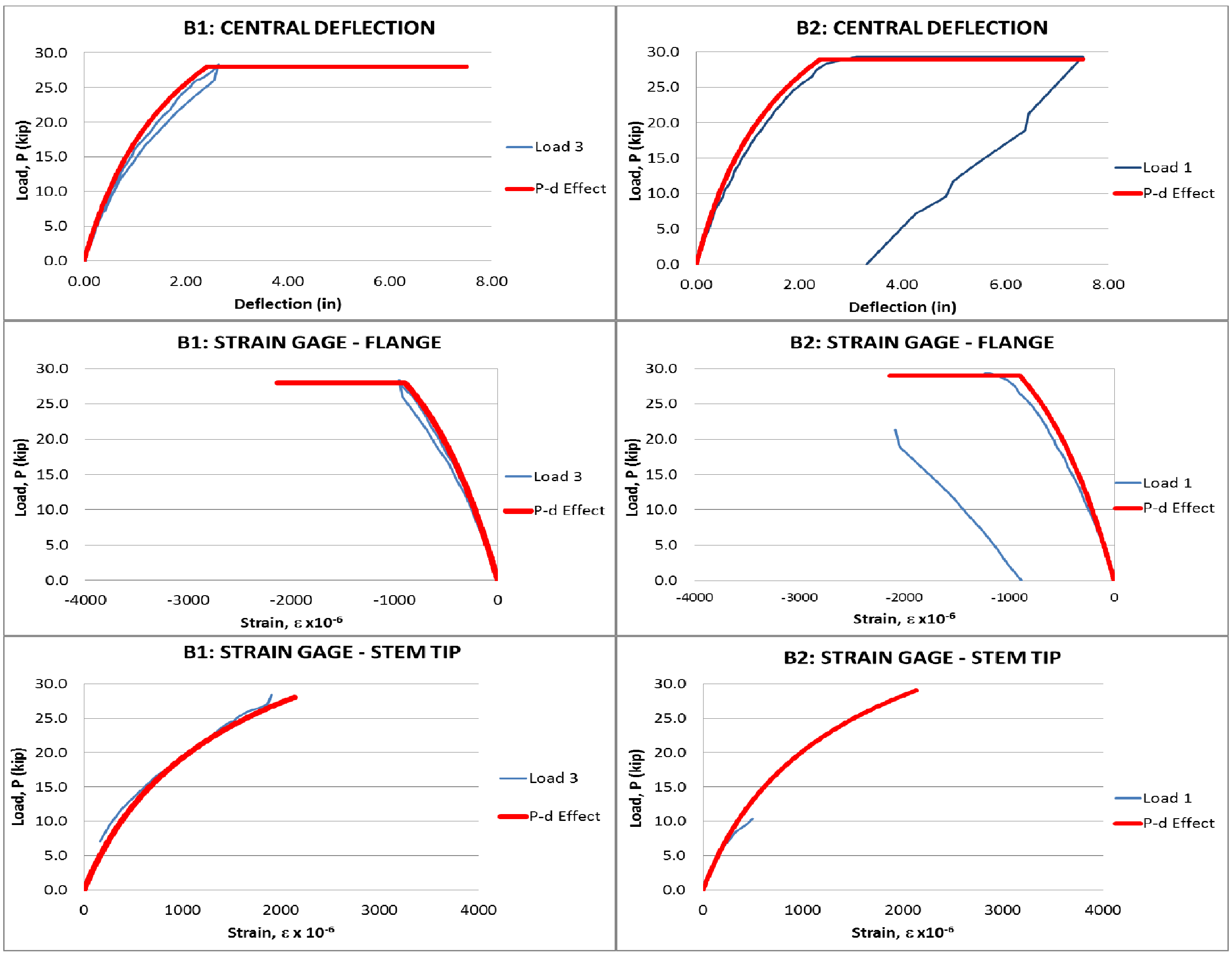


Figure 7: Comparison of Deflection and Strain Gage from the Spreadsheet "UHD-Test-WT-Brace" and the Tests on Braces B1 and B2

6. CONCLUSIONS

Two braces with WT5x11 shape and 15’0” long are tested under eccentric compression load. The setup includes a hollow jack that stretch a strand reacting against connector devices attached to the flange, which simulates a typical gusset plate connection. The tests permit reading the central deflection and the strains at stem tip and flange.

The theoretical calculations are obtained from two methods, the current AISC code and the P-δ methods. The code based spreadsheet “UHD-WT-Brace” provides the eccentric compression capacity of the brace considering the actual initial conditions. This spreadsheet shows that the eccentricity cannot be neglected because the load estimated is unsafe, inclusive in the order of 100% error or more.

Another spreadsheet “UHD-WT-Test-Brace is developed to estimate the non-linear deformations due to the P-δ effect obtaining the theoretical load vs. deflection and load vs. strain curves. The results of the spreadsheets compare very well with the test results.

The strength and behavior of a WT brace may be estimated with the current code and following a non-linear method that consider the P-δ effect.

7. ACKNOWLEDGMENTS

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8. AUTHORIZATION AND DISCLAIMER

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