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QUASI-STATIC CYCLIC TESTING OF INDIVIDUAL FULL-SCALE CIRCULAR STEEL TUBULAR BRACES EQUIPPED WITH CAST CONNEX™ HIGH-STRENGTH CONNECTORS

by

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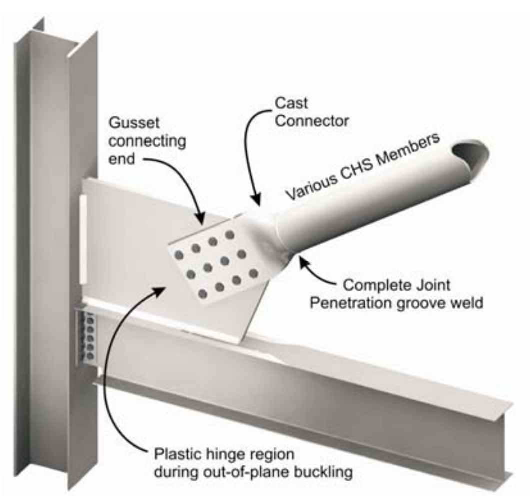
1. INTRODUCTION

Seismic-resistant cast steel structural connectors for circular HSS (CHS) steel braces were developed at the University of Toronto (de Oliveira et al. 2006, 2008a, 2008b). The technology has since been licensed to Cast Connex Corporation, which now markets the connectors under its High-Strength Connector product line. A brace assembly featuring one of these connectors is depicted in Figure 1.1. At one end, the connectors are designed with a circular shape and preparation to allow for complete joint penetration shop welding to a range of tubular braces of a given outer diameter for the full development of their expected yield strength. At the other end, the connectors are shaped such that a double shear bolted splice connection or longitudinal fillet welds can be used for connecting the shop-welded brace-connector assembly to conventional gusset plates secured to the beam-column intersection. Nominally, a free length equal to two times the gusset plate thickness is left in the gusset plates beyond the ends of the connectors to accommodate the inelastic rotations associated with brace out-of-plane post-buckling deformations. These characteristics are intended to meet the AISC seismic requirements for Special Concentrically Braced Frames (AISC 2005a) and the CSA-S16 seismic provisions for Moderately Ductile (Type MD) Braced Frames and Braced Steel Frames with Limited Ductility (Type LD) (CSA 2005).

This report describes a cyclic test program that was conducted on four brace specimens to evaluate the performance of the brace connectors for bracing members of typical lengths with boundary conditions representative of typical field conditions. The braces were fabricated with the heaviest walled circular tubing conforming to ASTM A500 Grade C (ASTM 2007) or equivalent for each brace size. The brace sizes tested were HSS 102x8.0 (HSS 4.000x0.313), HSS 141x9.5 (HSS 5.563x0.375), HSS 168x13 (HSS 6.625x0.500), and HSS 219x16 (HSS 8.625x0.625). Figure 1.2 shows some of the test specimens as received in the laboratory. The test protocol applied during the testing was based on the qualifying cyclic test program for buckling-restrained braces specified in the 2005 AISC seismic provisions.



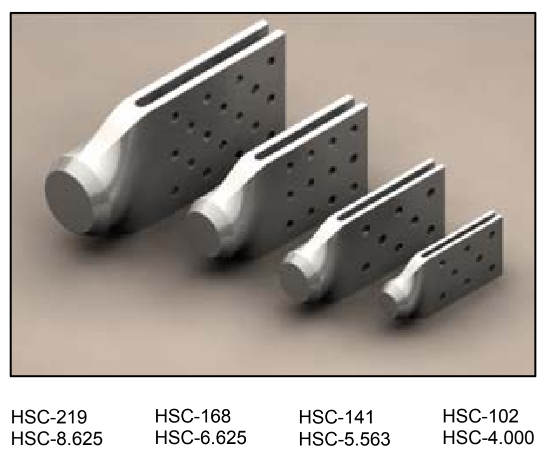


Fig. 1.1 *Cast ConneX™ High-Strength Connectors for circular hollow steel braces*

Fig. 1.2 *Test specimens featuring Cast ConneX™ High-Strength Connectors as received in the laboratory*

The test program was conducted at the Hydro-Québec Structural Engineering Laboratory at École Polytechnique de Montréal as part of a collaborative research effort between University of Toronto, École Polytechnique, and Cast Connex Corporation.

Section 2 of the report describes the test setup, specimens, displacement protocol, and all ancillary tests. The observed brace performance and test results are presented in Section 3. Section 4 provides the overall conclusions for the test program.

2. TEST PROGRAM

2.1 Test Setup

The tests were conducted on single brace-connector assemblies in a 12 MN (2,700 kip) capacity MTS load frame with boundary conditions that replicated the end connection detail typically encountered in concentrically braced steel frames featuring a single diagonal brace. Figure 2.1 shows the load frame used in the test program. The frame can accommodate test specimens as large as 3 m (10'-0") wide and 8.1 m (26'-6") tall. The height of the frame's crosshead is adjusted to the height required to meet the test specifications. The crosshead supports a high performance double-acting, double-ended structural actuator with a fatigue rated force capacity of 10 MN (2,250 kip) in tension and compression. The actuator has a total stroke of 500 mm (20") and is equipped with a built-in displacement transducer and a load cell having a fatigue rated capacity of 10 MN. The actuator is powered by 1360 lpm (360 gpm) hydraulic power supply with 19 l (5 gal) pressure and return accumulators. An MTS Flextest GT digital controller with a 2096 Hz internal clock was used to control the actuator.

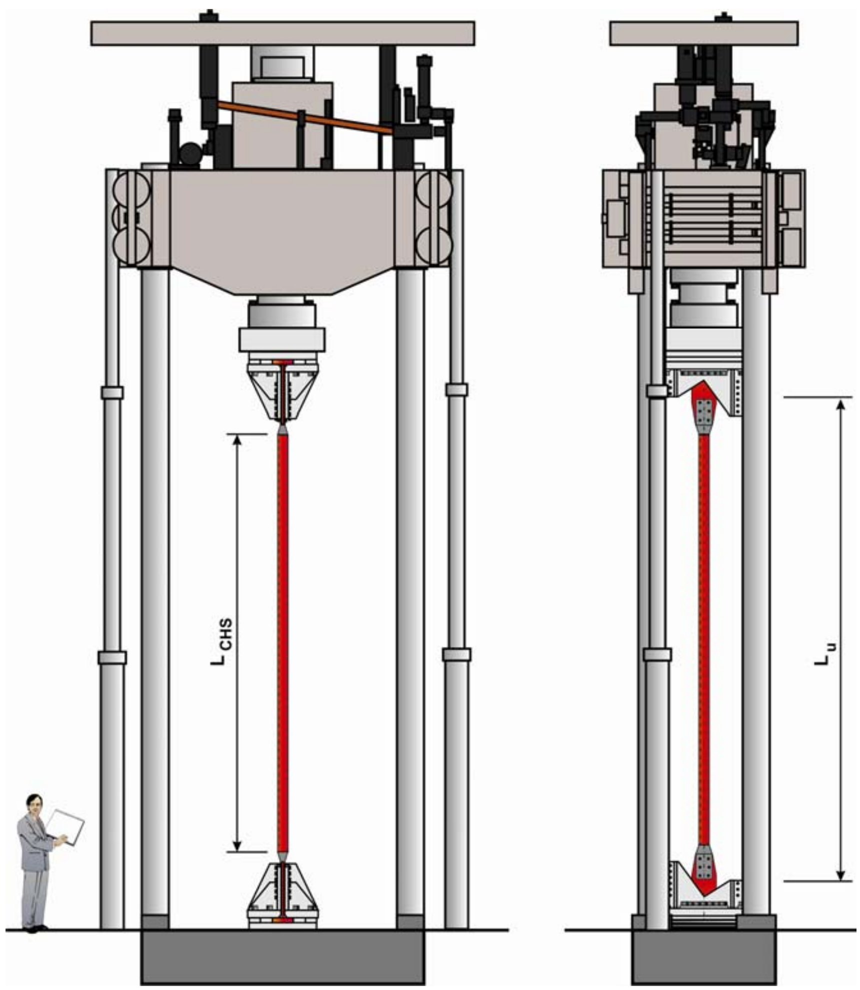


Fig. 2.1 *Test load frame with brace specimen: a) Elevation view from South); b) Side view from West*

The reference bracing configuration adopted for the study is shown in Figure 2.2. The brace inclination with respect to the horizontal is 35° and a single tapered gusset plate welded to the beam and column is used to connect the brace to the frame. The gusset plate is detailed to accommodate the inelastic rotation associated with brace out-of-plane buckling deformations. This is achieved by leaving a free length equal to two times the gusset plate thickness, t_g, between the line of restraint and the end of the cast connectors, as recommended in the AISC 2005 seismic provisions for special concentrically braced steel frames. The unbraced length of the brace, L_u, is given by the length between the plastic hinges that form in the gusset plates during overall brace buckling. This is equal to the distance between the centers of the two end plastic hinges, i.e. 1.0 t_g beyond the ends of the connectors.

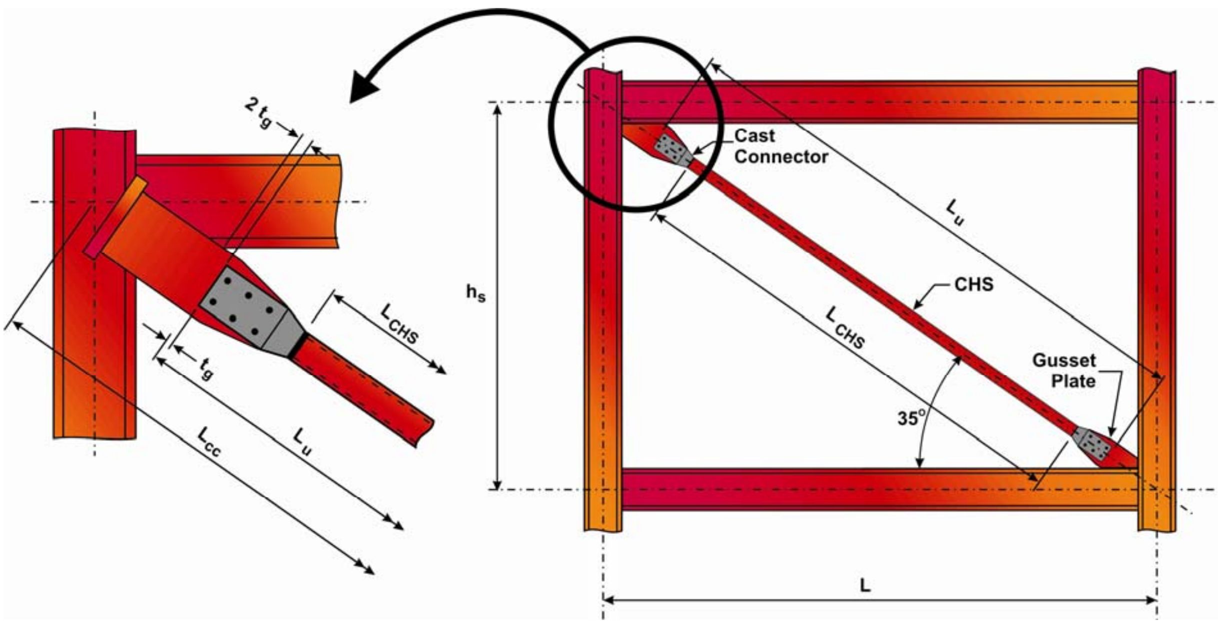


Fig. 2.2 *Reference bracing configuration*

Specially designed and fabricated grips bolted to the MTS frame and actuator were used to replicate the end conditions of the reference bracing configuration, as shown in Figure 2.3. Tapered gusset plate anchorages were fabricated for each test. The gusset plate anchorages were terminated with a T-stub designed to develop the applied tension and compression forces through direct bearing. Pretensioned ASTM A490 bolts acting in double shear were used to connect the cast connectors to the gusset plates. The number and diameter of the bolts used in each assembly are given in Section 2.2 (Table 2.1). Although pretensioned bolts were used, the connection was designed as a bearing-type connection.

Laboratory installation of each brace-connector assembly in the load frame involved first installing the two T-stub gusset plate anchorages in the specially designed grips. The brace-connector specimen was then bolted to the gusset anchorage connected to the actuator then lifted above and subsequently bolted to the lower gusset anchorage, as shown in Figure 2.4.

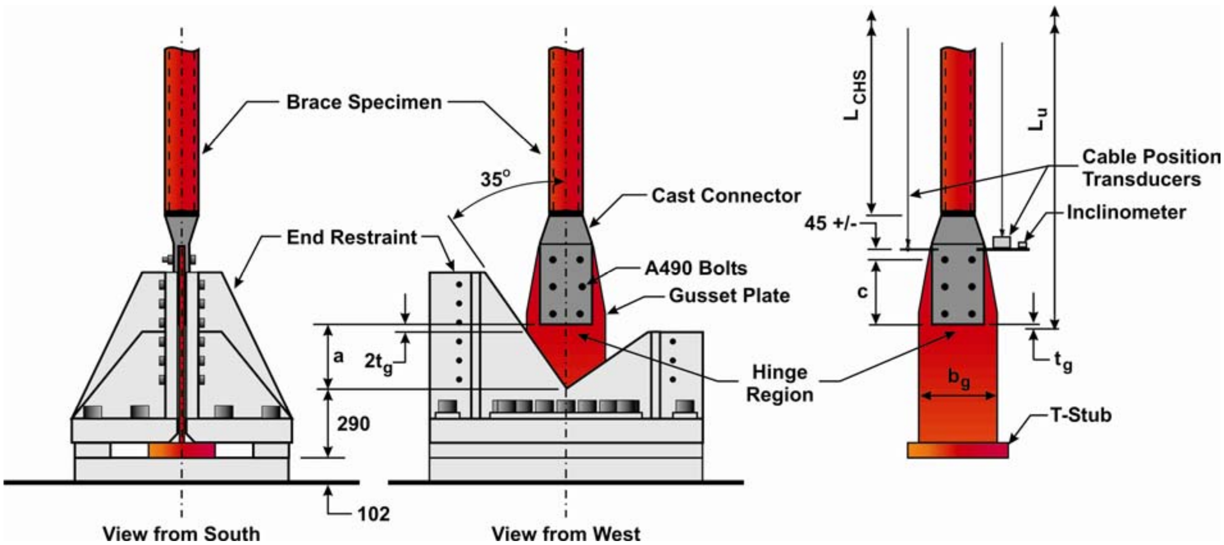


Fig. 2.3 *Detail of the grips and end connections*

Fig. 2.4 *Lowering the brace-connector assembly to connect the specimen to the lower gusset plate (view from the S-W, HSS 102x8.0 Specimen)*

2.2 Instrumentation

The applied force was monitored using the actuator's load cell and white-wash was applied to the brace assemblies to assist in the observation of yielding. Two string potentiometers measuring deformations over the length of the tubular sections were used to control the axial deformations applied to the brace specimens. The potentiometers were mounted on the North and South sides of each specimen, just beyond the ends of the HSS. Potentiometers were also set up to measure the in- and out-of-plane deformation of the brace at its mid-length during the testing. The potentiometers had the following manufacturer's specifications: CELESCO model PT01A ±1016 mm (±40 inches) and ±1270 mm (±50 inches) with a precision of 1.27 mm (5 one-hundredths of an inch). Inclinometers were affixed to the cast connectors to measure the out-of-plane rotation of the brace ends during buckling. The inclinometers were CROSSBOW Model CXTLA01 with a rotation range of ±20º and a tolerance of ±0.04°. One of the potentiometers used to measure the brace assembly's axial deformation and an inclinometer are visible in Figures 2.5.

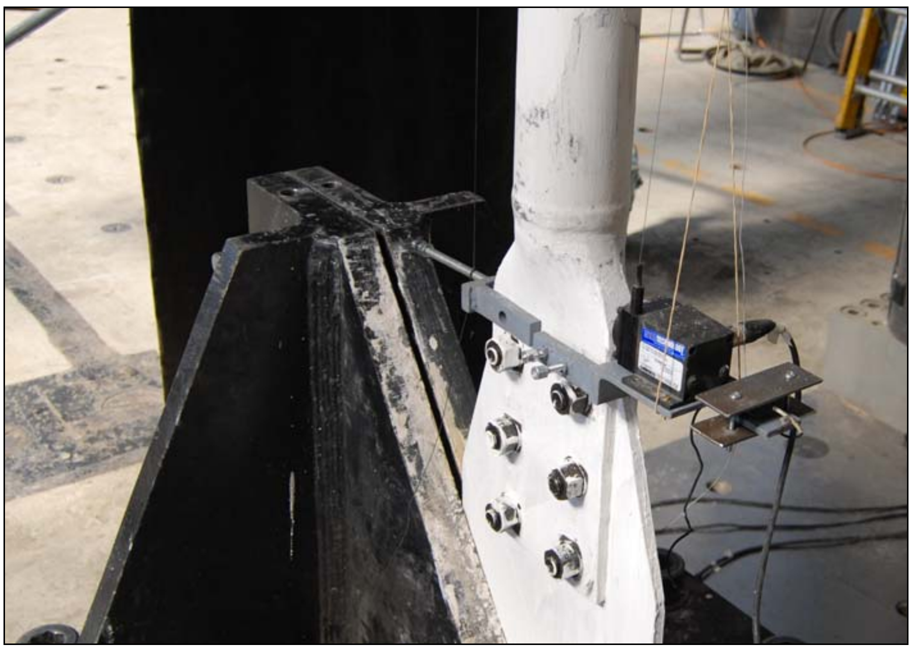


Fig. 2.5 *Lower specimen end after having been bolted to the gusset plate and installation of the instrumentation (view from the S-W, HSS 102x8.0 Specimen)*

2.3 Test Specimens

All of the cast connectors were shop welded to the HSS braces by the Canam Group Inc. (Québec). Welding between the connectors and the HSS segments is discussed further in Section 2.4 of this report. All of the braces were fabricated using circular tubing conforming to ASTM A500 Grade C except for the HSS 219x16 member, which was produced to ASTM A106 (ASTM 2008). However, according to the mill test certificate, results from tensile tests on coupons, and measurements taken in the laboratory, the shape met all of the relevant structural requirements for A500 grade C including minimum yield and tensile strengths and sectional geometry characteristics. CHS produced to ASTM A500 Grade C has a minimum specified yield strength, F_y, of 317 MPa (46 ksi), a minimum specified tensile strength, F_u, of 427 MPa (62 ksi), and a minimum elongation of 21% in 50 mm (2-inches). Table 2.1 provides the specified geometrical properties of the specimens. The specimens were numbered from 1 to 4 and were each fabricated using the corresponding HSS section shown in Table 2.1. Detailed drawings of the specimens are provided in Appendix A.

Table 2.1 *Specified geometric properties of the test specimens*

No.	Shape	L_u * [mm] (ft.-in.)	L_{CHS} * [mm] (ft.-in.)	t_g x b_g † [mm] (in.)	Bolts	a ‡ [mm] (in.)	c ‡ [mm] (in.)
1	HSS 102 x 8.0	4293 (14'-1")	3503 (11'-6")	13 x 318 (½"x12½")	6 – ¾" Ø	252 ($9^{15}/_{16}$")	216 (8½")
2	HSS 141 x 9.5	6617 (21'-8½")	5564 (18'-3")	19 x 330 (¾"x13")	6 – 1" Ø	274 ($10^{3}/_{4}$")	279 (11")
3	HSS 168 x 13	6147 (20'-2")	5004 (16'-5")	25 x 391 (1"x$^{3}/_{8}$")	8 – 1" Ø	330 (13")	279 (11")
4	HSS 219 x 16	6160 (20'-2½")	4650 (15'-3")	32 x 511 (1¼"x$20^{1}/_{8}$")	12 – 1" Ø	428 ($16^{7}/_{8}$")	394 (15½")

* Refer to Figures 2.1 and 2.2
† Refer to Figure 2.3 for b_g, t_g is the thickness of the gusset plate
‡ Refer to Figure 2.3

Table 2.2 gives the nominal properties of the brace cross-sections: t_{des} (design wall thickness), A_g (gross cross-sectional area), and r (radius of gyration). The effective brace slenderness ratio, KL/r, is computed assuming an effective length, KL = 1.0 L_u. As shown, all of the braces tested have intermediate slenderness varying from 85 to 141.

Table 2.2 *Structural design properties of the test specimens*

No.	HSS Designation	t_{des} * [mm] (in.)	A_g [mm^2] (in.^{2})	r [mm] (in.)	KL/r [ ]	$1.1R_yP_n$ [kN] (kip)	$R_yF_yA_g$ [kN] (kip)	$R_tF_uA_g$ [kN] (kip)
1	HSS 102 x 8.0	7.38 (0.291)	2190 (3.39)	33.4 (1.32)	128	353 (79.3)	969 (218)	1213 (273)
2	HSS 141 x 9.5	8.86 (0.349)	3690 (5.71)	46.9 (1.85)	141	494 (111)	1635 (368)	2050 (460)
3	HSS 168 x 13	11.81 (0.465)	5810 (9.00)	55.5 (2.18)	111	1241 (279)	2580 (580)	3220 (725)
4	HSS 219 x 16	14.76 (0.581)	9480 (14.7)	72.4 (2.85)	85	2840 (640)	4200 (946)	5260 (1184)

* t_{des} is shown on the basis of 0.93 $t_{nominal}$ as recommended by AISC. Note that CISC recommends t_{des} = 0.90 $t_{nominal}$

As per AISC seismic provisions, the required tensile strength of brace connections in special concentrically braced frames must be equal to or exceed the brace expected yield strength, $R_yF_yA_g$. Similarly, the required compressive strength of the brace connection must be equal to or exceed the brace expected compressive strength, $1.1R_yP_n$. In these expressions, R_yF_y is the expected yield strength of the brace material and P_n is the nominal brace compressive strength, determined according to the AISC specifications (AISC 2005b). For ASTM A500 Grade C HSS members, the expected yield strength is given by, R_yF_y = 1.4 x 317 = 444 MPa (64 ksi), and the expected tensile strength is given by, R_tF_u = 1.3 x 427 = 555 MPa (81 ksi) (AISC 2005a). Values of the expected brace compressive and tensile strengths for each specimen are also given in Table 2.2 above.

Table 2.3 compares the diameter-to-thickness (D/t) ratio of the brace specimens to the limits prescribed in the AISC and CSA-S16 seismic provisions. The AISC limit is equal to $0.044E/F_y$ = 27.8 (E = 200 000 MPa). At the time of writing, the AISC Seismic Provisions Task Committee (TC 9) was considering a reduced D/t limit, corresponding to 85% of the current AISC limit, as one possible option to delay HSS brace fracture. This limit is also listed in the table for reference. In CSA-S16, the D/t limit varies linearly between $10000/F_y$ and $13000/F_y$ for brace KL/r between 100 and 200, respectively. As shown, all of the specimens are significantly more compact than required by the code provisions suggesting that brace fracture under cyclic inelastic loading will be delayed during testing. This will impart a more arduous demand on the brace assembly connections than would be expected if the braces were less compact and failed prematurely due to local buckling.

Table 2.3 *Diameter-to-thickness ratios of the test specimens*

No.	Shape	t_{des} * [mm] (in.)	D/t [ ]	AISC limit [ ]	0.85 AISC limit [ ]	CSA limit [ ]
1	HSS 102 x 8.0	7.39 (0.291)	13.75	27.8	23.6	34.2
2	HSS 141 x 9.5	8.86 (0.349)	15.95	27.8	23.6	35.4
3	HSS 168 x 13	11.81 (0.465)	14.25	27.8	23.6	32.6
4	HSS 219 x 16	14.76 (0.581)	14.84	27.8	23.6	31.5

* t_{des} is shown on the basis of 0.93 $t_{nominal}$ as recommended by AISC. Note that CISC recommends t_{des} = 0.90 $t_{nominal}$

2.4 Cast Connectors

Table 2.4 lists the Cast ConneX™ High-Strength Connector that was used in the fabrication of each brace specimen. The connectors are produced using a cast steel having a nominal yield strength of 345 MPa (50 ksi) and an ultimate strength of 550 MPa (80 ksi).

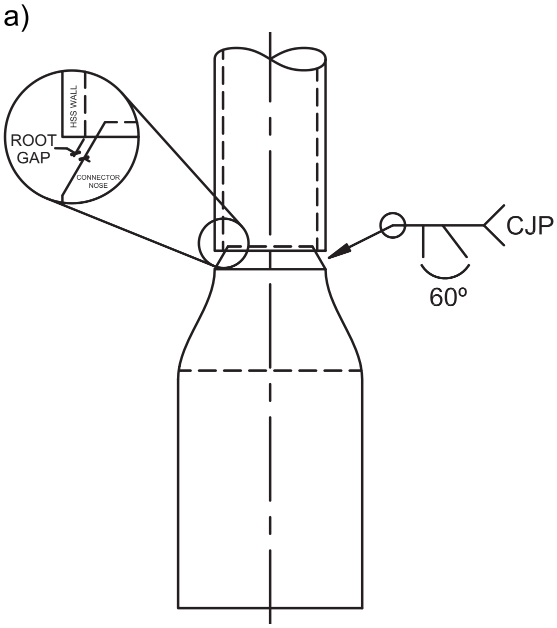
Table 2.4 *High-Strength Connectors used for each specimen*

No.	Shape	High-Strength Connector
1	HSS 102 x 8.0	HSC-102 (HSC-4.000)
2	HSS 141 x 9.5	HSC-141 (HSC-5.563)
3	HSS 168 x 13	HSC-168 (HSC-6.625)
4	HSS 219 x 16	HSC-219 (HSC-8.625)

The connectors are manufactured using steel produced to ASTM A958 Grade SC8620 Class 80/50 (ASTM 2000) with a silicon content less than 0.55-percent by weight. The chemistry of this grade of steel also meets the chemical requirements of ASTM A514, which is a prequalified weldable structural steel base metal according to CSA W59 (CSA, 2003).

The weld detail specified for the weld between the connectors and each HSS segment is a circumferential complete joint penetration groove weld with a convex finished contour. The nose of the connector protrudes into the hollow section and acts as a form of backing for the weld. It is recommended by Cast Connex Corporation that a root gap be left between the inside edge of the HSS wall and the nose of the connector, as shown in Figure 2.6, to help ensure complete penetration is achieved. Because of the thermal mass of the connector, preheating of the casting in the vicinity of the connection is recommended prior to welding.

a)



b)

Fig. 2.6 *Complete joint penetration groove weld:*
a) Weld detail; b) Sliced HSS 141x9.5 brace assembly showing CJP weld

Engaging the full area of the HSS with the weld is critical, as the brace will experience yielding of its entire cross-section during a design level seismic event.

Tests on brace specimens equipped with cast connectors in addition to experimental central linking elements were carried out in a separate research study. One of the specimens tested in that study exhibited incomplete welding between the end connector and an HSS segment and, as a result, fracture occurred at the welded connection after several inelastic cycles of tensile brace yielding and compressive buckling were applied to the brace-link assembly. Although a weld fracture has never occurred in the laboratory or in the field on a conventional brace equipped with the cast end connectors, the experiments conducted on the central-link braces illustrate the importance of quality welding in seismic applications.

Fig. 2.7 *Brace specimen with central link element – weld fracture due to improper welding*

2.5 Test Displacement Protocol

The displacement protocol adopted for the test program was based on the qualifying test protocol prescribed for buckling-restrained braces in the AISC seismic provisions (AISC 2005a). The protocol is based on the brace axial deformation at yield, δ_{by}, and the brace axial deformation at the design story drift, δ_{bm}. The values used for these parameters were established as described below.

At the time of testing, the actual material properties of the HSS braces were not known, thus the brace axial deformation at yield, δ_{by}, was estimated using the expected yield strength of steel, R_yF_y = 1.4 x 317 MPa = 444 MPa, and assuming a Young's modulus of E = 200000 MPa. The yield strain for the HSS material assumed for the purpose of developing the displacement protocol was thus computed as 0.00222.

An estimate of the design story drift, δ_{bm}, applicable to typical braced steel frames was determined based on codified design procedures and expected seismic performance as follows. In tension-compression braced frame systems, the design of the bracing members is typically governed by compression strength requirements. For intermediate brace slenderness varying between 80 and 120, the brace compressive strength, P_n, corresponds to an axial stress between 0.65 and 0.38 F_y for ASTM A500 Grade C CHS with F_y = 317 MPa. This corresponds to axial strains ranging between 0.1% and 0.06%. The maximum (more critical) value of 0.1% was retained.

Figure 2.8 shows the relationships between unit brace axial deformation ($\delta/L_{c\text{-}c}$) and the resulting story drift, Δ/h_s. The ratio between these two parameters varies between 0.47 and 0.50 for a brace inclination varying between 35° and 45°. Therefore, an axial strain $\delta/L_{c\text{-}c}$ = 0.1% will result in a story drift of approximately 0.2%.

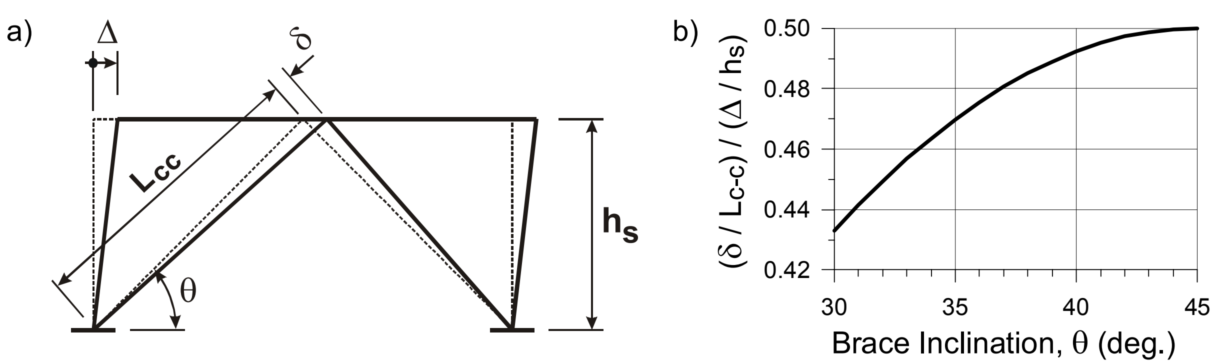


Fig. 2.8 *Brace axial deformation vs story drift: a) Geometry; b) Relationship between brace axial deformation and story drift.*

The total story drift in braced steel frames also includes the contribution from axial deformations of beams and columns. Figure 2.9 shows the contribution of brace axial deformations to the total story drift for 1- to 12-story chevron and split-x braced steel frames designed according to the seismic provisions of the 2005 National Building Code of Canada (NRCC 2005) and CSA-S16 steel design standard (CSA 2005). Similar results are expected for frames designed according to U.S. seismic provisions. Brace axial deformations typically contribute to 30 to 70% of total story drifts. Adopting an average ratio of 0.5, a brace axial strain of 0.1% is expected to lead to a total story drift of 0.4 %.

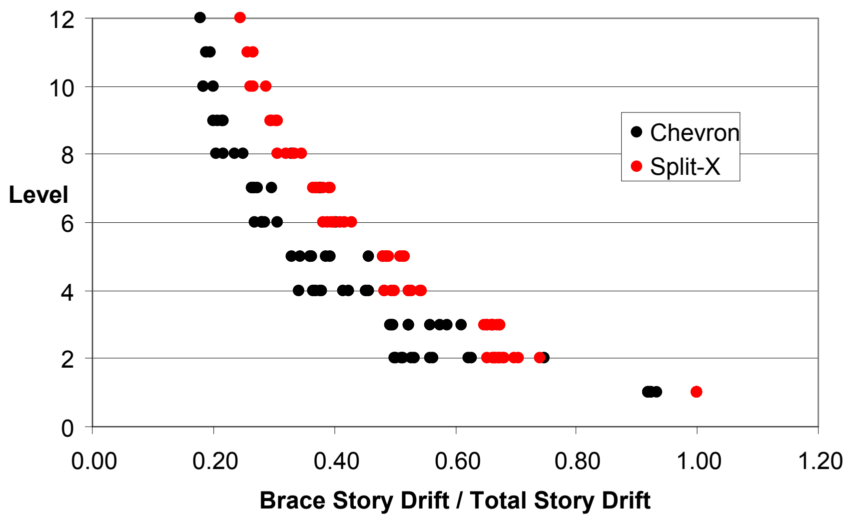


Fig. 2.9 *Contribution of brace axial deformation to total story drift for 1- to 12-story braced steel frame buildings designed according to 2005 Canadian seismic provisions.*

According to ASCE 7-05, the total story drift should be multiplied by the deflection amplification factor, C_d, to obtain the design story drift. For Special Concentrically Braced Frames (SCBFs), C_d = 5.0 and the anticipated design story drift is thus equal to 2.0%. This value corresponds to the story drift limit prescribed in ASCE 7-05 for braced steel frames used in Occupancy Category I or II buildings, i.e. the most widely used buildings that do not have special functionality requirements. For higher building categories, more stringent drift limits apply and the expected inelastic demand on bracing members will be lower than what was considered in this test program. According to NBCC 2005, the anticipated story drift for Moderately Ductile (Type MD) concentrically braced steel frames is obtained by multiplying the story drift under the specified seismic loads by the product of R_dR_o = 3.9. This is lower than the C_d amplification factor used in the U.S. and would therefore lead to smaller δ_{bm} values. The test program was therefore based on the U.S. requirements.

In SCBFs designed according to current seismic provisions, it is anticipated that the inelastic response will be constrained to the bracing members. Hence, under strong ground motions, the anticipated 2.0% design story drift will in fact nearly entirely translate into axial brace deformations as the contribution from beam and column axial deformations to the total story drift will still remain essentially equal to 0.2% (half of 0.4%). In view of the uncertainty associated to the prediction of inelastic story drifts, it was conservatively assumed in this test program that the entire design story drift would transpose into brace axial deformations. From Figure 2.8, the axial brace deformation corresponding to the design story drift, δ_{bm}, can be taken equal to 0.01 L_{c-c}.

The loading sequence prescribed in AISC seismic provisions for BRB systems is given in Appendix B. It comprises 2 cycles at each of the following increasing amplitudes: 1.0 δ_{by}, 0.5 δ_{bm}, 1.0 δ_{bm}, 1.5 δ_{bm}, and 2.0 δ_{bm}. At the end of the test, additional cycles at amplitude 1.5 δ_{bm} must be applied until the cumulative inelastic deformation reaches 200 δ_{by}.

The loading protocol adopted in the test program was based on story drift demand. The number and amplitude of cycles were determined to essentially lead to the same axial brace deformation demand when following the above assumptions. It consisted of 4 cycles at Δ/h_s of 0.1%, 0.2%, 0.4% and 0.6%. This was followed by 2 cycles at Δ/h_s = 1.0%, 2.0%, 3.0%, and 4.0%. Additional cycles at an amplitude corresponding to Δ/h_s = 3.0% were applied until the cumulative inelastic strain demand reached 200. All cycles started with a compressive excursion.

The eight large amplitude cycles with amplitude between Δ/h_s = 1.0% and Δ/h_s = 4.0% correspond to the BRB test cycles from 0.5 δ_{bm} to 2.0 δ_{bm}. The additional cycles at Δ/h_s = 3.0% correspond to the additional BRB test cycles at 1.5 δ_{bm}. Compared to the BRB protocol, a larger number of small amplitude cycles were applied in this test program to better characterize the brace elastic response, the brace buckling strength and the initiation of brace yielding in tension. These cycles do not induce significant inelastic deformations in the specimens and it is believed that this addition did not impose excessive demand on the specimens.

The loading protocol in this test program is similar to the one adopted by Fell et al. (2006) which comprised, in addition to the small amplitude cycles, 2 cycles at amplitudes corresponding to Δ/h_s = 1.025%, 1.085%, 2.675%, 4.0%, and 5.0%.

For consistency with the initial assumption of a brace inclination of 35°, a factor of 0.47 was used between the story drift and brace axial deformation used in the test program (refer to Figure 2.8). In addition, the brace deformations that were imposed on the brace specimens were modified to account for the fact that most of the brace axial deformation actually develops within the CHS brace segment comprised within the end brace connections (length L_{CHS} in Figures. 2.1 to 2.3). Following capacity design principles, brace connections are designed with larger cross-section to remain elastic and develop the full brace axial strength. Strains in the connections therefore remain small. In particular, deformations associated with yielding and buckling are concentrated in the brace segment of length L_{CHS}. To reflect this, the axial deformations applied in the tests, δ, were determined from: $\delta = (0.47\ \Delta/h_s)(L_{c\text{-}c}/L_{CHS})\ L_{CHS}$. Similarly, an axial strain equal to δ/L_{CHS} was used for the calculation of the accumulated inelastic strain demand (plastic strain = $\delta/L_{CHS} - 0.00222$).

Values of L_{CHS} are given in Table 2.1. The $L_{c\text{-}c}/L_{CHS}$ ratios were determined from the prototype braced frame configurations assumed for the brace specimens (see Appendix A). These ratios are equal to 1.49, 1.36, 1.44, and 1.59 for Specimens 1 to 4, respectively. Figure 2.10 shows the loading protocol for the HSS 102x8.0 Specimen ($L_{c\text{-}c}/L_{CHS}$ = 1.49). In all cases, the resulting displacement protocol was such that the minimum cumulative inelastic deformation of 200 was reached before the end of the last cycle corresponding to Δ/h_s = 4.0%. In some of the tests, the specimen did not fail before the end of the test loading protocol. In that case, additional cycles with increasing amplitudes were applied until brace fracture occurred.

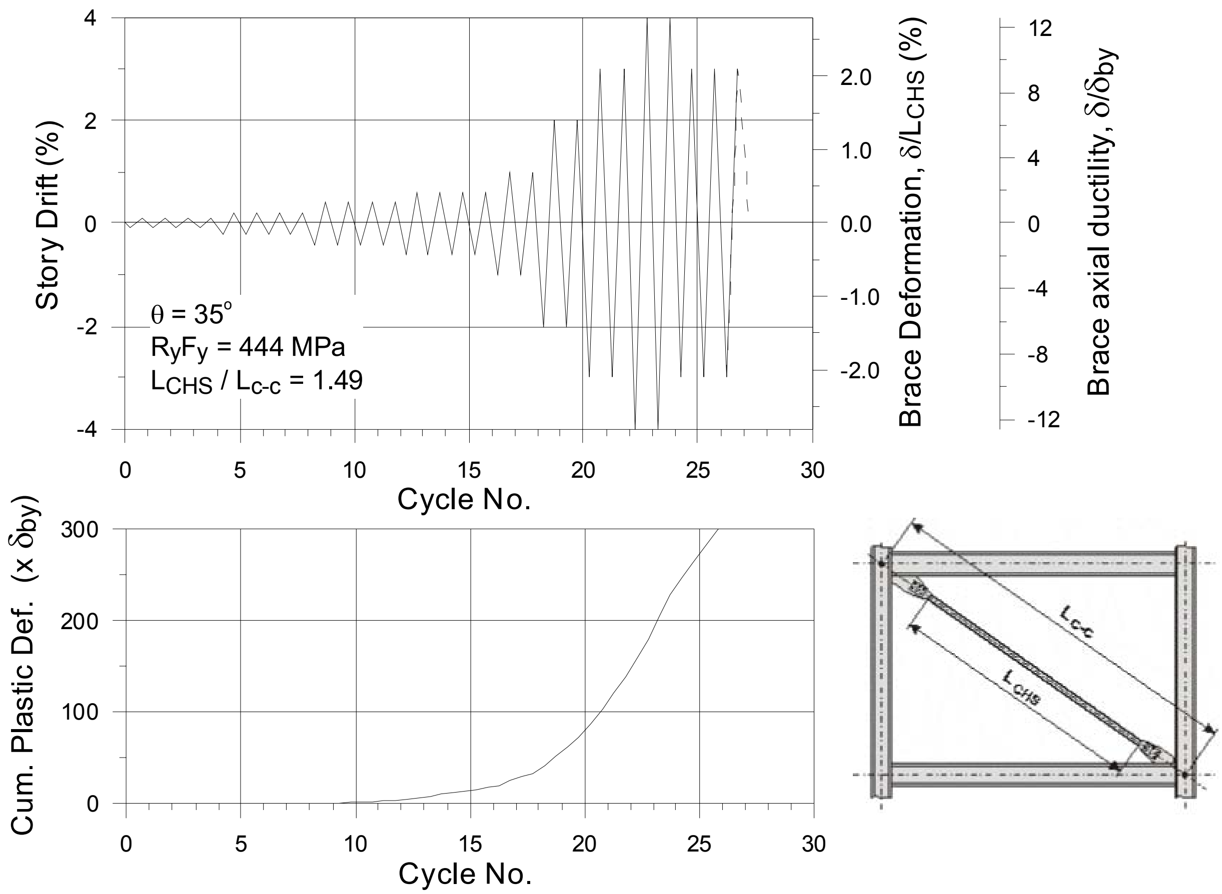


Fig. 2.10 *Test loading protocol for Specimen MTS-01 ($L_{c\text{-}c}/L_{CHS}$ = 1.49).*

It is noted that the imposed strain demand in the braces (δ/L_{CHS}) varied between 0.64 to 0.75 Δ/h_s for the assumed brace configuration (single diagonal brace, θ = 35°). In chevron (inverted-V) bracing or split-X bracing, the brace inclination is typically closer to 45° and the $L_{c\text{-}c}/L_{CHS}$ ratio is expected to be lower, closer to 1.3. Using these two values, the strain demand would be equal to 0.65 Δ/h_s, which means that the loading protocol as defined for this test program would be equally applicable to these other two common bracing configurations.

In the tests, the axial deformation that was applied to the test specimens was controlled by means of two cable position transducers that were located along each side of the braces (refer to Section 2.2). The attachment points of the transducers were located on the cast connectors, between the points where hinges were expected to form in the gusset plate upon brace buckling. As shown in Figure 2.11a, when buckling of the brace occurs, the actual displacement that is applied by the load frame, δ', is larger than the intended displacement δ. The additional displacement applied can be estimated by using the simple plastic mechanism shown in Figure 2.11b and assuming small deformations: $\delta'/\delta = L_u/L_t$, where L_u is the distance between expected gusset hinges and L_t is the distance between the transducers. The ratio L_u/L_t is equal to 1.15, 1.12, 1.13, and 1.18 for Specimens 1 to 4, respectively. Negative (compression) deformations upon buckling were amplified by the same ratios. This additional displacement was not imparted prior to buckling and when the braces were straightened in tension. Controlling the applied displacement in this manner resulted in the application of compressive displacements that were larger than required throughout the protocol.

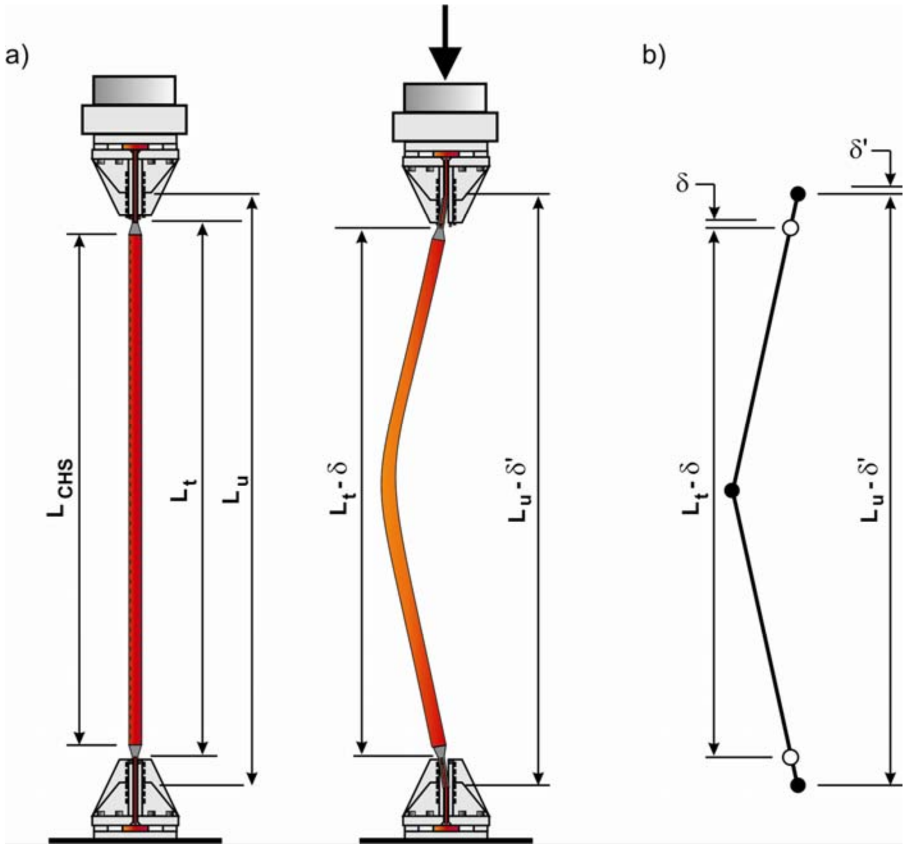


Fig. 2.11 *Imposed axial displacement after occurrence of buckling in compression: a) Actual response; b) Simplified model.*

2.6 Measured Specimen Properties and Ancillary Tests

The as-fabricated geometric properties of each brace assembly were measured in the laboratory. The wall thickness of the brace cross-section could not be measured as the cast connectors were already in place when the brace specimens were received at the laboratory. It was thus requested that additional HSS segments of the same heat and length as that which was used for the preparation of the brace assemblies be shipped with the braces for the purpose of tensile testing. Three wall thickness measurements were taken at each end of the additional HSS samples. These were then averaged, t_{AVE}, to determine the cross-sectional area of the brace, A. The length of the HSS segment, L_{HSS}, in each brace assembly was also measured and recorded, as was the total brace length, L_{TOT}, as measured from the exterior ends of the castings. The initial deformation of the brace at its midspan was measured both in the in-plane, Δ_{N-S}, and out-of-plane, Δ_{E-W}, directions. Gusset plate thickness, t_p, and width, b_g, at the free plastic hinge length were also measured on the gusset plate anchorages. The as-fabricated properties of the brace assemblies are summarized in Table 2.5. For Specimen 2, the additional tube segment that was shipped with the specimens did not correspond to the test specimen and could not be used to obtain actual geometrical and material properties. A replacement sample was not available at the time of writing.

Table 2.5 *Measured geometric properties of the brace assemblies*

		1 HSS 102x8.0	2 HSS 141x9.5	3 HSS 168x13	4 HSS 219x16
t_{AVE}	[mm] (in.)	7.58 (0.298)	– *	11.54 (0.454)	15.21 (0.599)
A	[mm^2] (in.^{2})	2240 (3.47)	– *	5682 (8.81)	9740 (15.1)
L_{HSS}	[mm] (in.)	3499 (137.8)	5613 (221.0)	5035 (198.2)	4637 (182.6)
L_{TOT}	[mm] (in.)	4260 (167.7)	6575 (258.9)	6095 (240.0)	6082 (239.4)
t_p	[mm] (in.)	12.85 (0.506)	19.10 (0.752)	25.7 (1.01)	31.9 (1.26)
B_g	[mm] (in.)	318 (12.52)	331 (13.03)	391 (15.39)	510 (20.08)
Δ_{N-S}	[mm] (in.)	1 (0.039)	1 (0.039)	1 (0.039)	1 (0.039)
Δ_{E-W}	[mm] (in.)	0 (0)	1 (0.039)	3 (0.118)	3 (0.118)

* Sample not available at the time of writing

The mill test certificates as provided by Canam Group Inc. for the HSS materials used in the fabrication of the brace assemblies are provided in Appendix C. The measured material properties for the HSS were determined based on the average of three coupons cut from each supplementary HSS segment. Coupons cut from the supplementary HSS segments were prepared and tensile tested according to ASTM E8M (ASTM, 2004). Detailed tensile test results are presented in Appendix D; the average results for the measured physical properties of the HSS material are summarized in Table 2.6.

Table 2.6 *Average measured physical properties of the HSS material used in the fabrication of the brace assemblies*

No.	Shape	F_y		F_u	
		[MPa]	[ksi]	[MPa]	[ksi]
1	HSS 102 x 8.0	521	75.6	548	79.5
2	HSS 141 x 9.5	– *	– *	– *	– *
3	HSS 168 x 13	473	68.6	509	73.8
4	HSS 219 x 16	431	62.5	561	81.4

* Sample not available at the time of writing

As is evident from the tensile tests results, in almost all cases, the tubular material exhibited a yield strength higher than the expected yield strength for the ASTM A500 Grade C material, R_yF_y = 1.4 x 317 = 444 MPa (64 ksi).

Table 2.7 lists the yield and ultimate strengths, the elongation, the reduction, and the Charpy impact energy as tested at -20ºC (-4ºF) of the material used in the production of the cast connectors. These values were determined by the manufacturer through the destructive examination of test bars cast from the same heat and heat-treated with the connectors. Appendix E contains the Chemical & Physical Analyses, Magnetic Particle Inspection, and Ultrasonic Examination Reports for all of the High-Strength Connectors used in these tests.

Table 2.7 *Physical properties of the Cast Connectors*

No.	High-Strength Connector	F_y		F_u		Elongation [%]	Reduction [%]	Impact Energy @ -20ºC (-4ºF)	
		[MPa]	[ksi]	[MPa]	[ksi]			[Joules]	[ft·lbf]
1	HSC-102	501	72.7	656	95.2	22.3	56.6	67	49
2	HSC-141	501	72.7	656	95.2	22.3	56.6	67	49
3	HSC-168	453	65.7	606	88.0	22.1	49.7	57	42
4	HSC-219	576	83.6	704	102	22.5	54.0	53	39

3. TEST RESULTS

3.1 Observed Specimen Response

All four of the brace assemblies equipped with the Cast ConneX™ High-Strength Connectors behaved as would be expected of ductile CHS buckling braces during the cyclic quasi-static testing. The first low amplitude cycles showed only minor inelasticity in the system; elastic brace buckling was observed early in the protocol in all cases. As the connections had not been designed to be slip-critical, bolt slip was noted in some of the tests. In these instances, bolt slip only occurred once during a tensile excursion as the slip load of the pretensioned bolts was never exceeded in compression in any test. Subsequent larger compressive excursions resulted in out-of-plane inelastic buckling of the bracing element, with significant tensile yielding occurring over the majority of the CHS member's length during the higher amplitude tensile excursions. As expected, fan-shaped plastic hinges formed beyond the ends of the connectors within the free length of the gusset plates as a result of overall member buckling. At higher amplitude compressive excursions, a discrete plastic hinge formed at the mid-length of the brace during inelastic buckling which eventually resulted in local buckling of the CHS wall.

All four of the brace assemblies equipped with the cast steel connectors survived the full displacement protocol. This result was expected since, as described in Section 2.3, the braces were of intermediate slenderness and were quite compact in comparison to the code-prescribed diameter-to-thickness limits. In all cases, the eventual failure of the brace occurred at the mid-length of the CHS element during a tensile excursion that followed the onset of significant local buckling of the CHS. Local buckling was demonstrated first through an ovalization of the cross section. At larger compressive deformations, the ovalization was followed by the formation of a crescent-shaped snap-through local buckle in the compressive face of the CHS segment. In all cases, failure of the brace occurred in the tensile excursion immediately following the formation of the crescent-shaped local buckle. White wash on the cast connectors remained intact and no sign of yielding could be observed on the connectors following any of the tests.

The subsections below present photographs, the hysteretic response, and the time-history information for each of the brace-connector assemblies tested. In each of the hysteretic plots, the force transmitted axially through the brace is plotted against the imparted axial strain in the CHS, which is given by the total applied deformation divided by the length of the CHS segment, Δ/L_{CHS}, since the strains in the cast connections and gusset plates are small, particularly after the onset of brace yielding or buckling. A vertical dashed line shows the axial strain corresponding to 4-percent drift and thus the completion of the displacement protocol as defined in section 2.4 above. Also shown in the hysteretic plots are the tensile strength, $(F_yA)_{measured}$, as determined from tensile coupon testing and measurement as described in section 2.5 of this report. Two additional horizontal lines show the tensile strength, F_yA, and the expected yield strength, R_yF_yA, as calculated using the design sectional properties, the minimum specified yield strength, and the code prescribed overstrength factor of 1.4 for ASTM A500 Grade C material.

3.2 HSS 102x8.0 Specimen Equipped with HSC-102 Connectors

Fig. 3.1 *Brace specimen prior to testing, after completion of installation and instrumentation (view from S-W, HSS 102x8.0 Specimen)*

a)

b)

Fig. 3.2 *Deformations induced by out-of-plane buckling of the brace specimen:*
a) Overall specimen response (view from S-W, HSS 102x8.0 Specimen);
b) Inelastic rotation of the gusset plate in the free plastic hinge length
(view from S-E, HSS 102x8.0 Specimen)

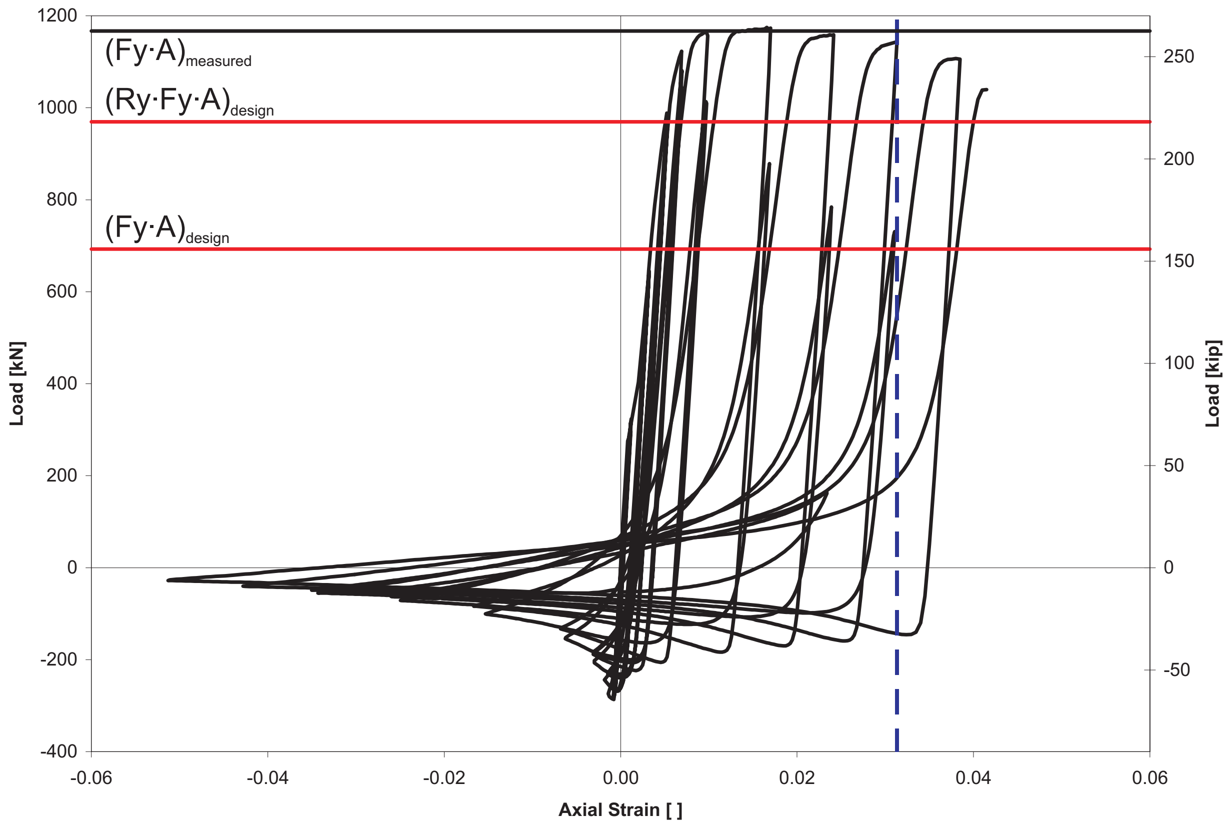


Fig. 3.3 *Load-displacement response of HSS 102x8.0 Specimen*
$(F_yA)_{measured}$ determined by coupon testing and measurement:
A = 2240 mm^2 (3.47 in.^{2}); Fy = 521 MPa (75.6 ksi)

Table 3.1 *Results Summary*

Peak tensile load	1174 kN (264 kip)
Peak compressive load	287 kN (64.5 kip)
Peak tensile strain in the CHS	4.19 %
Peak compressive strain in the CHS	5.13 %

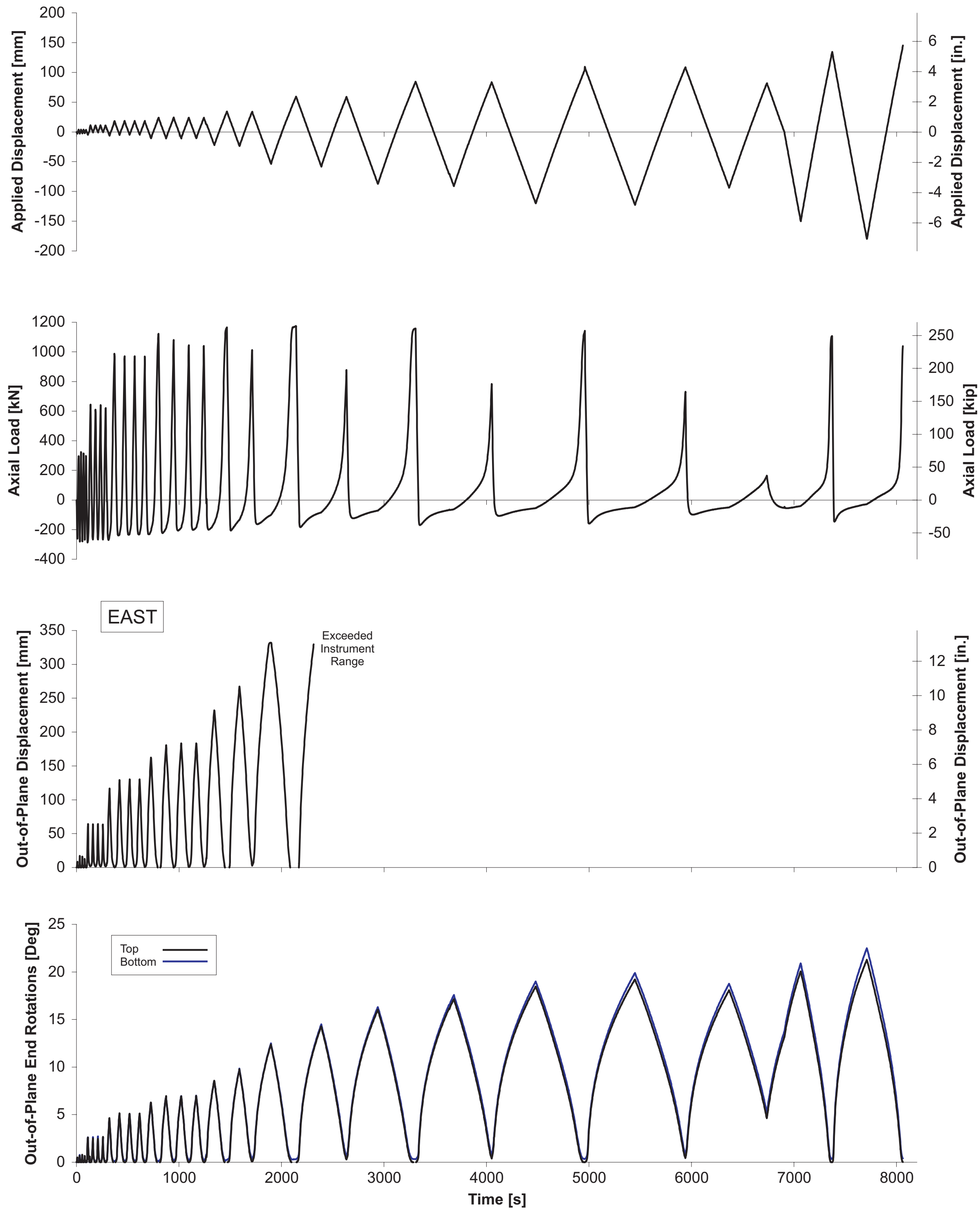


Fig. 3.4 *Time-history plots for HSS 102x8.0 Specimen*

3.3 HSS 141x9.5 Specimen Equipped with HSC-141 Connectors

Fig. 3.5 *Brace specimen prior to testing, after completion of installation and instrumentation (view from S-W, HSS 141x9.5 Specimen)*

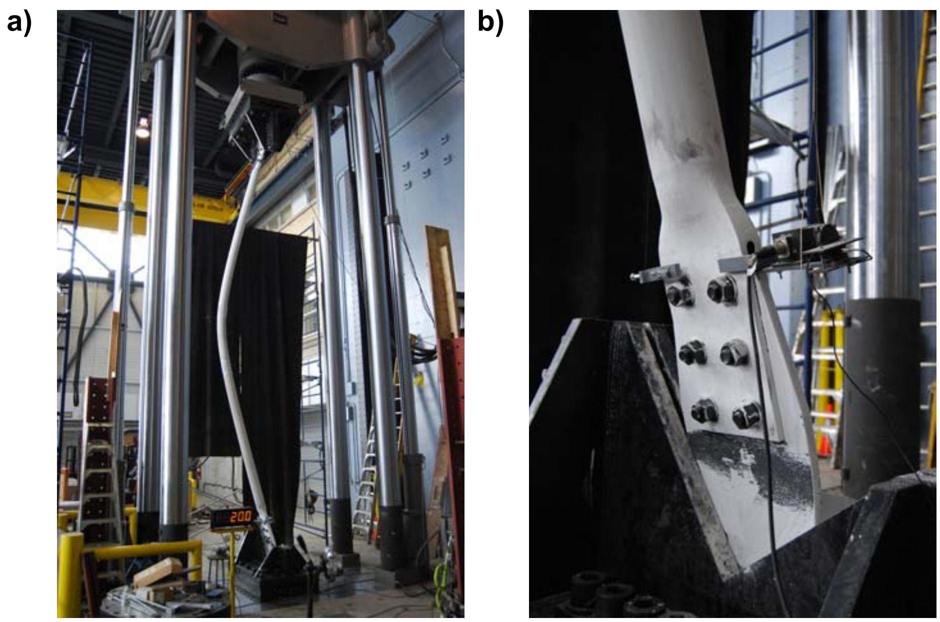


Fig. 3.6 *Deformations induced by out-of-plane buckling of the brace specimen: a) Overall specimen response (view from S-W, HSS 141x9.5 Specimen); b) Inelastic rotation of the gusset plate in the free plastic hinge length (view from S-W, HSS 141x9.5 Specimen)*

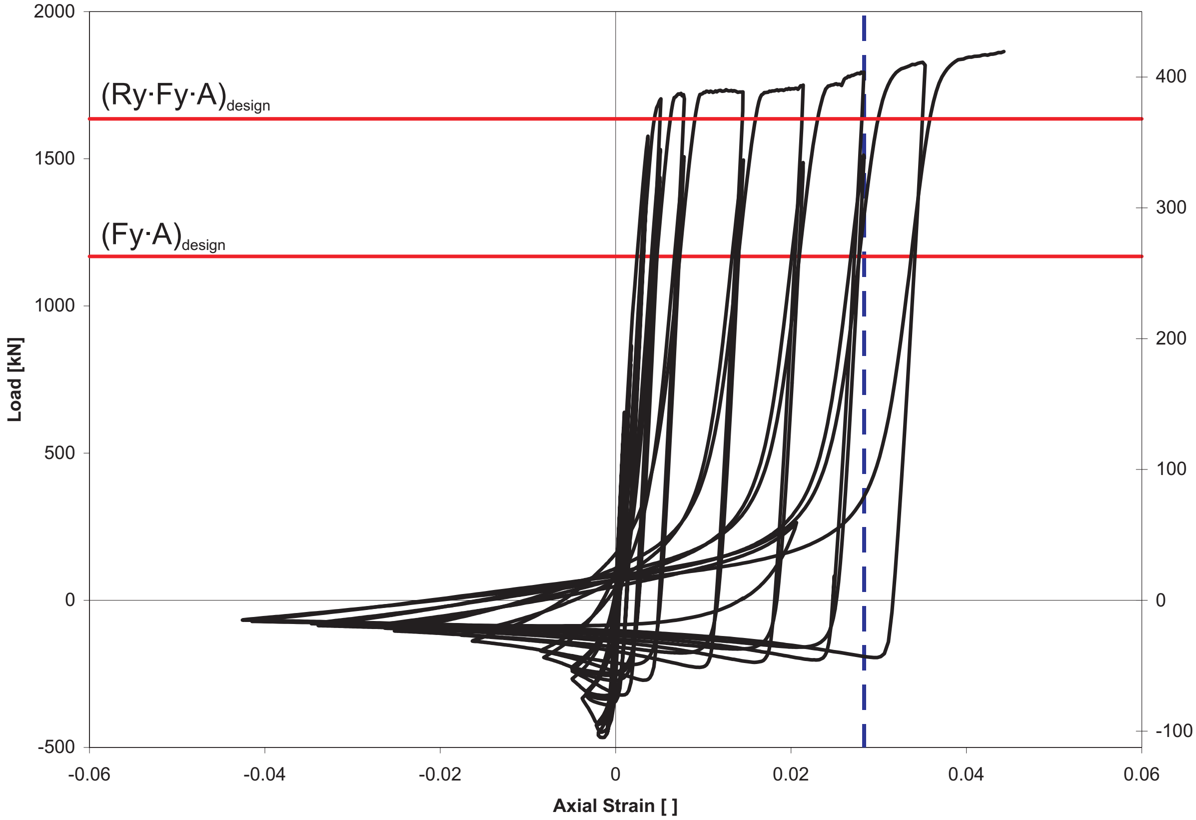


Fig. 3.7 *Load-displacement response of HSS 141x9.5 Specimen*
$(F_yA)_{measured}$ not available at the time of report writing

Table 3.2 *Results Summary*

Peak tensile load	1864 kN (419 kip)
Peak compressive load	466 kN (104.9 kip)
Peak tensile strain in the CHS	4.43 %
Peak compressive strain in the CHS	4.26 %

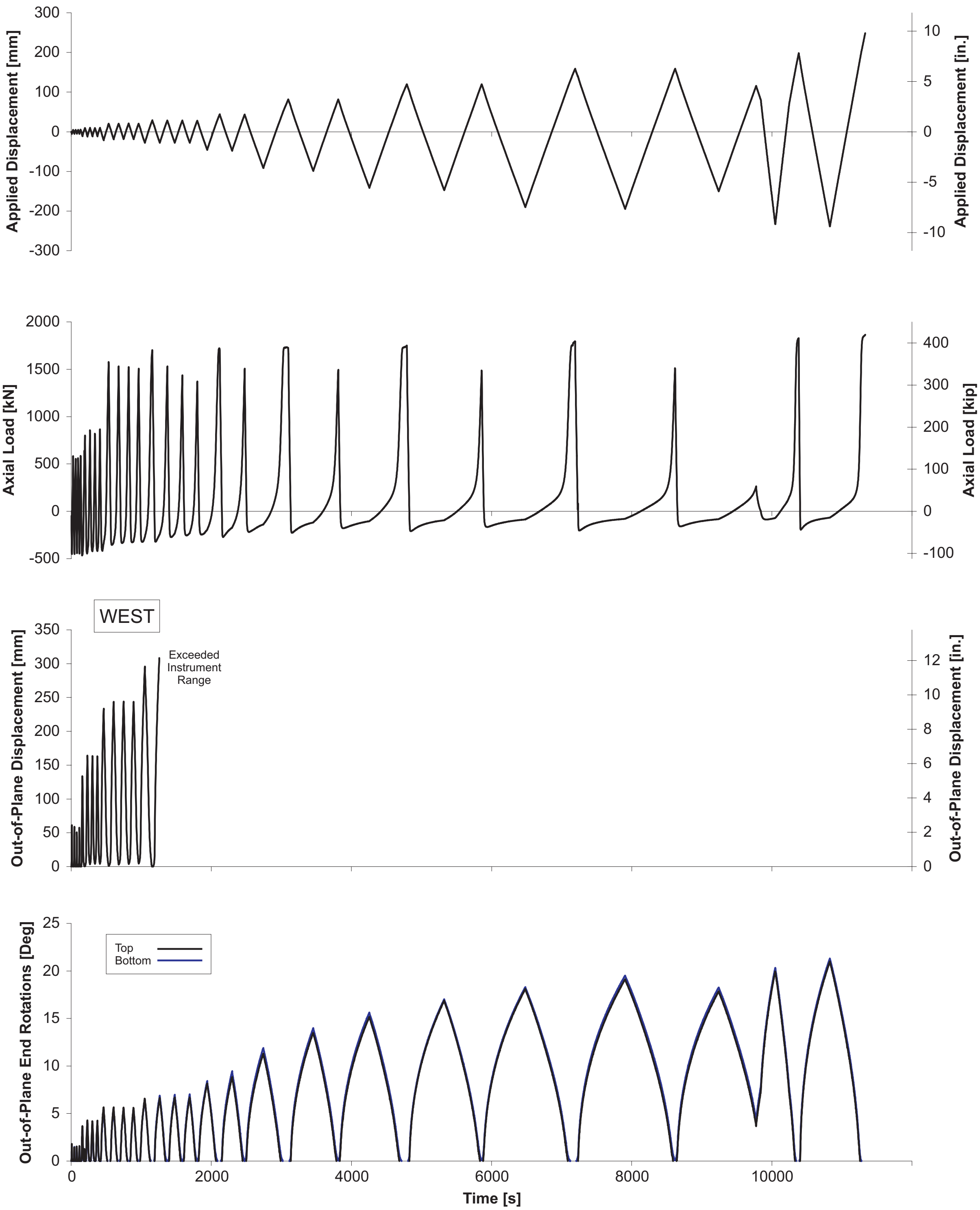


Fig. 3.8 *Time-history plots for HSS 141x9.5 Specimen*

3.4 HSS 168x13 Specimen Equipped with HSC-168 Connectors

Fig. 3.9 *Brace specimen prior to testing, after completion of installation and instrumentation (view from S-W, HSS 168x13 Specimen)*

a) **b)**

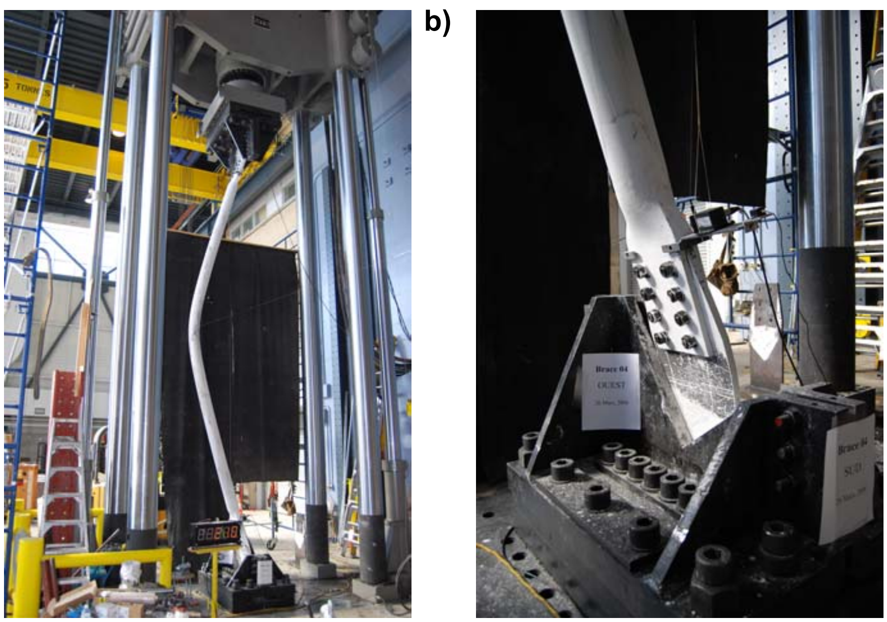


Fig. 3.10 *Deformations induced by out-of-plane buckling of the brace specimen:*
a) Overall specimen response (view from S-W, HSS 168x13 Specimen)
b) Inelastic rotation of the gusset plate in the free plastic hinge length
(view from S-W, HSS 168x13 Specimen)

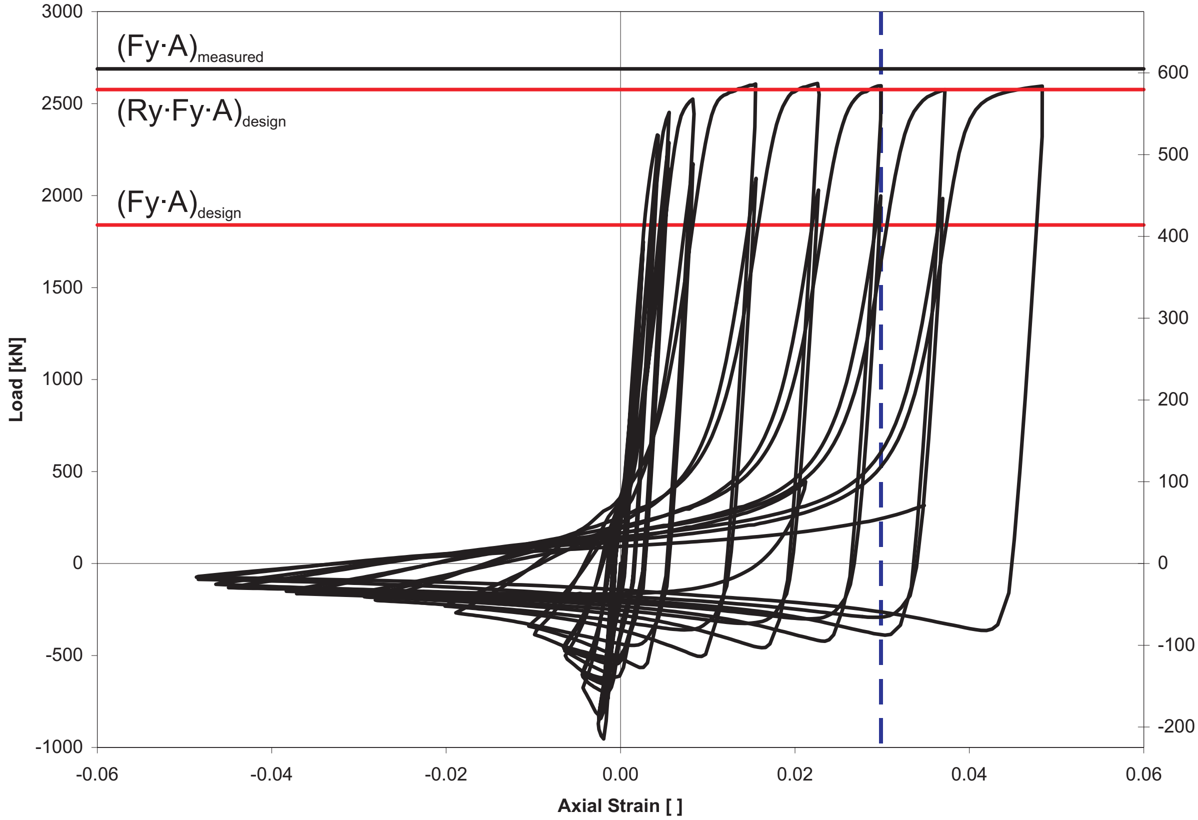


Fig. 3.11 *Load-displacement response of HSS 168x13 Specimen*
$(F_yA)_{measured}$ determined by coupon testing and measurement:
A = 5680 mm^2 (8.81 in.^{2}); Fy = 473 MPa (68.6 ksi)

Table 3.3 *Results Summary*

Peak tensile load	2610 kN (587 kip)
Peak compressive load	954 kN (215 kip)
Peak tensile strain in the CHS	4.84 %
Peak compressive strain in the CHS	4.86 %

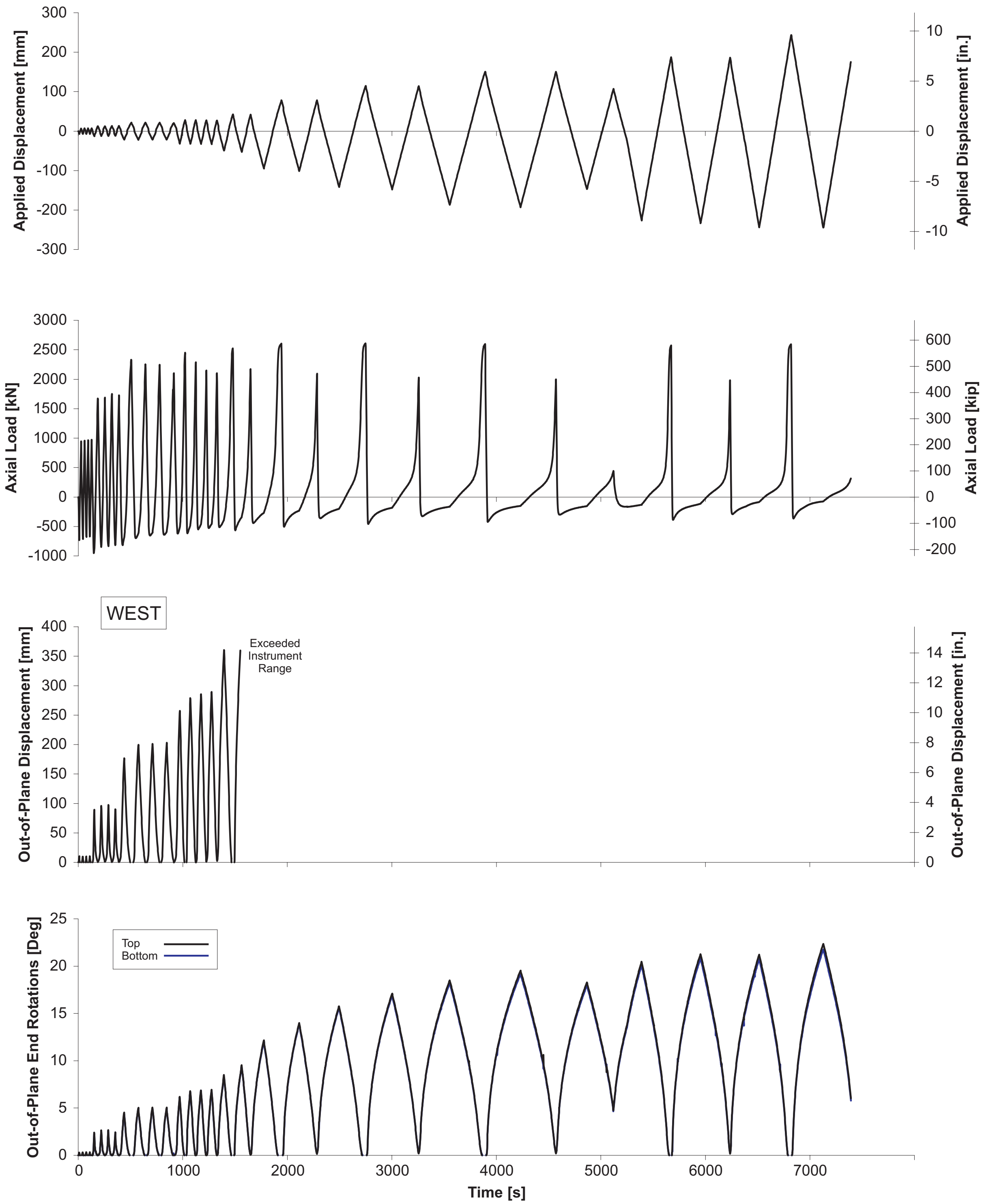


Fig. 3.12 *Time-history plots for HSS 168x13 Specimen*

3.5 HSS 219x16 Specimen Equipped with HSC-219 Connectors

Fig. 3.13 *Brace specimen prior to testing, after completion of installation and instrumentation (view from S-W, HSS 219x16 Specimen)*

a) b)

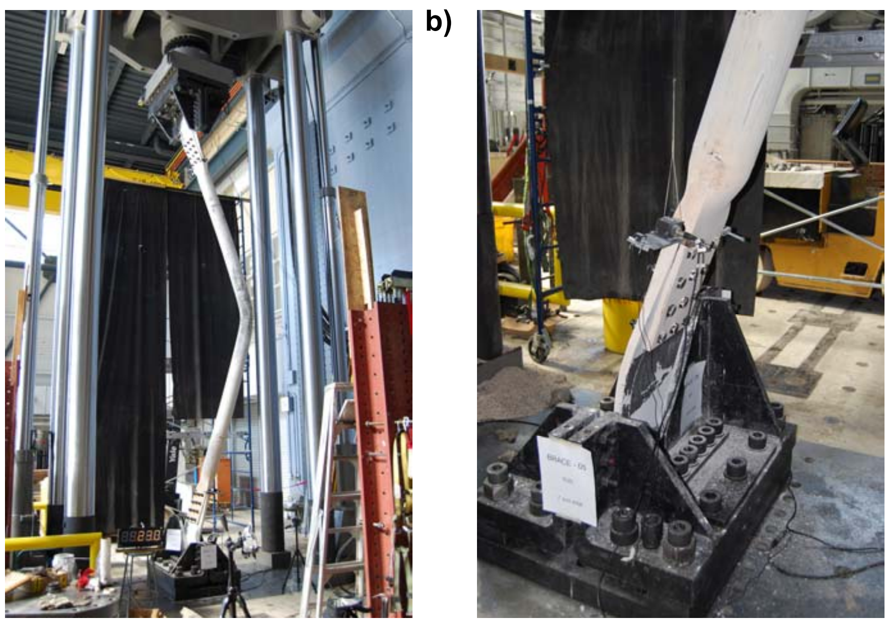


Fig. 3.14 *Deformations induced by out-of-plane buckling of the brace specimen: a) Overall specimen response (view from S-W, HSS 219x16 Specimen); b) Inelastic rotation of the gusset plate in the free plastic hinge length (view from S-E, HSS 219x16 Specimen)*

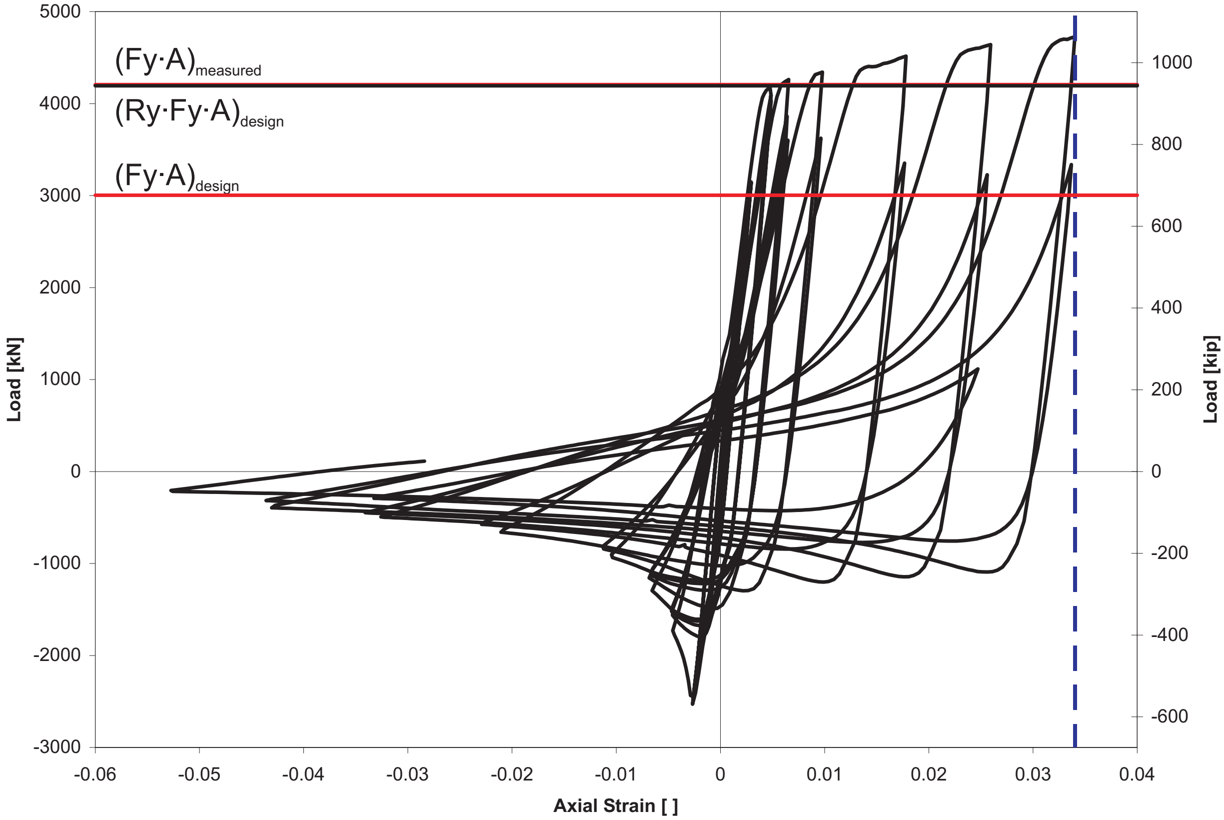


Fig. 3.15 *Load-displacement response of HSS 219x16 Specimen $(F_yA)_{measured}$ determined by coupon testing and measurement: A = 9740 mm^2 (15.10 in.^{2}); Fy = 431 MPa (62.5 ksi)*

Table 3.4 *Results Summary*

Peak tensile load	4720 kN (1063 kip)
Peak compressive load	2530 kN (569 kip)
Peak tensile strain in the CHS	3.63 %
Peak compressive strain in the CHS	5.27 %

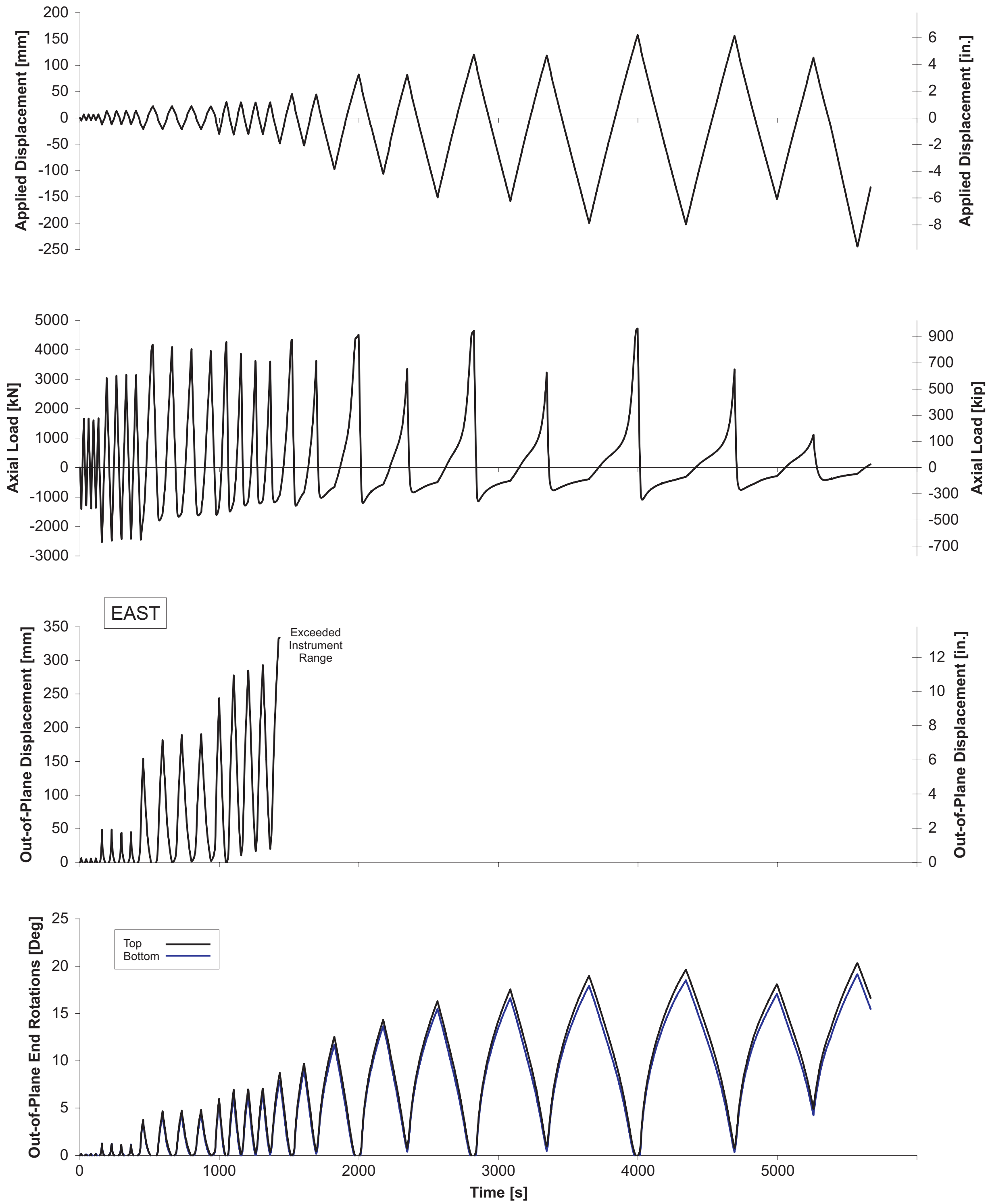


Fig. 3.16 *Time-history plots for HSS 219x16 Specimen*

4. CONCLUSIONS

All four of the brace assemblies equipped with the Cast ConneX™ High-Strength Connectors that were tested in this study behaved as would be expected of ductile circular hollow section buckling braces during cyclic quasi-static inelastic loading. Furthermore, all four brace assemblies met the AISC-prescribed BRB seismic loading protocol. This testing, in conjunction with the proof-of-concept testing that was carried out previously at the University of Toronto, confirms that the standardized cast steel connectors meet the requirements for ductile seismic bracing connections for braces of typical lengths, under a variety of loading protocols, and with boundary conditions representative of typical field conditions.

5. REFERENCES

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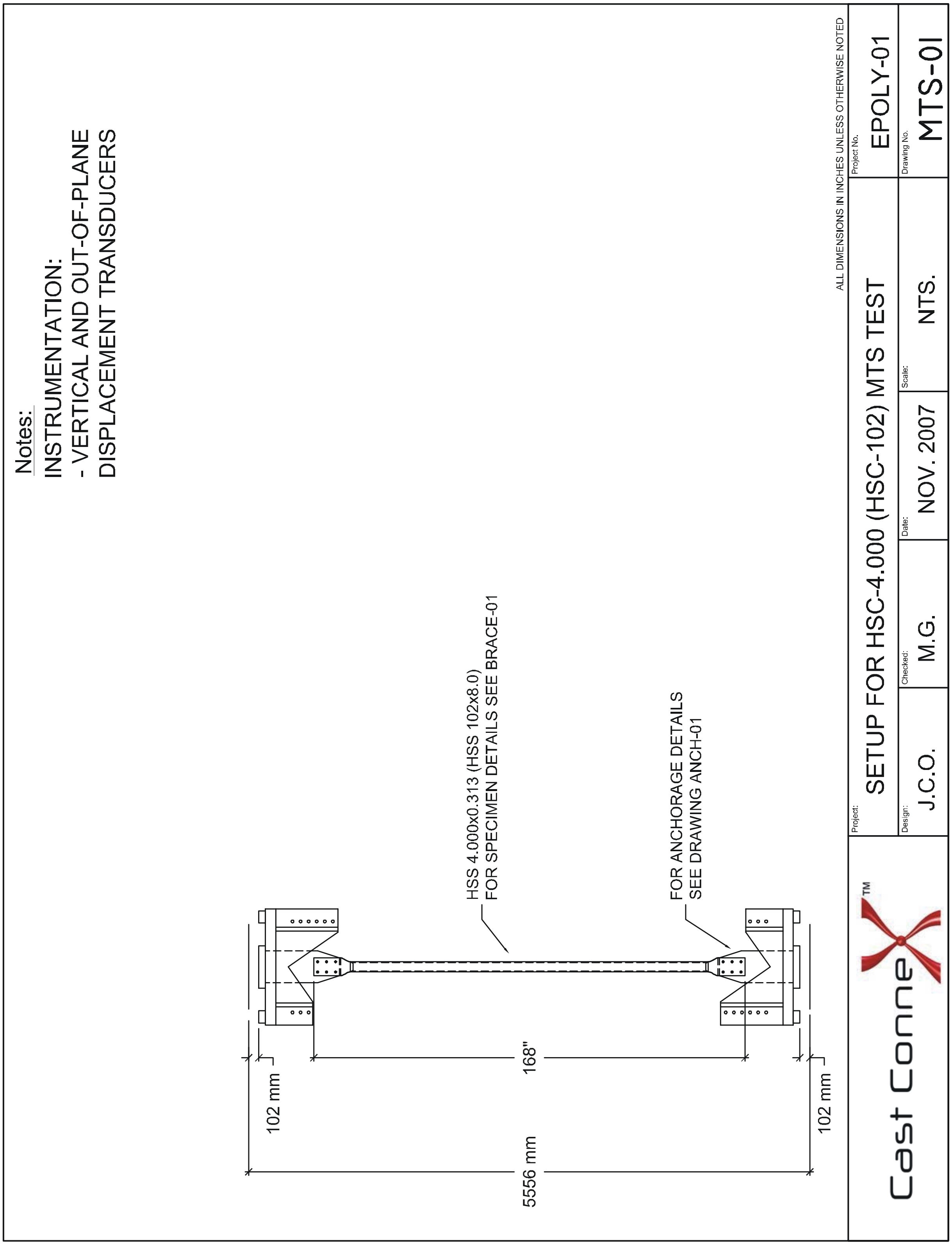
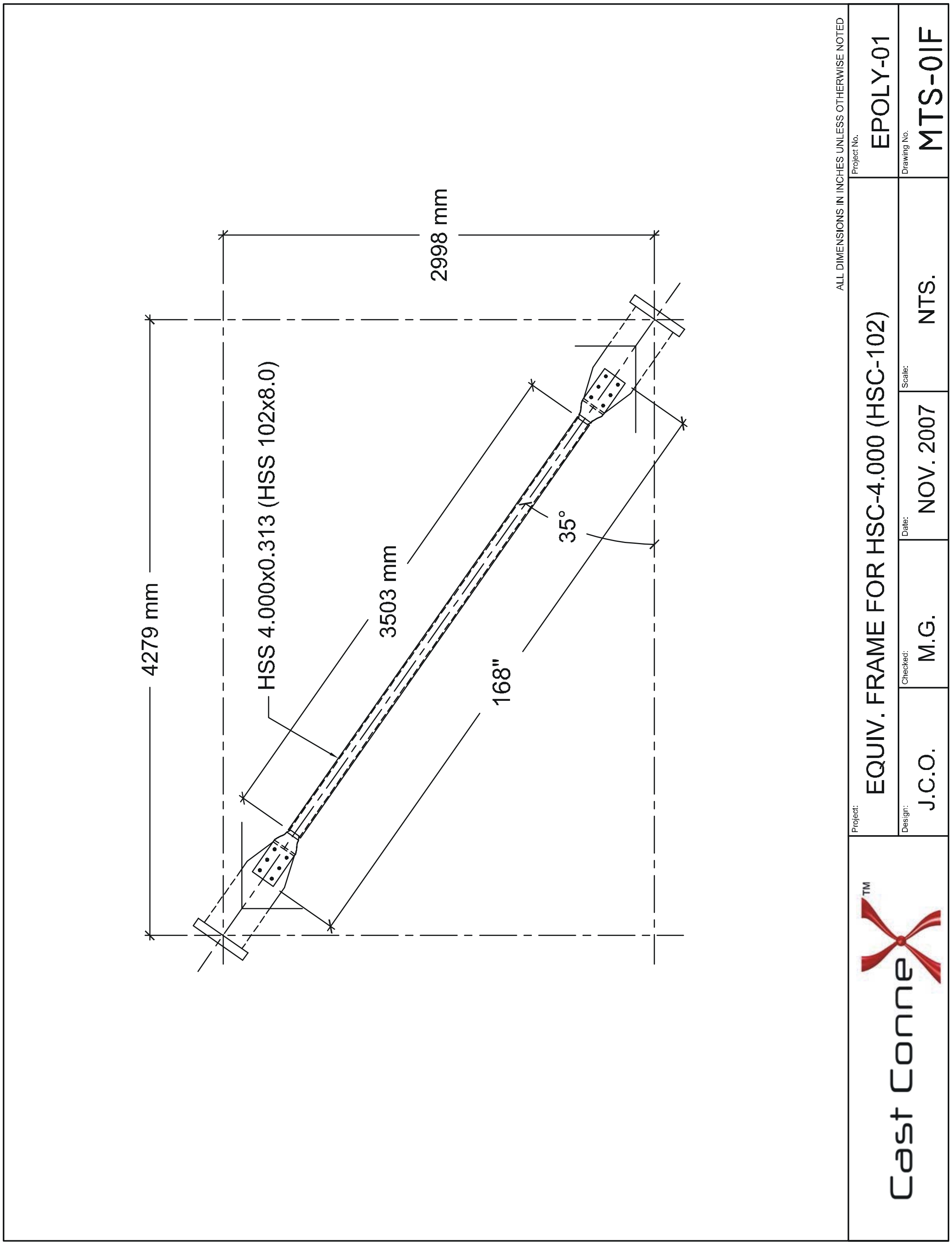
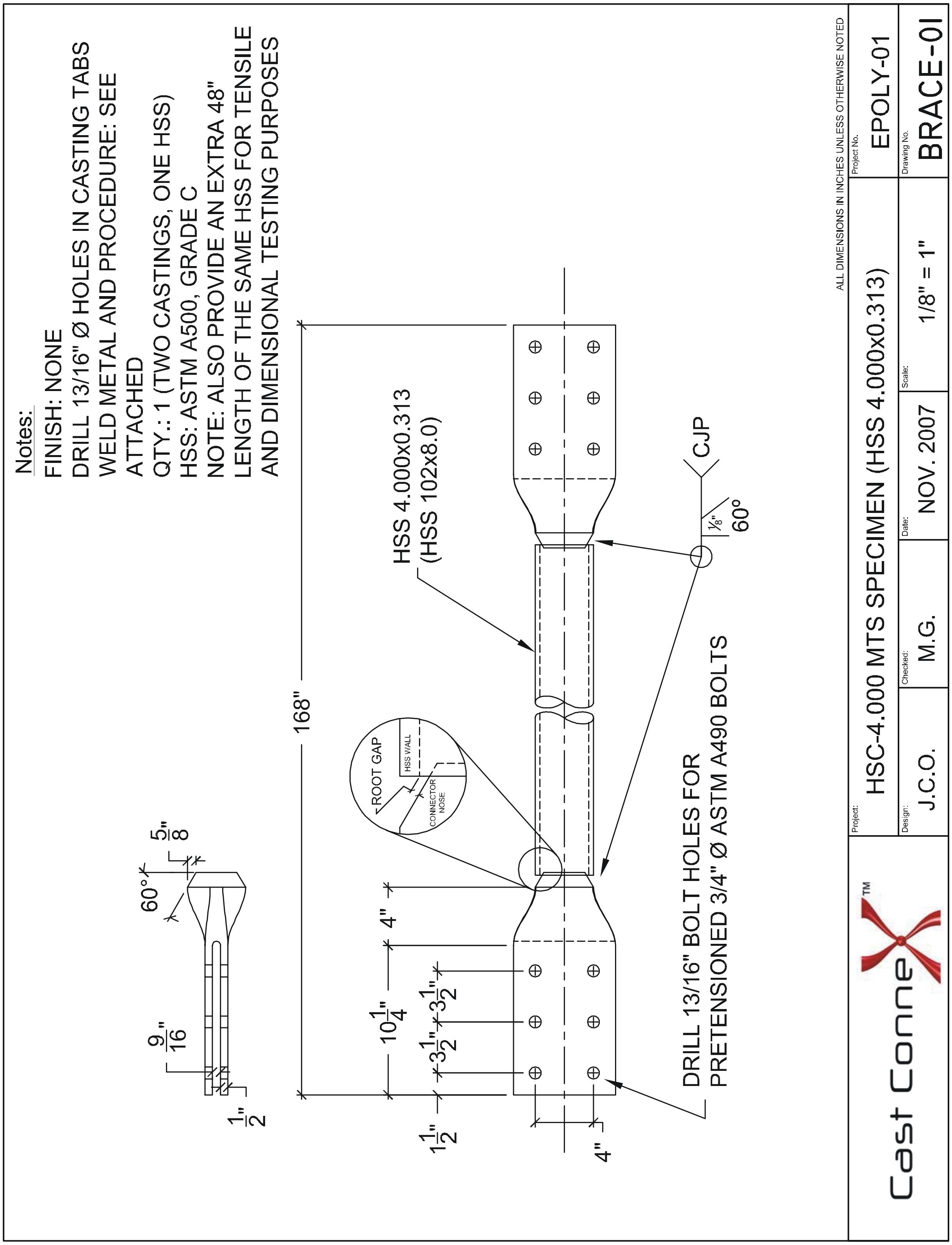
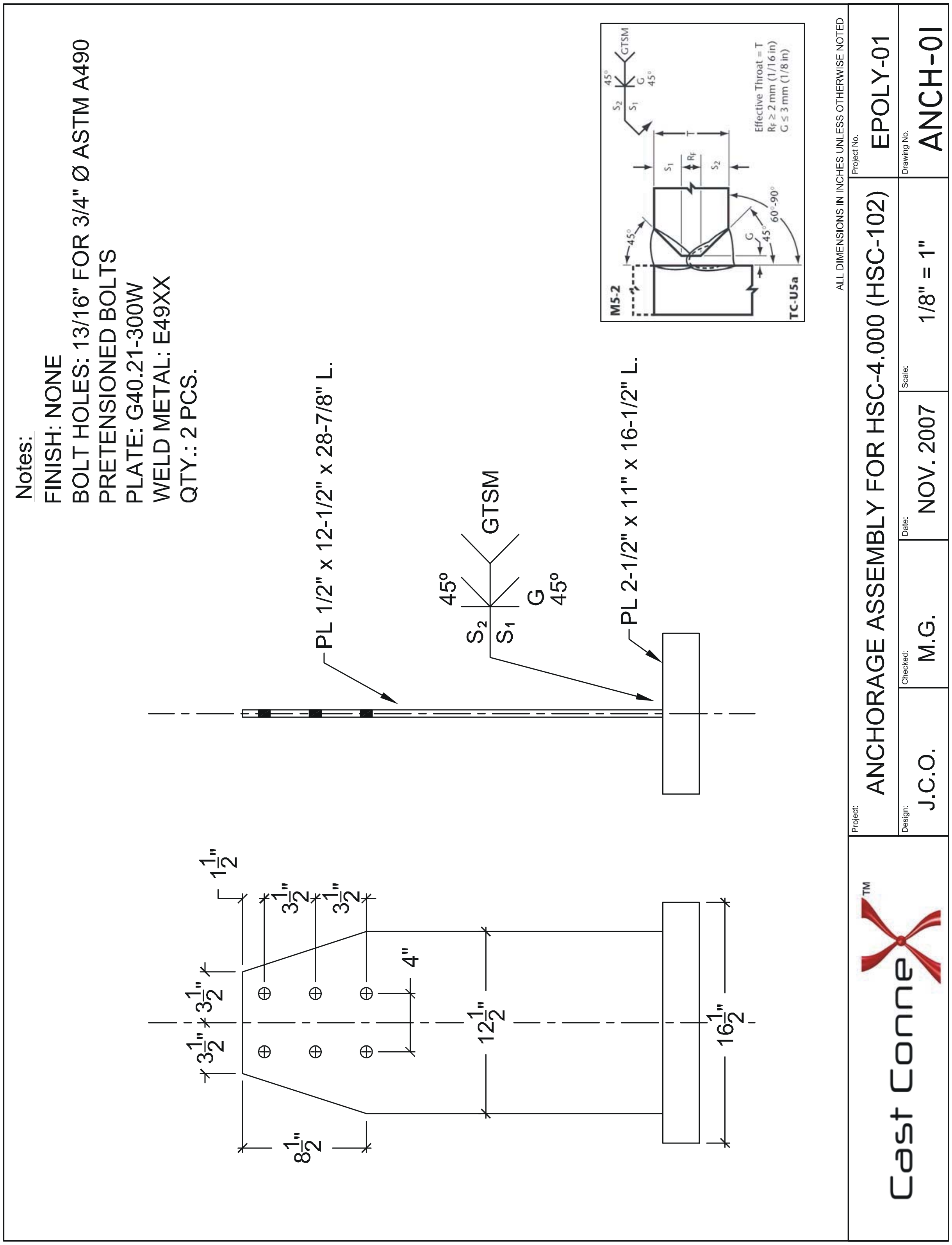
APPENDIX A

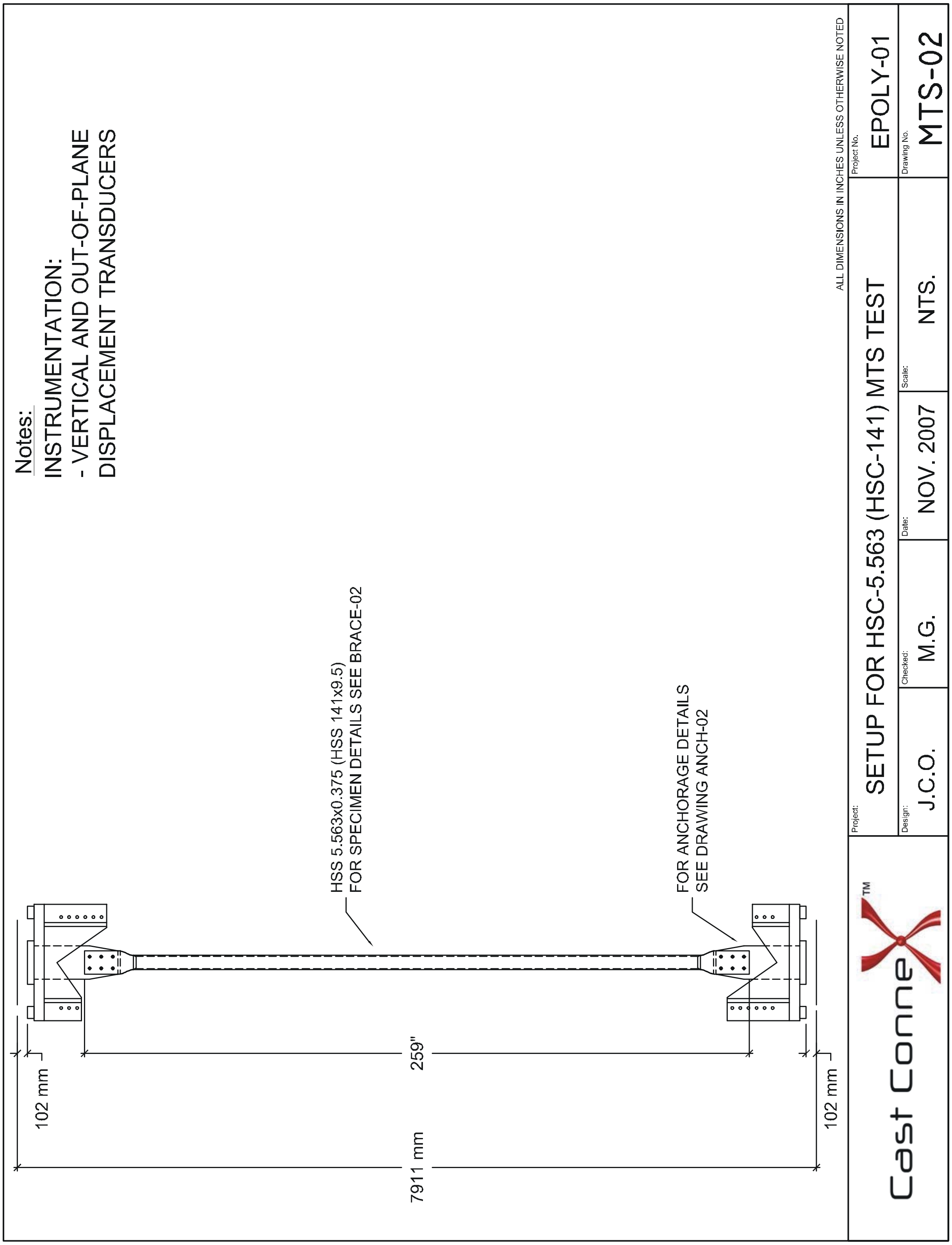
Drawings of the Test Specimens

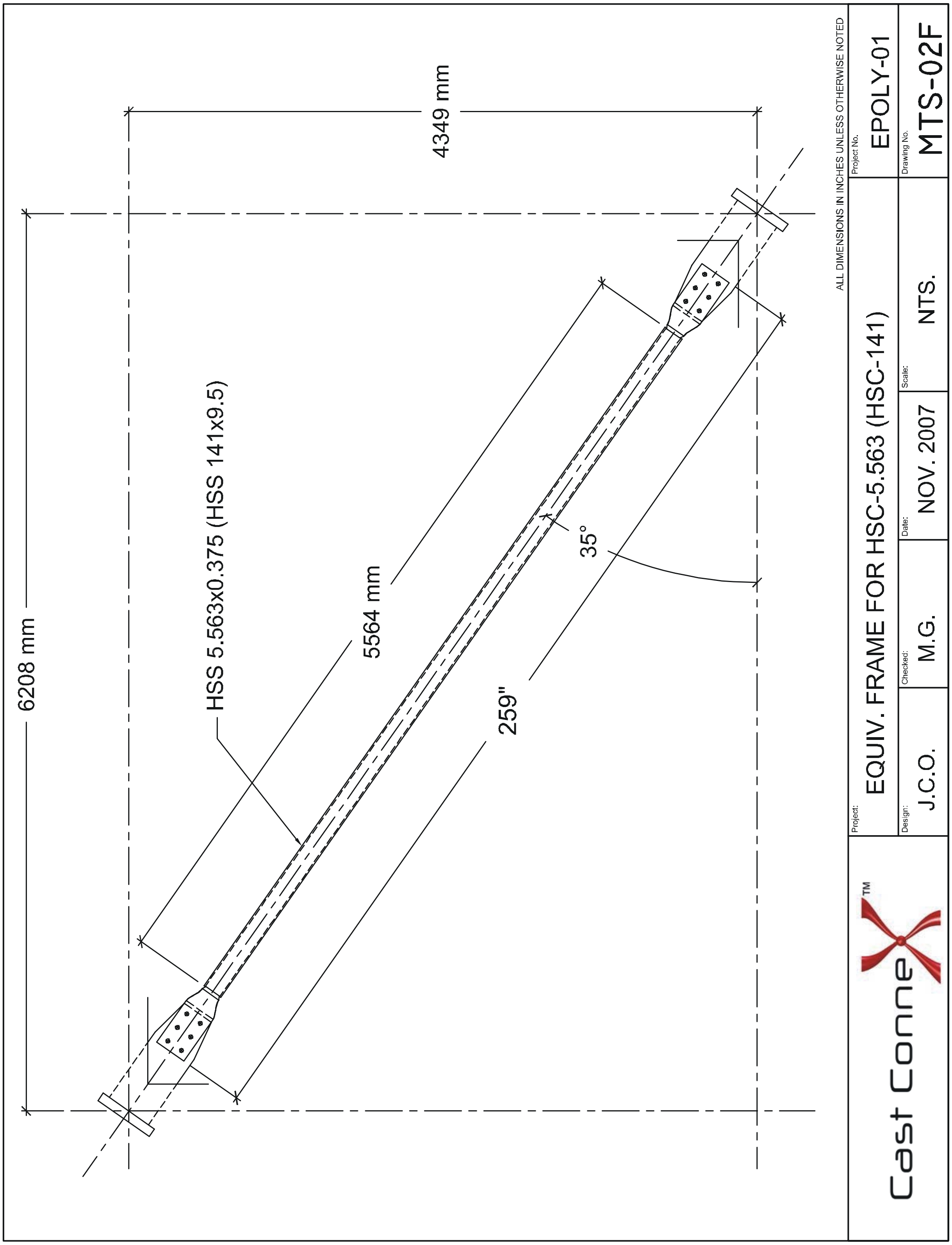

Notes:
INSTRUMENTATION:
- VERTICAL AND OUT-OF-PLANE
DISPLACEMENT TRANSDUCERS
HSS 4.000x0.313 (HSS 102x8.0)
FOR SPECIMEN DETAILS SEE BRACE-01
FOR ANCHORAGE DETAILS
SEE DRAWING ANCH-01
102 mm
168"
102 mm
5556 mm
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project:
SETUP FOR HSC-4.000 (HSC-102) MTS TEST
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.
Drawing No.
MTS-01

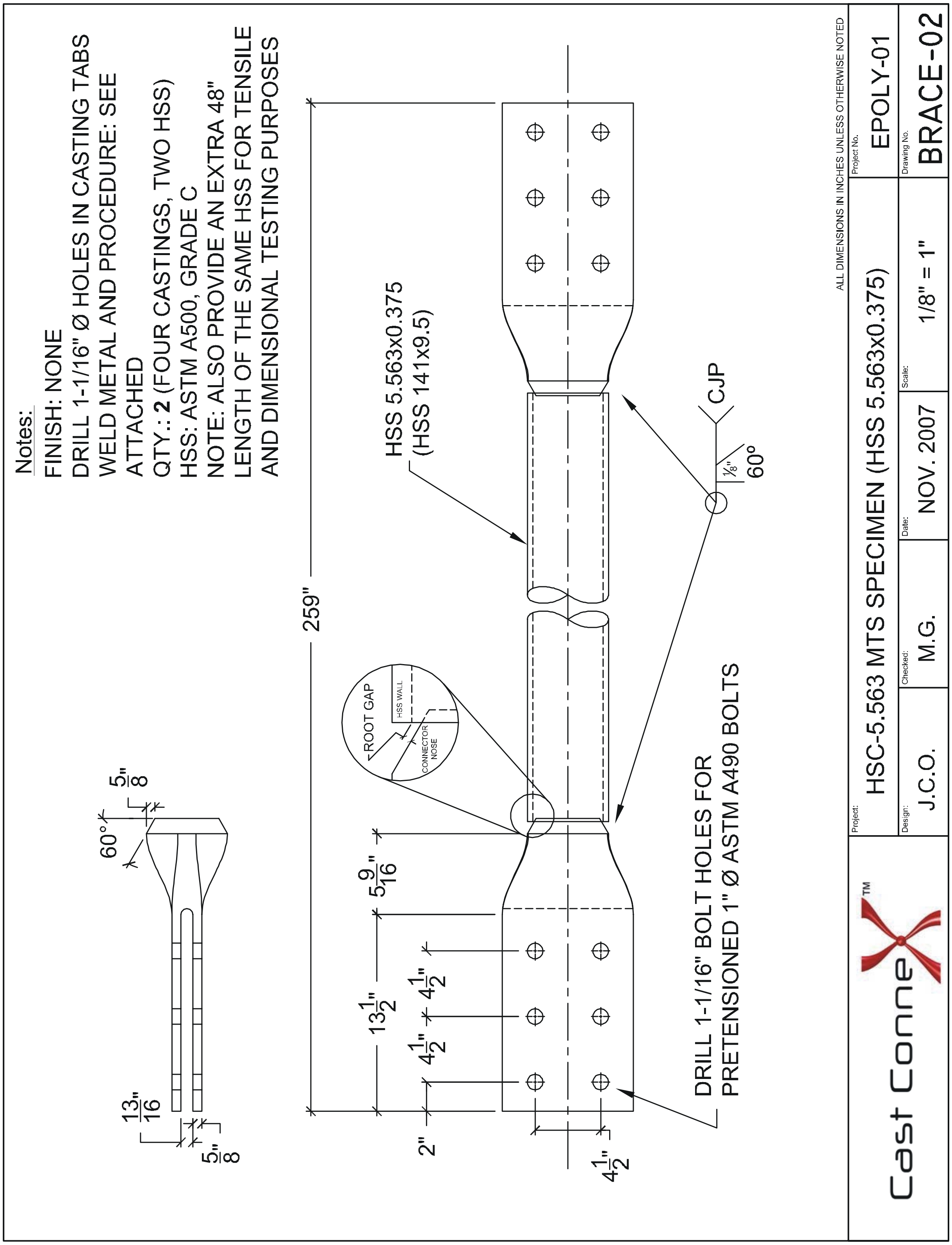

2998 mm
4279 mm
3503 mm
HSS 4.000x0.313 (HSS 102x8.0)
168"
35°
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project:
EQUIV. FRAME FOR HSC-4.000 (HSC-102)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.
Drawing No.
MTS-0IF
Cast ConneX™

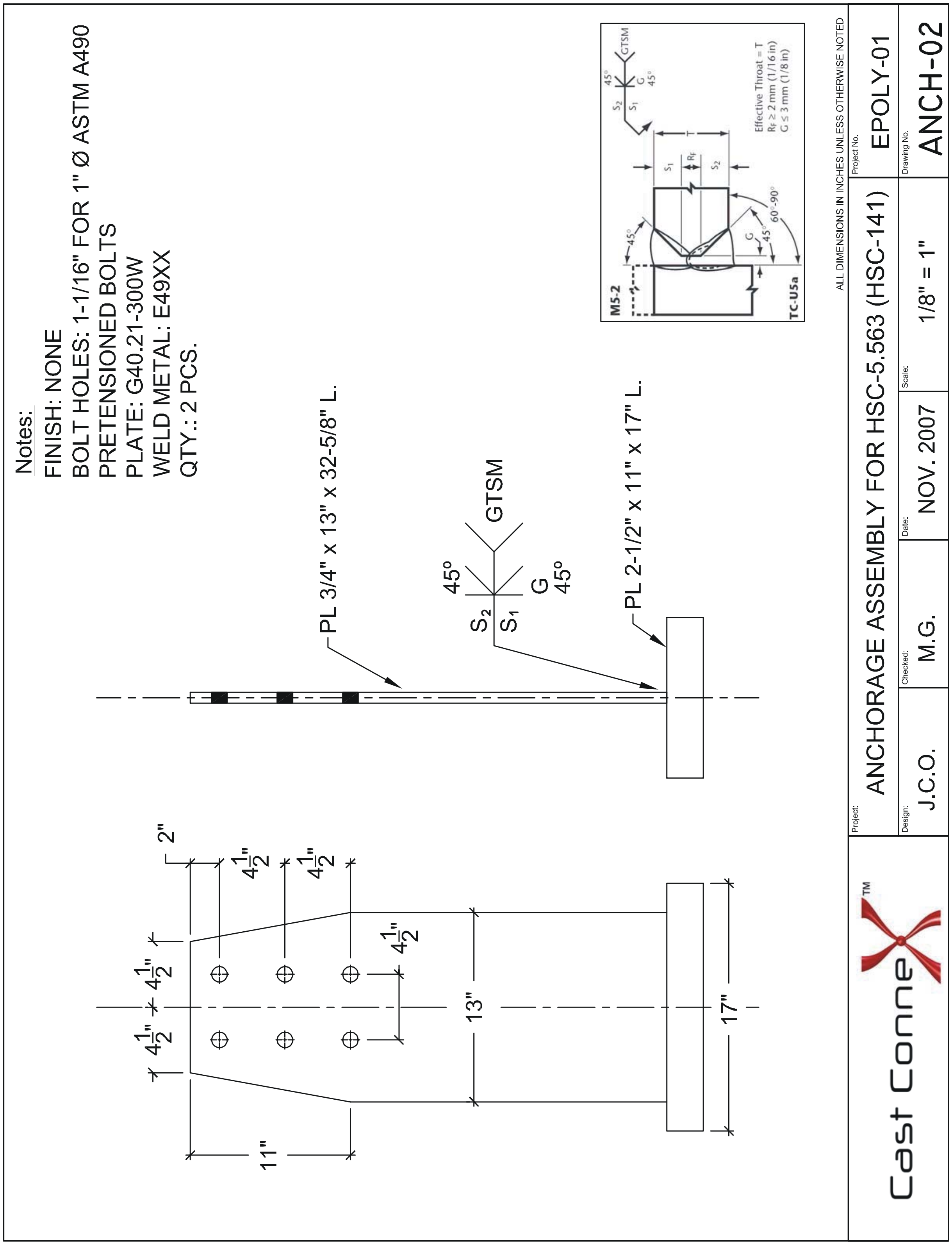

Notes:
FINISH: NONE
DRILL 13/16" Ø HOLES IN CASTING TABS
WELD METAL AND PROCEDURE: SEE ATTACHED
QTY.: 1 (TWO CASTINGS, ONE HSS)
HSS: ASTM A500, GRADE C
NOTE: ALSO PROVIDE AN EXTRA 48" LENGTH OF THE SAME HSS FOR TENSILE AND DIMENSIONAL TESTING PURPOSES
HSS 4.000x0.313
(HSS 102x8.0)
CJP
1/8"
60°
168"
ROOT GAP
HSS WALL
CONNECTOR NOSE
DRILL 13/16" BOLT HOLES FOR PRETENSIONED 3/4" Ø ASTM A490 BOLTS
60°
5/8"
9/16"
1/2"
4"
10 1/4"
3 1/2"
3 1/2"
1 1/2"
4"
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX™
Project:
HSC-4.000 MTS SPECIMEN (HSS 4.000x0.313)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
1/8" = 1"
Drawing No.
BRACE-01

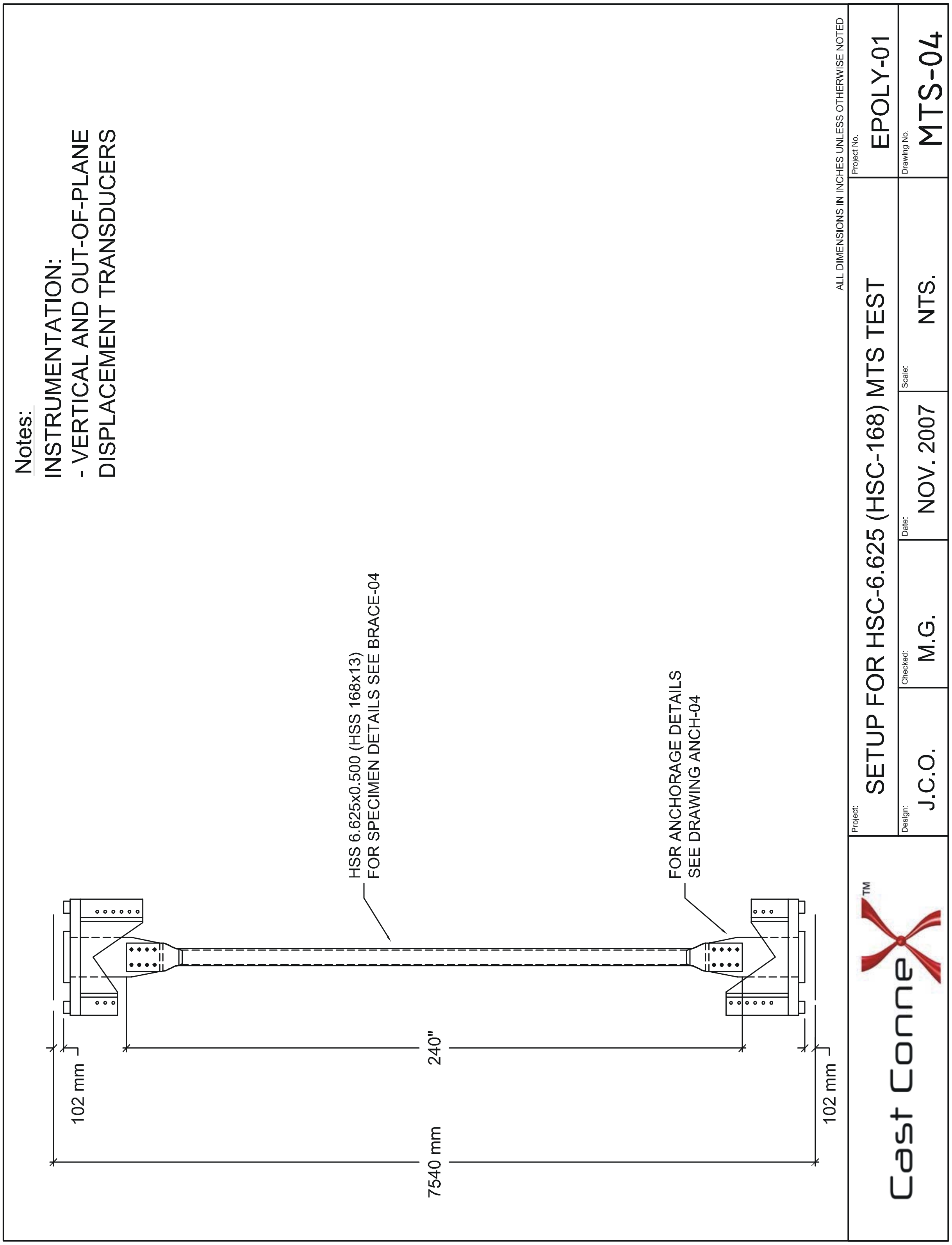

Notes:
FINISH: NONE
BOLT HOLES: 13/16" FOR 3/4" Ø ASTM A490
PRETENSIONED BOLTS
PLATE: G40.21-300W
WELD METAL: E49XX
QTY.: 2 PCS.
PL 1/2" x 12-1/2" x 28-7/8" L.
PL 2-1/2" x 11" x 16-1/2" L.
GTSM
45°
45°
G
S2
S1
M5-2
TC-U5a
Effective Throat = T
RF ≥ 2 mm (1/16 in)
G ≤ 3 mm (1/8 in)
60°-90°
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project:
ANCHORAGE ASSEMBLY FOR HSC-4.000 (HSC-102)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
1/8" = 1"
Drawing No.
ANCH-01
Cast Connex

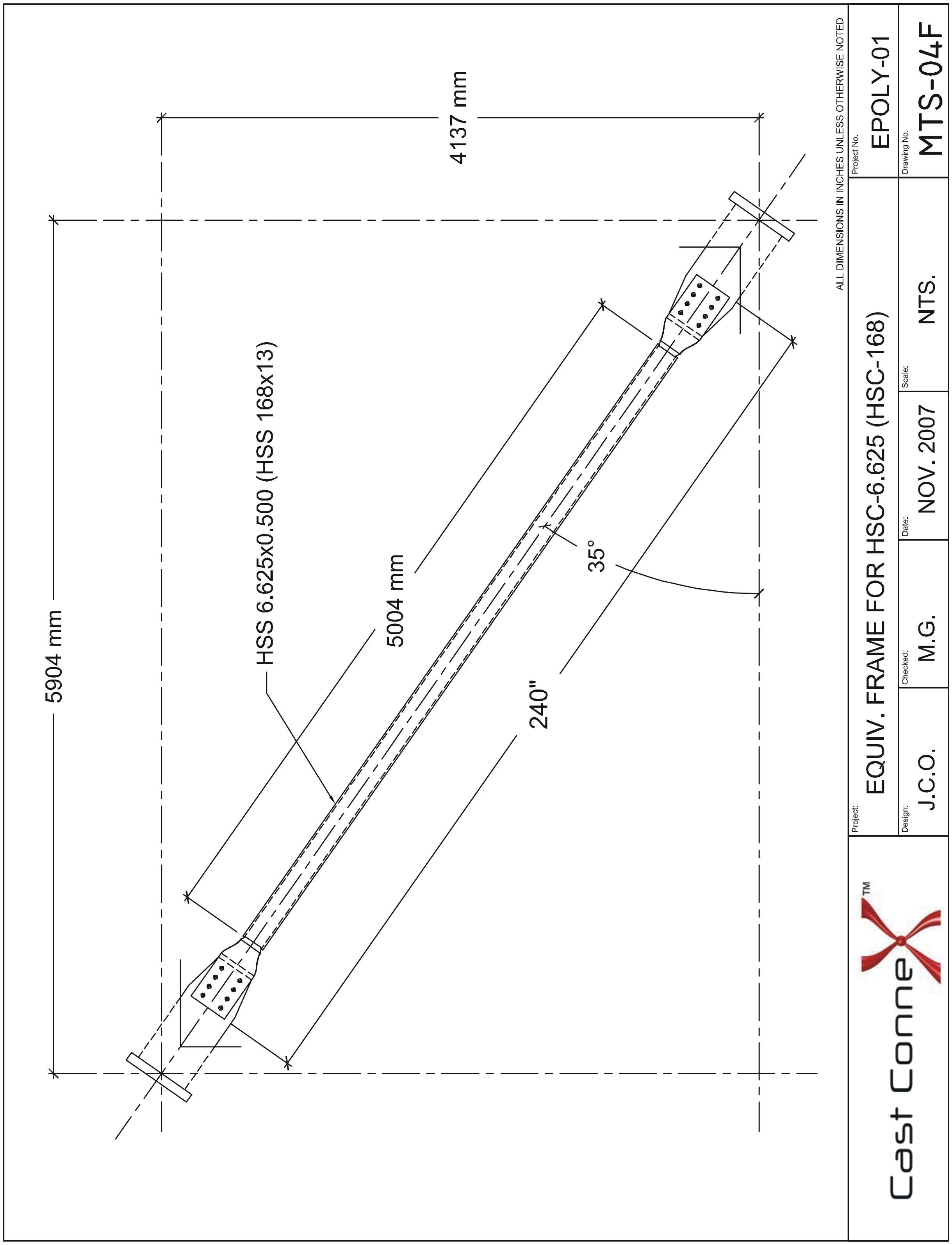

Notes:
INSTRUMENTATION:
- VERTICAL AND OUT-OF-PLANE DISPLACEMENT TRANSDUCERS
HSS 5.563x0.375 (HSS 141x9.5)
FOR SPECIMEN DETAILS SEE BRACE-02
FOR ANCHORAGE DETAILS
SEE DRAWING ANCH-02
102 mm
259"
102 mm
7911 mm
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX™
Project:
SETUP FOR HSC-5.563 (HSC-141) MTS TEST
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.
Drawing No.
MTS-02

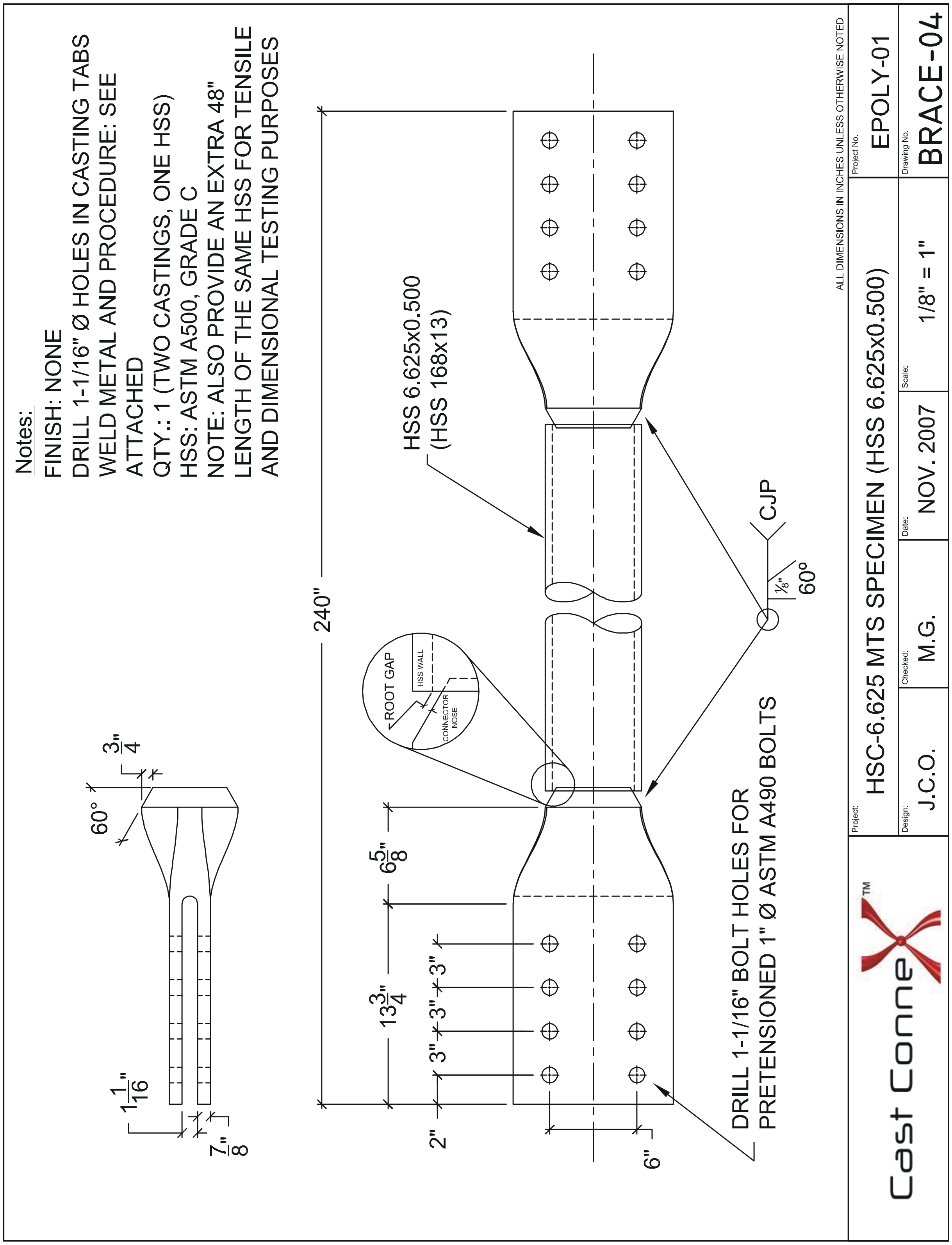

4349 mm
6208 mm
HSS 5.563x0.375 (HSS 141x9.5)
5564 mm
35°
259"
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project:
EQUIV. FRAME FOR HSC-5.563 (HSC-141)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.
Drawing No.
MTS-02F

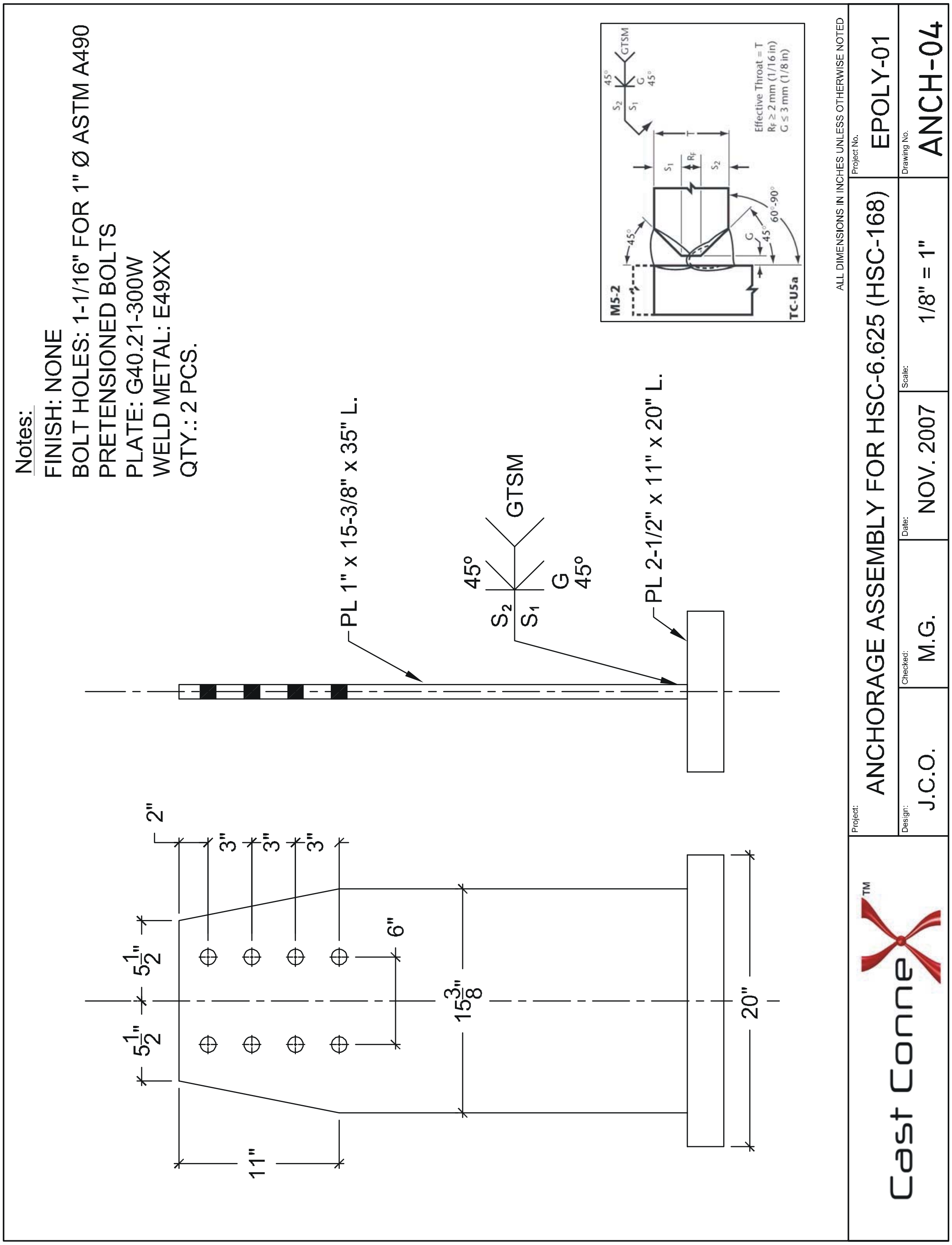

Notes:
FINISH: NONE
DRILL 1-1/16" Ø HOLES IN CASTING TABS
WELD METAL AND PROCEDURE: SEE ATTACHED
QTY.: **2** (FOUR CASTINGS, TWO HSS)
HSS: ASTM A500, GRADE C
NOTE: ALSO PROVIDE AN EXTRA 48" LENGTH OF THE SAME HSS FOR TENSILE AND DIMENSIONAL TESTING PURPOSES
HSS 5.563x0.375
(HSS 141x9.5)
CJP
60°
259"
ROOT GAP
HSS WALL
CONNECTOR NOSE
DRILL 1-1/16" BOLT HOLES FOR
PRETENSIONED 1" Ø ASTM A490 BOLTS
60°
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project:
HSC-5.563 MTS SPECIMEN (HSS 5.563x0.375)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
1/8" = 1"
Drawing No.
BRACE-02
Cast ConneX™

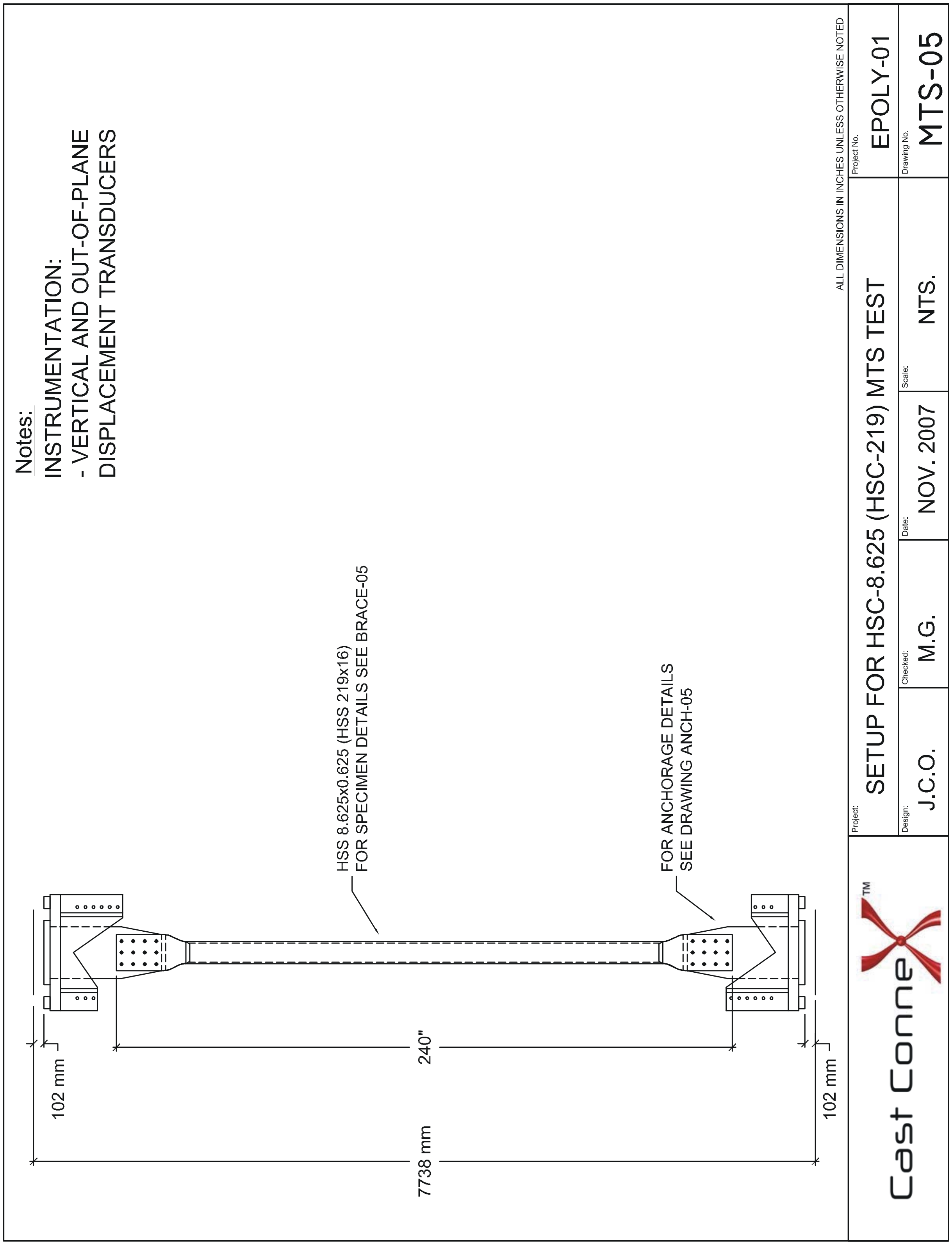

Notes:
FINISH: NONE
BOLT HOLES: 1-1/16" FOR 1" Ø ASTM A490
PRETENSIONED BOLTS
PLATE: G40.21-300W
WELD METAL: E49XX
QTY.: 2 PCS.
PL 3/4" x 13" x 32-5/8" L.
PL 2-1/2" x 11" x 17" L.
GTSM
45°
G
45°
S2
S1
2"
4 1/2"
4 1/2"
4 1/2"
4 1/2"
4 1/2"
4 1/2"
13"
17"
11"
M5-2
TC-U5a
45°
45°
60°-90°
G
T
S1
RF
S2
Effective Throat = T
RF ≥ 2 mm (1/16 in)
G ≤ 3 mm (1/8 in)
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX™
Project:
ANCHORAGE ASSEMBLY FOR HSC-5.563 (HSC-141)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
1/8" = 1"
Drawing No.
ANCH-02

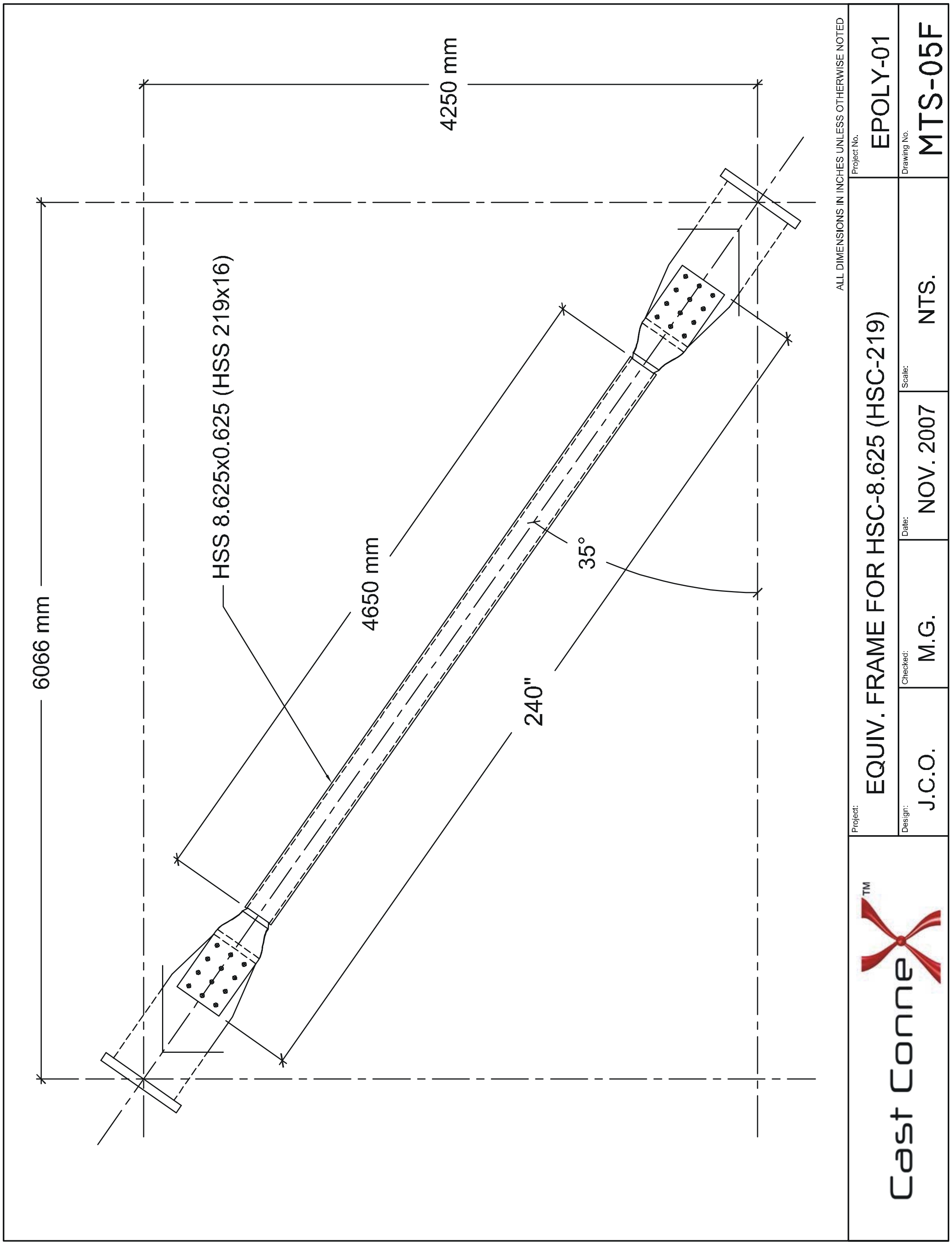

Notes:
INSTRUMENTATION:
- VERTICAL AND OUT-OF-PLANE
DISPLACEMENT TRANSDUCERS
HSS 6.625x0.500 (HSS 168x13)
FOR SPECIMEN DETAILS SEE BRACE-04
FOR ANCHORAGE DETAILS
SEE DRAWING ANCH-04
102 mm
240"
102 mm
7540 mm
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX
Project:
SETUP FOR HSC-6.625 (HSC-168) MTS TEST
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.
Drawing No.
MTS-04

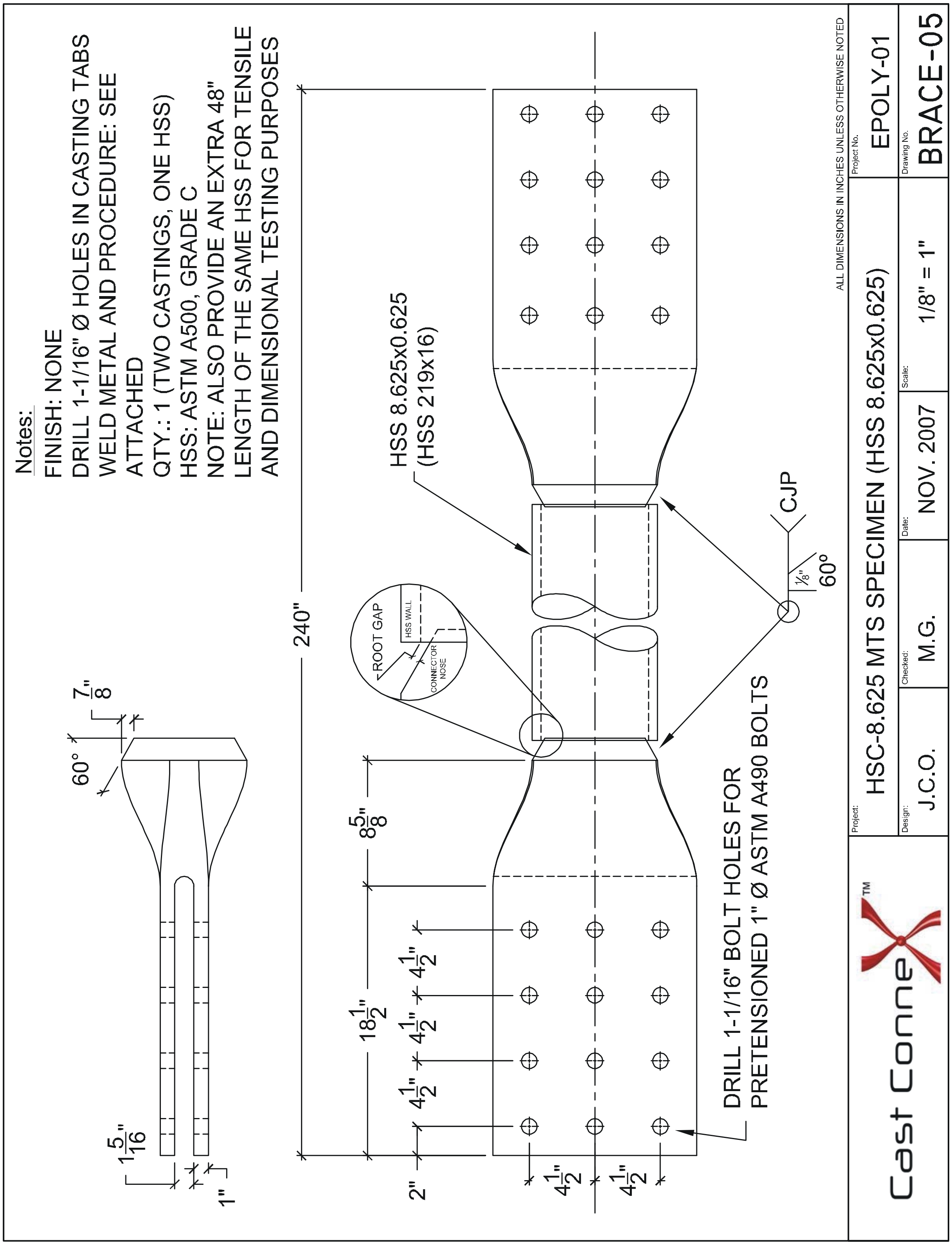

4137 mm
5904 mm
5004 mm
HSS 6.625x0.500 (HSS 168x13)
240"
35°
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project No.
EPOLY-01
Drawing No.
MTS-04F
Project:
EQUIV. FRAME FOR HSC-6.625 (HSC-168)
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.

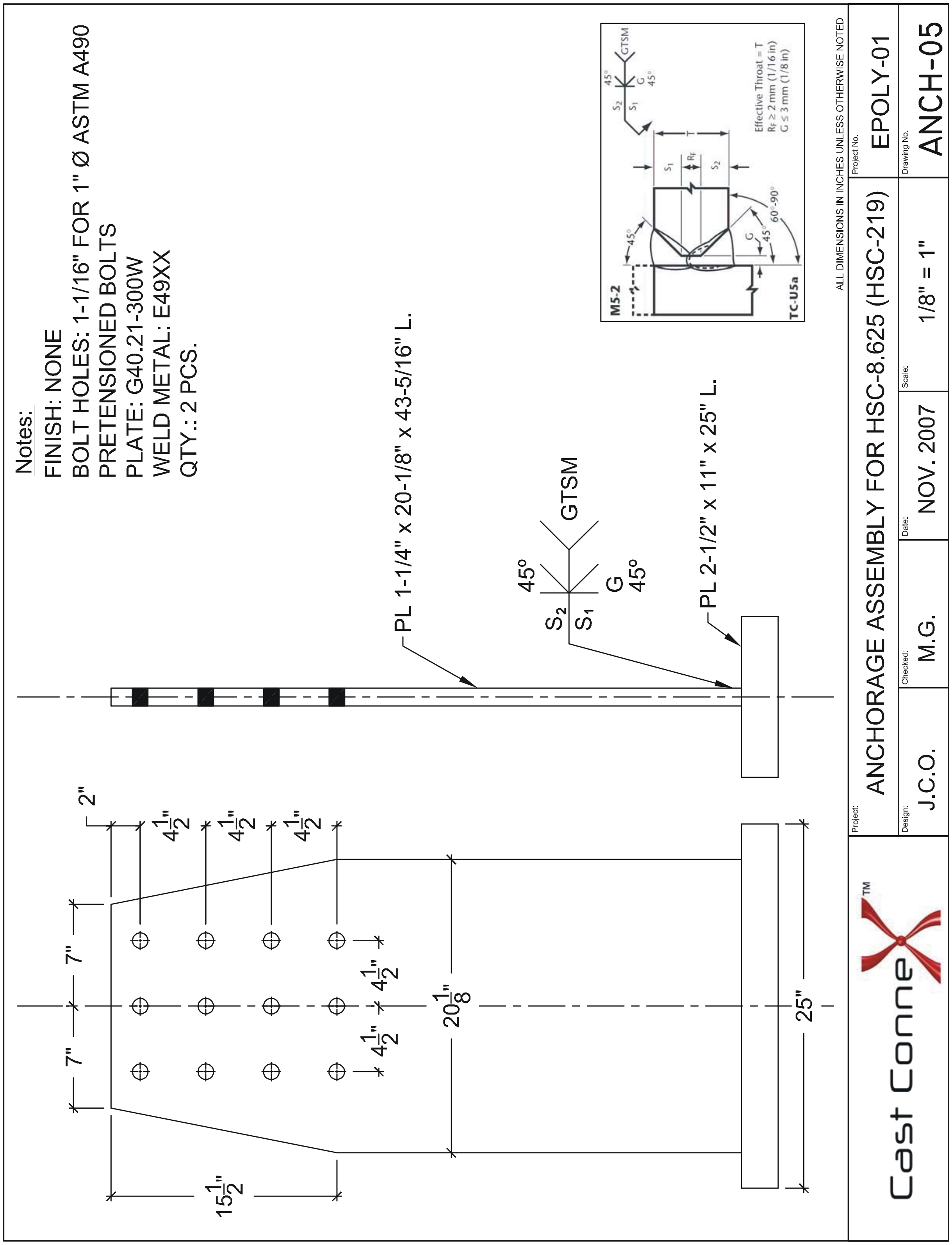

Notes:
FINISH: NONE
DRILL 1-1/16" Ø HOLES IN CASTING TABS
WELD METAL AND PROCEDURE: SEE ATTACHED
QTY.: 1 (TWO CASTINGS, ONE HSS)
HSS: ASTM A500, GRADE C
NOTE: ALSO PROVIDE AN EXTRA 48" LENGTH OF THE SAME HSS FOR TENSILE AND DIMENSIONAL TESTING PURPOSES
60°
240"
2"
3"
3"
3"
6"
ROOT GAP
HSS WALL
CONNECTOR NOSE
HSS 6.625x0.500
(HSS 168x13)
CJP
60°
DRILL 1-1/16" BOLT HOLES FOR PRETENSIONED 1" Ø ASTM A490 BOLTS
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX™
Project: HSC-6.625 MTS SPECIMEN (HSS 6.625x0.500)
Project No. EPOLY-01
Design: J.C.O.
Checked: M.G.
Date: NOV. 2007
Scale: 1/8" = 1"
Drawing No. BRACE-04


Notes:
FINISH: NONE
BOLT HOLES: 1-1/16" FOR 1" Ø ASTM A490
PRETENSIONED BOLTS
PLATE: G40.21-300W
WELD METAL: E49XX
QTY.: 2 PCS.
PL 1" x 15-3/8" x 35" L.
PL 2-1/2" x 11" x 20" L.
GTSM
45°
G
45°
S2
S1
2"
3"
3"
3"
6"
5 1/2"
5 1/2"
15 3/8"
20"
11"
M5-2
TC-U5a
Effective Throat = T
RF ≥ 2 mm (1/16 in)
G ≤ 3 mm (1/8 in)
60°-90°
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX
Project:
ANCHORAGE ASSEMBLY FOR HSC-6.625 (HSC-168)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
1/8" = 1"
Drawing No.
ANCH-04


Notes:
INSTRUMENTATION:
- VERTICAL AND OUT-OF-PLANE DISPLACEMENT TRANSDUCERS
HSS 8.625x0.625 (HSS 219x16)
FOR SPECIMEN DETAILS SEE BRACE-05
FOR ANCHORAGE DETAILS
SEE DRAWING ANCH-05
102 mm
240"
102 mm
7738 mm
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX™
Project:
SETUP FOR HSC-8.625 (HSC-219) MTS TEST
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.
Drawing No.
MTS-05


4250 mm
6066 mm
HSS 8.625x0.625 (HSS 219x16)
4650 mm
35°
240"
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project:
EQUIV. FRAME FOR HSC-8.625 (HSC-219)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
NTS.
Drawing No.
MTS-05F
Cast ConneX™


Notes:
FINISH: NONE
DRILL 1-1/16" Ø HOLES IN CASTING TABS
WELD METAL AND PROCEDURE: SEE ATTACHED
QTY.: 1 (TWO CASTINGS, ONE HSS)
HSS: ASTM A500, GRADE C
NOTE: ALSO PROVIDE AN EXTRA 48" LENGTH OF THE SAME HSS FOR TENSILE AND DIMENSIONAL TESTING PURPOSES
60°
7/8"
1 5/16"
1"
240"
8 5/8"
18 1/2"
4 1/2"
4 1/2"
4 1/2"
2"
4 1/2"
4 1/2"
HSS 8.625x0.625 (HSS 219x16)
ROOT GAP
HSS WALL
CONNECTOR NOSE
CJP
1/8"
60°
DRILL 1-1/16" BOLT HOLES FOR PRETENSIONED 1" Ø ASTM A490 BOLTS
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Cast ConneX™
Project:
HSC-8.625 MTS SPECIMEN (HSS 8.625x0.625)
Project No.
EPOLY-01
Design:
J.C.O.
Checked:
M.G.
Date:
NOV. 2007
Scale:
1/8" = 1"
Drawing No.
BRACE-05



Notes:
FINISH: NONE
BOLT HOLES: 1-1/16" FOR 1" Ø ASTM A490
PRETENSIONED BOLTS
PLATE: G40.21-300W
WELD METAL: E49XX
QTY.: 2 PCS.
PL 1-1/4" x 20-1/8" x 43-5/16" L.
PL 2-1/2" x 11" x 25" L.
GTSM
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
Project: ANCHORAGE ASSEMBLY FOR HSC-8.625 (HSC-219)
Project No. EPOLY-01
Design: J.C.O.
Checked: M.G.
Date: NOV. 2007
Scale: 1/8" = 1"
Drawing No. ANCH-05

APPENDIX B

Qualifying Test Protocol for Buckling-Restrained Braces

(Excerpt from AISC 2005 Seismic Provisions)

APPENDIX T

QUALIFYING CYCLIC TESTS OF BUCKLING-RESTRAINED BRACES

T1. SCOPE

This appendix includes requirements for qualifying cyclic tests of individual buckling-restrained braces and buckling-restrained brace subassemblages, when required in these provisions. The purpose of the testing of individual braces is to provide evidence that a buckling-restrained brace satisfies the requirements for strength and inelastic deformation by these provisions; it also permits the determination of maximum brace forces for design of adjoining elements. The purpose of testing of the brace subassemblage is to provide evidence that the brace-design can satisfactorily accommodate the deformation and rotational demands associated with the design. Further, the subassemblage test is intended to demonstrate that the hysteretic behavior of the brace in the subassemblage is consistent with that of the individual brace elements tested uniaxially.

Alternative testing requirements are permitted when approved by the engineer of record and the *authority having jurisdiction*.

This appendix provides only minimum recommendations for simplified test conditions.

T2. SYMBOLS

The numbers in parentheses after the definition of a symbol refers to the Section number in which the symbol is first used.

Δ_b Deformation quantity used to control loading of the test specimen (total brace end rotation for the *subassemblage test specimen*; total brace axial deformation for the *brace test specimen*) (T6).

Δ_{bm} Value of deformation quantity, Δ_b, corresponding to the *design story drift* (T6).

Δ_{by} Value of deformation quantity, Δ_b, at first significant yield of *test specimen* (T6).

T3. DEFINITIONS

Brace test specimen. A single buckling-restrained brace element used for laboratory testing intended to model the brace in the Prototype.

Design methodology. A set of step-by-step procedures, based on calculation or experiment, used to determine sizes, lengths, and details in the design of buckling-restrained braces and their connections.

Inelastic deformation. The permanent or plastic portion of the axial displacement in a buckling-restrained brace.

Prototype. The brace, connections, members, steel properties, and other design, detailing, and construction features to be used in the actual building frame.

Subassemblage test specimen. The combination of the brace, the connections and testing apparatus that replicate as closely as practical the axial and flexural deformations of the brace in the *prototype*.

Test specimen. Brace test specimen or subassemblage test specimen.

T4. SUBASSEMBLAGE TEST SPECIMEN

The *subassemblage test specimen* shall satisfy the following requirements:

(1) The mechanism for accommodating inelastic rotation in the subassemblage test specimen brace shall be the same as that of the *prototype*. The rotational deformation demands on the subassemblage test specimen brace shall be equal to or greater than those of the prototype.

(2) The axial yield strength of the steel core, P_{ysc}, of the brace in the subassemblage test specimen shall not be less than that of the prototype where both strengths are based on the core area, A_{sc}, multiplied by the yield strength as determined from a coupon test.

(3) The cross-sectional shape and orientation of the steel core projection of the subassemblage test specimen brace shall be the same as that of the brace in the prototype.

(4) The same documented design methodology shall be used for design of the subassemblage as used for the prototype, to allow comparison of the rotational deformation demands on the subassemblage brace to the prototype. In stability calculations, beams, columns, and gussets connecting the core shall be considered parts of this system.

(5) The calculated margins of safety for the prototype connection design, steel core projection stability, overall buckling and other relevant subassemblage test specimen brace construction details, excluding the gusset plate, for the prototype, shall equal or exceed those of the subassemblage test specimen construction.

(6) Lateral bracing of the subassemblage test specimen shall replicate the lateral bracing in the prototype.

(7) The *brace test specimen* and the prototype shall be manufactured in accordance with the same quality control and assurance processes and procedures.

Extrapolation beyond the limitations stated in this section shall be permitted subject to qualified peer review and approval by the *authority having jurisdiction*.

T5. BRACE TEST SPECIMEN

The *brace test specimen* shall replicate as closely as is practical the pertinent design, detailing, construction features, and material properties of the *prototype*.

T5.1. Design of Brace Test Specimen

The same documented *design methodology* shall be used for the brace test specimen and the prototype. The design calculations shall demonstrate, at a minimum, the following requirements:

(1) The calculated margin of safety for stability against overall buckling for the prototype shall equal or exceed that of the brace test specimen.

(2) The calculated margins of safety for the brace test specimen and the prototype shall account for differences in material properties, including yield and ultimate stress, ultimate elongation, and toughness.

T5.2. Manufacture of Brace Test Specimen

The brace test specimen and the prototype shall be manufactured in accordance with the same quality control and assurance processes and procedures.

T5.3. Similarity of Brace Test Specimen and Prototype

The brace test specimen shall meet the following requirements:

(1) The cross-sectional shape and orientation of the steel core shall be the same as that of the prototype.

(2) The axial yield strength of the steel core, P_{ysc}, of the brace test specimen shall not vary by more than 50 percent from that of the prototype where both strengths are based on the core area, A_{sc}, multiplied by the yield strength as determined from a coupon test.

(3) The material for, and method of, separation between the steel core and the buckling restraining mechanism in the brace test specimen shall be the same as that in the prototype.

Extrapolation beyond the limitations stated in this section shall be permitted subject to qualified peer review and approval by the *authority having jurisdiction*.

T5.4. Connection Details

The connection details used in the brace test specimen shall represent the prototype connection details as closely as practical.

T5.5. Materials

(1) Steel core: The following requirements shall be satisfied for the steel core of the brace test specimen:

   (a) The specified minimum yield stress of the brace test specimen steel core shall be the same as that of the prototype.

(b) The measured yield stress of the material of the steel core in the brace test specimen shall be at least 90 percent of that of the prototype as determined from coupon tests.

(c) The specified minimum ultimate stress and strain of the brace test specimen steel core shall not exceed those of the prototype.

(2) Buckling-restraining mechanism

Materials used in the buckling-restraining mechanism of the brace test specimen shall be the same as those used in the prototype.

T5.6. Connections

The welded, bolted, and pinned joints on the test specimen shall replicate those on the prototype as close as practical.

T6. LOADING HISTORY

T6.1. General Requirements

The *test specimen* shall be subjected to cyclic loads according to the requirements prescribed in Sections T6.2 and T6.3. Additional increments of loading beyond those described in Section T6.3 are permitted. Each cycle shall include a full tension and full compression excursion to the prescribed deformation.

T6.2. Test Control

The test shall be conducted by controlling the level of axial or rotational deformation, Δ_b, imposed on the test specimen. As an alternate, the maximum rotational deformation may be applied and maintained as the protocol is followed for axial deformation.

T6.3. Loading Sequence

Loads shall be applied to the test specimen to produce the following deformations, where the deformation is the steel core axial deformation for the test specimen and the rotational deformation demand for the *subassemblage test specimen* brace:

(1) 2 cycles of loading at the deformation corresponding to $\Delta_b = \Delta_{by}$

(2) 2 cycles of loading at the deformation corresponding to $\Delta_b = 0.50\Delta_{bm}$

(3) 2 cycles of loading at the deformation corresponding to $\Delta_b = 1\Delta_{bm}$

(4) 2 cycles of loading at the deformation corresponding to $\Delta_b = 1.5\Delta_{bm}$

(5) 2 cycles of loading at the deformation corresponding to $\Delta_b = 2.0\Delta_{bm}$.

(6) Additional complete cycles of loading at the deformation corresponding to $\Delta_b = 1.5\Delta_{bm}$ as required for the *brace test specimen* to achieve a cumulative inelastic axial deformation of at least 200 times the yield deformation (not required for the subassemblage test specimen).

The design story drift shall not be taken as less than 0.01 times the story height for the purposes of calculating Δ_{bm}. Other loading sequences are permitted to be used to qualify the test specimen when they are demonstrated to be of equal or greater severity in terms of maximum and cumulative inelastic deformation.

T7. INSTRUMENTATION

Sufficient instrumentation shall be provided on the *test specimen* to permit measurement or calculation of the quantities listed in Section T9.

T8. MATERIALS TESTING REQUIREMENTS

T8.1. Tension Testing Requirements

Tension testing shall be conducted on samples of steel taken from the same material as that used to manufacture the steel core. Tension test results from certified mill test reports shall be reported but are not permitted to be used in place of specimen testing for the purposes of this Section. Tension-test results shall be based upon testing that is conducted in accordance with Section T8.2.

T8.2. Methods of Tension Testing

Tension testing shall be conducted in accordance with ASTM A6, ASTM A370, and ASTM E8, with the following exceptions:

(1) The yield stress that is reported from the test shall be based upon the yield strength definition in ASTM A370, using the offset method of 0.002 strain.

(2) The loading rate for the tension test shall replicate, as closely as is practical, the loading rate used for the *test specimen*.

(3) The coupon shall be machined so that its longitudinal axis is parallel to the longitudinal axis of the steel core.

T9. TEST REPORTING REQUIREMENTS

For each *test specimen,* a written test report meeting the requirements of this Section shall be prepared. The report shall thoroughly document all key features and results of the test. The report shall include the following information:

(1) A drawing or clear description of the test specimen, including key dimensions, boundary conditions at loading and reaction points, and location of lateral bracing, if any.

(2) A drawing of the connection details showing member sizes, grades of steel, the sizes of all connection elements, welding details including filler metal, the size and location of bolt or pin holes, the size and grade of connectors, and all other pertinent details of the connections.

(3) A listing of all other essential variables as listed in Section T4 or T5, as appropriate.

(4) A listing or plot showing the applied load or displacement history.

(5) A plot of the applied load versus the deformation, Δ_b. The method used to determine the deformations shall be clearly shown. The locations on the *test specimen* where the loads and deformations were measured shall be clearly identified.

(6) A chronological listing of significant test observations, including observations of yielding, slip, instability, transverse displacement along the test specimen and fracture of any portion of the test specimen and connections, as applicable.

(7) The results of the material tests specified in Section T8.

(8) The manufacturing quality control and quality assurance plans used for the fabrication of the test specimen. These shall be included with the welding procedure specifications and welding inspection reports.

Additional drawings, data, and discussion of the test specimen or test results are permitted to be included in the report.

T10. ACCEPTANCE CRITERIA

At least one subassemblage test that satisfies the requirements of Section T4 shall be performed. At least one brace test that satisfies the requirements of Section T5, shall be performed. Within the required protocol range all tests shall satisfy the following requirements:

(1) The plot showing the applied load vs. displacement history shall exhibit stable, repeatable behavior with positive incremental stiffness.

(2) There shall be no fracture, brace instability or brace end connection failure.

(3) For brace tests, each cycle to a deformation greater than Δ_{by} the maximum tension and compression forces shall not be less than the nominal strength of the core.

(4) For brace tests, each cycle to a deformation greater than Δ_{by} the ratio of the maximum compression force to the maximum tension force shall not exceed 1.3.

Other acceptance criteria may be adopted for the *brace test specimen* or *subassemblage test specimen* subject to qualified peer review and approval by the *authority having jurisdiction*.

APPENDIX C

Mill Test Certificates

HSS 102x8.0 (HSS 4.000x0.313)
Certified to ASTM A500 Grades B & C
Standard Specification for Cold-Formed Welded and Seamless Carbon Steel Structural Tubing in Rounds and Shapes

WELDED TUBE OF CANADA
111 RAYETTE ROAD
CONCORD, ONTARIO L4K 2E9
FAX: (905) 738-4070
TEL: (905) 669-1111
TOLL FREE: 1-800-565-TUBE (8823)

TEST REPORT
RAPPORT D'ESSAI

NUMBER/NUMERO : 574622
DATE(M/M D/J Y/A): 12/18/07
PAGE: 1

ACIER LEROUX/DIV.RUSSEL METALS
1231 GRAHAM BELL AVE
BOUCHERVILLE
PQ J4B 5A1 CDA

YOUR P.O. NO. / VOTRE No DE COMMANDE	OUR ORDER NO./ NOTRE No DE COMMANDE	ITEM NO./ No DE L'ITEM	DESCRIPTION/ SIGNALEMENT
M 94015088	303402	025277	4.000-0.000-313-04-576.000 ASTM A500-03a GR B & C

HEAT NO. HEAT CODE	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Sn	V	Cb	Ti	N	B	ASA	Ca	CE		**YIELD** (0.2% offset) ksi(MPa)	*TENSILE* ksi(MPa)	1.5" wide strip ELONG 2",%
751182	.060	.630	.013	.006	.050	.046	.018	.040	.007	.005	.002	.047	.002	.004	.000	.038	.002	.179	TUBE	76.9(530)	81.1(559)	30.0

CE = C + Mn/6 + (Ni + Cu)/15 + (Cr + Mo + V)/5
ASA = Acid Soluble Aluminum
Country of Origin CANADA
Does not contain mercury, cadmium or lead.

We hereby certify that the product was manufactured, sampled, tested and inspected in accordance with the specification and any other requirements designated on the purchase order or contract. The tests were found to meet all such requirements.

Nous certifions que ce product a ete manufacture, echantillonne, eprouve et inspecte d'apres les specifications et autres exigences sur le bon de commande ou le contrat. Les essays ont rencontres tous les exigences.

LEROUX
094035089

QA003160/02

Authorized By/Authorize Par : DAVE DUFRESNE, Q. A. MANAGER
Welded Tube of Canada is Registered to the ISO 9001-2000 Quality System Standard

HSS 141x9.5 (HSS 5.563x0.375)

A copy of the mill test report was not available at the time of writing.

HSS 168x13 (HSS 6.625x0.500)
Certified to ASTM A500 Grades B & C
Standard Specification for Cold-Formed Welded and Seamless Carbon Steel Structural Tubing in Rounds and Shapes

Atlas Tube Canada ULC
200 Clark St.
Harrow, Ontario, Canada
N0R 1G0
Tel: 519-738-3541
Fax: 519-738-3537

Atlas TUBE

MATERIAL TEST REPORT

Ref.B/L: 80284628
Date: 03.10.2008
Customer: 1427

Sold to

Canam Steel
The Canam Manac Group
115 Boul, Canam Nord - C.P
ST. GEDEON DE BEAUCE Q
CANADA

Shipped to

Canam Steel
The Canam Manac Group
115 Bou, Canam NOrd - C.P
ST. GEDEON DE BEAUCE Q
CANADA

Material: 6.625x500x42'0"0(2x1)PB   Material No: R06625500   Made in: Canada
Sales order: 371564   Purchase Order: C-46551 * Hot

Heat No	Pcs	C	Mn	P	S	Si	Al	Cu	Cb	Mo	Ni	Cr	V
* B440G		0.200	0.850	0.011	0.007	0.020	0.030	0.030	0.000	0.000	0.010	0.020	0.000

Bundle No	Yield	Tensile	Eln.2in	Certification
M100722871	064088 Psi	073320 Psi	37.5 %	ASTM A500-03A GRADE B&C

Material Note:
Sales Or.Note:

Authorized by Quality Assurance: [signature]

The results reported on this report represent the actual attributes of the material furnished and indicate full compliance with all applicable specification and contract requirements.

Steel Tube Institute OF NORTH AMERICA   Page : 5 Of 5   Metals Service Center Institute

HSS 216x16 (HSS 8.625x0.625)
Certified to ASTM A106 (similar to ASTM A500 Grade C)
Standard Specification for Seamless Carbon Steel Pipe for High-Temperature Service

MITTAL

A02 Inspection certificate "3.1" (EN 10 204)

A03 Document No.: 077/1/07/BP - Rev.2

A07	Customer's Order (P.O.) No./Item No.: 3637/3899 TUBULAR STEEL	A08	Manufacturer's Works Order No.: 1511/66036/07
A11	Supplier's Order No.: SAP: 30011185	A10	Advice - Note No.:
308, B12/13	Quantity delivered: pcs 5; mtrs / feet 50.560 / 165.880; B13 Actual mass kgs 3835	A06	Customer / Consignee: Mittal Steel North America, One South Dearborn Street, Mall Code 6-018, Chicago, IL 60603, U.S.A.
B09-11	Dimensions: 8" x 0.594" (219.1 x 15.10 mm)		
B02	Steel designation: ASTM A106-06/ASME SA106-04 Gr.B API 5L X42/X52		

601, B03, 304 Product, conditions and terms of delivery:
Seamless steel line pipes acc. to API 5L 43[rd] edit. 2004 PSL-1 / ASTM A 106-06 / ASME SA 106-04 Gr.B / NACE MR0175-03, grade X42/X52, bevelled ends acc. to API 5L, DRL, lacquer finished, certified acc. to EN 10204/3.1-2004
Hot rolled as rolled

Z99 ☐ continues on appendix

A04, 306 Marking: Manufacturer's mark, mill inspector's stamp

2

C71-92 Heat and product chemical analyses (%) — C70 Steel made by basic oxygen process, fully killed, strand cast.

B07 Heat No.:	C	Mn	Si	P	S	Cu	Ni	Cr	Mo	V	Ti	B	Nb	C_{eq}
65752K	0.114	1.35	0.223	0.010	0.009	0.12	0.04	0.05	0.004	0.071	0.012	0.00050	0.043	0.208
	0.112	1.350	0.222	0.011	0.009	0.115	0.036	0.053	0.004	0.074	0.013	0.0005	0.043	0.2061
	0.113	1.340	0.219	0.010	0.008	0.112	0.036	0.052	0.004	0.073	0.013	0.0005	0.042	0.2062

Z99 ☐ continues on appendix

B07 Test results: Heat No.	C00 Specimen No.	C11 Yield Point (psi)	C12 Tensile Strength (psi)	C13 Elongation (% 2")	C40-43 Impact Test (ft-lb)	C30-32 Hardness (HRB)
	B	35000 min.	60000 min.	30 min.		
	X42	42000 min.	60000 min.	30 min.		
C04 Requirements:	X52	52000 min.	66000 min.	27 min.	Ø	99 max.
65752K		64687	83107	37.5		89.4

Z99 ☐ continues on appendix

D01	Visual and dimensional inspection with satisfactory results	☒	D51	Hydraulic test - min. test pressure and test pressure duration psi / s	3000 / 5
C50	Flattening test - satisfactory	☒	D02	The pipes tested on tightness by NDT - in acc. to	☐
C51	Expanding test - satisfactory	☐			
C52	Bending test - satisfactory	☐			
C53	Ring expanding test (DIN EN 10236) - satisfactory	☐	D03	Nondestructive Elektromagnetic Testing	☐
C54	Ring tensile test (DIN EN 10237) - satisfactory	☐			

22 HRC = 99 HRB max., Mercury free, No Repair by Welding
MSNA Order No.: 3637/3899 Customer Name : TUBULAR STEEL Vessel name : MARITIME PEACE

Z01 All pipes conform to the above mentioned standards and ordering requirements and agreements.

Z02 Date of issue 19.6.2007/P Tel.:++420 595683644 / Fax:++420 595682062

APPENDIX D

Tensile Test Results

Physical properties determined from tensile tests carried out on coupons cut from supplementary HSS segments of the same heat and length as those which were used in the fabrication of the brace assemblies.

Shape	E (MPa)	$F_{y,\ 0.2\%}$ (MPa)	$F_{y,\ 0.5\%}$ (MPa)	F_u (MPa)	ε_u (%)	ε_{max} (%)
HSS 102 x 8.0	176700	540	539	563	0.014	0.131
	180700	521	522	548	0.030	0.178
	186100	502	506	534	0.054	0.202
HSS 141 x 9.5	XX	XX	XX	XX	XX	XX
	XX	XX	XX	XX	XX	XX
	XX	XX	XX	XX	XX	XX
HSS 168 x 13	202100	471	474	509	0.089	0.319
	225700	491	494	516	0.040	0.282
	210400	458	461	501	0.099	0.300
HSS 219 x 16	229000	429	431	565	0.119	0.334
	236300	432	433	557	0.105	0.323
	230800	431	433	561	0.107	0.293

X: Sample not available at time of report writing.

APPENDIX E

Chemical & Physical Analyses, Magnetic Particle Inspection, and Ultrasonic Examination Reports for Steel Castings

Casting Part Numbers	Brace Specimen	Casting Serial Numbers
HSC-102	HSS 102x8.0	41093A 41093D
HSC-141	HSS 141x9.5	41133A 41133B
HSC-168	HSS 168x13	41214A 41214F
HSC-219	HSS 219x16	41289B 41289C

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:21:14

Product#. . . : 47101
Customer Part#: HSC-102
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

Order/Item# . : 103542 / 1
Customer P.O.#: 0703

From: A. G. Anderson Ltd.
3040 Osler Street
London, Ontario

Phone: (519) 455-5420
Fax: (519) 455-0621

* * * * ISO 9001 Registration # CA03/2880.0 * * * *

Melt#	Quantity	Date	Heat Treat	SN#-SN#-SN#	Specification
B070698	1	11/29/07		41093 -A -	ASTM A958 Grade 80/50

. . . . C H E M I C A L S . . . .

C :.2130	SI:.4400	MN:.7360	P :.0150
S :.0090	CR:.5080	MO:.2300	NI:.6900

. . . . P H Y S I C A L S . . . .

Tensile	95188 PSI	Yield	72717 PSI
Elongation	22.3 %	Reduction	56.6 %
Impact @degC	-20 Deg C	Sample 1	68.0 JOULES
Sample 2	65.0 JOULES	Sample 3	70.0 JOULES

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:21:14

Product#. . . : 47101
Customer Part#: HSC-102
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

Order/Item# . : 103542 / 1
Customer P.O.#: 0703

***** Magnetic Particle Inspection Report *****

Code or Specification: ASTM E709 (2001)
Acceptance Level: ASTM A903/A903M (2003) Level 3
Test Procedure: AGA-2005-01-MP (2005)
Magnetizing Unit: Magnaflux TAQ-524 Wet Bench (FWDC)
Unit Serial Number: 73503
Calibration Date: September 14, 2007
Calibration Due Date: March 14 2008
Inspection Medium: Magnaflux 14A Redi-Bath
Medium Batch Number: 07H083
Method Used: Wet fluorescent, continuous
Personnel Qualification: CGSB 48.9712 level II

Date Tested: January 08, 2008
Shop Order Number: 41093-1
Serial Number: 41093-A
Part Number: HSC-102
Part Description: High Strength Connector
Inspected Area: 100 % (where accessible)
Inspection Results: No relevant indications noted
Acceptable Quantity: 1

Comments: Part tested & Inspected in the finished cast condition.

Inspector Signature: _______________
David Henrys

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:21:18

Product#. . . : 47101 Order/Item# . : 103542 / 1
Customer Part#: HSC-102 Customer P.O.#: 0703
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

From: A. G. Anderson Ltd. Phone: (519) 455-5420
3040 Osler Street Fax: (519) 455-0621
London, Ontario

* * * * ISO 9001 Registration # CA03/2880.0 * * * *

Melt#	Quantity	Date	Heat Treat	SN#-SN#-SN#	Specification
B070698	1	11/29/07		41093 -D -	ASTM A958 Grade 80/50

. . . . C H E M I C A L S . . . .

C :.2130	SI:.4400	MN:.7360	P :.0150
S :.0090	CR:.5080	MO:.2300	NI:.6900

. . . . P H Y S I C A L S . . . .

Tensile	95188 PSI	Yield	72717 PSI
Elongation	22.3 %	Reduction	56.6 %
Impact @degC	-20 Deg C	Sample 1	68.0 JOULES
Sample 2	65.0 JOULES	Sample 3	70.0 JOULES

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:21:18

Product#. . . : 47101 Order/Item# . : 103542 / 1
Customer Part#: HSC-102 Customer P.O.#: 0703
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

***** Magnetic Particle Inspection Report *****

Code or Specification: ASTM E709 (2001)
Acceptance Level: ASTM A903/A903M (2003) Level 3
Test Procedure: AGA-2005-01-MP (2005)
Magnetizing Unit: Magnaflux TAQ-524 Wet Bench (FWDC)
Unit Serial Number: 73503
Calibration Date: September 14, 2007
Calibration Due Date: March 14 2008
Inspection Medium: Magnaflux 14A Redi-Bath
Medium Batch Number: 07H083
Method Used: Wet fluorescent, continuous
Personnel Qualification: CGSB 48.9712 level II

Date Tested: January 9, 2008
Shop Order Number: 41093-1
Serial Number: 41093-D
Part Number: HSC-102
Part Description: High Strength Connector
Inspected Area: 100 % (where accessible)
Inspection Results: No relevant indications noted
Acceptable Quantity: 1

Comments: Part tested & Inspected in the finished cast condition.

Inspector Signature: ____________
Darryl Ulrich

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:27:20

Product#. . . : 47105
Customer Part#: HSC-141
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

Order/Item# . : 103551 / 1
Customer P.O.#: 0704

From: A. G. Anderson Ltd.
3040 Osler Street
London, Ontario

Phone: (519) 455-5420
Fax: (519) 455-0621

* * * * ISO 9001 Registration # CA03/2880.0 * * * *

Melt#	Quantity	Date	Heat Treat	SN#-SN#-SN#	Specification
B070698	2	11/29/07		41133 -A -B	ASTM A958 Grade 80/50

. . . . C H E M I C A L S . . . .

C :.2130	SI:.4400	MN:.7360	P :.0150
S :.0090	CR:.5080	MO:.2300	NI:.6900

. . . . P H Y S I C A L S . . . .

Tensile	95188 PSI	Yield	72717 PSI
Elongation	22.3 %	Reduction	56.6 %
Impact @degC	-20	Sample 1	68.0 JOULES
Sample 2	65.0 JOULES	Sample 3	70.0 JOULES

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:27:20

Product#. . . : 47105
Customer Part#: HSC-141
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

Order/Item# . : 103551 / 1
Customer P.O.#: 0704

***** Magnetic Particle Inspection Report *****

Code or Specification: ASTM E709 (2001)
Acceptance Level: ASTM A903/A903M (2003) Level 3
Test Procedure: AGA-2005-01-MP (2005)
Magnetizing Unit: Magnaflux TAQ-524 Wet Bench (FWDC)
Unit Serial Number: 73503
Calibration Date: September 14, 2007
Calibration Due Date: March 14 2008
Inspection Medium: Magnaflux 14A Redi-Bath
Medium Batch Number: 07H083
Method Used: Wet fluorescent, continuous
Personnel Qualification: CGSB 48.9712 level II

Date Tested: February 02, 2008
Shop Order Number: 41133-1
Serial Number: 41133-A & 41133-B
Part Number: HSC-141
Part Description: High Strength Connector
Inspected Area: 100 % (where accessible)
Inspection Results: No relevant indications noted
Acceptable Quantity: Two

Comments: Part tested & Inspected in the finished cast condition.

Inspector Signature: ______________
Jose M. Leal

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:28:08

Product#. . . : 47106 Order/Item# . : 103610 / 1
Customer Part#: HSC-168 Customer P.O.#: 0705
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

From: A. G. Anderson Ltd. Phone: (519) 455-5420
3040 Osler Street Fax: (519) 455-0621
London, Ontario

* * * * ISO 9001 Registration # CA03/2880.0 * * * *

Melt#	Quantity	Date	Heat Treat	SN#-SN#-SN#	Specification
C070689	1	12/04/07		41214 -A -	ASTM A958 Grade 80/50

. . . . C H E M I C A L S . . . .

C :.1920	SI:.4900	MN:.7670	P :.0130
S :.0160	CR:.5900	MO:.2400	NI:.6800

. . . . P H Y S I C A L S . . . .

Tensile	87955 PSI	Yield	65695 PSI
Elongation	22.1 %	Reduction	49.7 %
Impact @degC	-20	Sample 1	58.0 JOULES
Sample 2	56.0 JOULES	Sample 3	57.0 JOULES

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:28:08

Product#. . . : 47106 Order/Item# . : 103610 / 1
Customer Part#: HSC-168 Customer P.O.#: 0705
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

***** Magnetic Particle Inspection Report *****

Code or Specification: ASTM E709
Acceptance Level: ASTM A903 Level 3
Test Procedure: AGA-2005-01-MP (2005)
Magnetizing Unit: Magnaflux TAQ-524 Wet Bench (FWDC)
Unit Serial Number: 73503
Calibration Date: September 14, 2007
Calibration Due Date: March 14 2008
Inspection Medium: Magnaflux 14A Redi-Bath
Medium Batch Number: 07H083
Method Used: Wet fluorescent, continuous
Personnel Qualification: CGSB 48.9712 level II

Date Tested: January 29, 2008
Shop Order Number: 41214-1
Serial Number: 41214-A
Part Number: HSC-168
Part Description: High Strength Connector
Inspected Area: 100 % (where accessible)
Inspection Results: No relevant indications noted
Acceptable Quantity: 1

Comments: Part tested & Inspected in the finished cast condition.

Inspector Signature: ____________
David Henrys

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:28:10

```
Product#. . . : 47106                    Order/Item# . :  103610 /   1
Customer Part#: HSC-168                  Customer P.O.#: 0705
Customer. . . : Cast Connex Corporation
                101 College Street
                Suite 320
                MaRS Centre, Heritage Building
                Toronto ON M5G 1L7
                Canada

      From: A. G. Anderson Ltd.          Phone:  (519) 455-5420
            3040 Osler Street              Fax:  (519) 455-0621
            London, Ontario

        * * * * ISO 9001 Registration # CA03/2880.0 * * * *

 Melt#    Quantity   Date    Heat Treat   SN#-SN#-SN#       Specification
-------- --------  -------- ----------  ---------------  ------------------------
C070689        1  12/04/07              41214 -F    -    ASTM A958 Grade 80/50

   . . . . . . . . . . . . . C H E M I C A L S . . . . . . . . . . . .
    C :.1920         SI:.4900         MN:.7670         P :.0130
    S :.0160         CR:.5900         MO:.2400         NI:.6800

   . . . . . . . . . . . . . P H Y S I C A L S . . . . . . . . . . . .
   Tensile      87955 PSI                  Yield        65695 PSI
   Elongation   22.1 %                     Reduction    49.7 %
   Impact @degC -20                        Sample 1     58.0     JOULES
   Sample 2     56.0      JOULES           Sample 3     57.0     JOULES
```

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:28:10

```
Product#. . . : 47106                    Order/Item# . :  103610 /   1
Customer Part#: HSC-168                  Customer P.O.#: 0705
Customer. . . : Cast Connex Corporation
                101 College Street
                Suite 320
                MaRS Centre, Heritage Building
                Toronto ON M5G 1L7
                Canada

   *****       Magnetic Particle Inspection Report        *****

     Code or Specification: ASTM E709
          Acceptance Level: ASTM A903 Level 3
            Test Procedure: AGA-2005-01-MP (2005)
          Magnetizing Unit: Magnaflux TAQ-524 Wet Bench (FWDC)
        Unit Serial Number: 73503
          Calibration Date: September 14, 2007
      Calibration Due Date: March 14 2008
         Inspection Medium: Magnaflux 14A Redi-Bath
       Medium Batch Number: 07H083
               Method Used: Wet fluorescent, continuous
  Personnel Qualification: CGSB 48.9712 level II

               Date Tested: January 14, 2008
         Shop Order Number: 41214-1
             Serial Number: 41214-F
               Part Number: HSC-168
          Part Description: High Strength Connector
            Inspected Area: 100 % (where accessible)
        Inspection Results: No relevant indications noted
       Acceptable Quantity: One

   Comments: Part tested & Inspected in the finished cast
             condition.

                   Inspector Signature: _______________
                                          Jose M. Leal
```

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:28:41

Product#. . . : 47109
Customer Part#: HSC-219
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

Order/Item# . : 103641 / 1
Customer P.O.#: 0706

From: A. G. Anderson Ltd.
3040 Osler Street
London, Ontario

Phone: (519) 455-5420
Fax: (519) 455-0621

* * * * ISO 9001 Registration # CA03/2880.0 * * * *

Melt#	Quantity	Date	Heat Treat	SN#-SN#-SN#	Specification
C070678	1	11/28/07		41289 -B -	ASTM A958 Grade 80/50

. . . . C H E M I C A L S . . . .

C :.1950	SI:.5000	MN:.7700	P :.0190
S :.0110	CR:.5500	MO:.2300	NI:.6200

. . . . P H Y S I C A L S . . . .

Tensile	102095 PSI	Yield	83595 PSI
Elongation	22.5 %	Reduction	54.0 %
Impact @degC	-20	Sample 1	50.0 JOULES
Sample 2	54.0 JOULES	Sample 3	54.0 JOULES

2/14/08 CHEMICAL AND PHYSICAL ANALYSIS 12:28:41

Product#. . . : 47109
Customer Part#: HSC-219
Customer. . . : Cast Connex Corporation
101 College Street
Suite 320
MaRS Centre, Heritage Building
Toronto ON M5G 1L7
Canada

Order/Item# . : 103641 / 1
Customer P.O.#: 0706

***** Magnetic Particle Inspection Report *****

Code or Specification: ASTM E709 (2001)
Acceptance Level: ASTM A903/A903M (2003) Level 3
Test Procedure: AGA-2005-01-MP (2005)
Magnetizing Unit: Magnaflux TAQ-524 Wet Bench (FWDC)
Unit Serial Number: 73503
Calibration Date: September 14, 2007
Calibration Due Date: March 14 2008
Inspection Medium: Magnaflux 14A Redi-Bath
Medium Batch Number: 07H083
Method Used: Wet fluorescent, continuous
Personnel Qualification: CGSB 48.9712 level II

Date Tested: February 04, 2008
Shop Order Number: 41289-1
Serial Number: 41289-B,
Part Number: HSC-219
Part Description: High Strength Connector
Inspected Area: 100 % (where accessible)
Inspection Results: No relevant indications noted
Acceptable Quantity: 1

Comments: Part tested & Inspected in the finished cast condition.

Inspector Signature: ____________
Jose M. Leal

```
2/14/08                    CHEMICAL AND PHYSICAL ANALYSIS                12:28:44

Product#. . . : 47109                          Order/Item# . :  103641 /   1
Customer Part#: HSC-219                        Customer P.O.#: 0706
Customer. . . : Cast Connex Corporation
                101 College Street
                Suite 320
                MaRS Centre, Heritage Building
                Toronto ON M5G 1L7
                Canada
-----------------------------------------------------------------------------
         From: A. G. Anderson Ltd.             Phone:  (519) 455-5420
               3040 Osler Street                 Fax:  (519) 455-0621
               London, Ontario

           * * * * ISO 9001 Registration # CA03/2880.0 * * * *
      ---------------------------------------------------------------------

 Melt#    Quantity   Date   Heat Treat   SN#-SN#-SN#        Specification
-------- -------- -------- ---------- --------------- -------------------------
C070678        1  11/28/07               41289 -C    -   ASTM A958 Grade 80/50

    . . . . . . . . . . . . .  C H E M I C A L S  . . . . . . . . . . . .
     C :.1950          SI:.5000          MN:.7700          P :.0190
     S :.0110          CR:.5500          MO:.2300          NI:.6200

    . . . . . . . . . . . . .  P H Y S I C A L S  . . . . . . . . . . . .
    Tensile       102095 PSI                      Yield        83595 PSI
    Elongation    22.5 %                          Reduction    54.0 %
    Impact @degC -20                              Sample 1     50.0    JOULES
    Sample 2      54.0    JOULES                  Sample 3     54.0    JOULES
```

```
2/14/08                    CHEMICAL AND PHYSICAL ANALYSIS                12:28:44

Product#. . . : 47109                          Order/Item# . :  103641 /   1
Customer Part#: HSC-219                        Customer P.O.#: 0706
Customer. . . : Cast Connex Corporation
                101 College Street
                Suite 320
                MaRS Centre, Heritage Building
                Toronto ON M5G 1L7
                Canada
-----------------------------------------------------------------------------
   *****        Magnetic Particle Inspection Report        *****

     Code or Specification: ASTM E709 (2001)
          Acceptance Level: ASTM A903/A903M (2003) Level 3
            Test Procedure: AGA-2005-01-MP (2005)
          Magnetizing Unit: Magnaflux TAQ-524 Wet Bench (FWDC)
        Unit Serial Number: 73503
          Calibration Date: September 14, 2007
      Calibration Due Date: March 14 2008
         Inspection Medium: Magnaflux 14A Redi-Bath
       Medium Batch Number: 07H083
               Method Used: Wet fluorescent, continuous
   Personnel Qualification: CGSB 48.9712 level II

               Date Tested: February 04, 2008
         Shop Order Number: 41289-1
             Serial Number: 41289-C,
               Part Number: HSC-219
          Part Description: High Strength Connector
            Inspected Area: 100 % (where accessible)
        Inspection Results: No relevant indications noted
       Acceptable Quantity: 1

   Comments: Part tested & Inspected in the finished cast
             condition.

                      Inspector Signature: ______________
                                              Jose M. Leal
-----------------------------------------------------------------------------
```

AITEC®

ULTRASONIC EXAMINATION REPORT

Branch Office: 60 Otonabee Dr., Kitchener, ON N2C 1L6 Tel. (519) 893-6760 * Fax (519) 893-2191

Job Number: 52050122	Client Specifications: ASTM A609
Client Name: [redacted]	Acceptance: ASTM A609 Class I
Date/Time Of Examination: January 16, 2008	Procedure: UT-GP-01 Rev. 5
Work Location: London, Ontario	Technique: Contact
	P.O. Number:

Type of Fabrication: **Weld** ☐ **Casting** ☐ **Forging** ☒ **Plate** ☐ **Other** ☐

Part/Assy No.:	Dwg No.:	Heat No.:	Pattern No.:
HSC-219			Product #47109

Scope: Ultrasonic Inspection was performed on (23) twenty three pieces.

Serial Numbers: 41133A, 41133B, 41133C, 41133D, 41133E, 41133F, 41214A, 41214B, 41214E, 41214F
41214G, 41289D, 42055A, 41093A, 41093B, 41093C, 41093D, 41288A, 41288B, 41288C
41289A, 41289B, 41289C

Results:. All (23) twenty three pieces were found to have no rejectable discontinuities located.

Total Parts Inspected	Total Parts Accepted	Total Parts Rejected
23	23	0

Scan: A Scan

Surface Finish: As Cast

ULTRASONIC EQUIPMENT				TRANSDUCER			
Make	**Model**	**S/N**	**Cal. Date**	**Angle**	**Size**	**Frequency**	**S/N**
Panametrics	Epoch IV	40214506	Jan 18/08	0° Dual	.5 x .5	2.25 MHz	024711

Calibration Block: 4340 Steel	**Serial No.:** 92-7938
Couplant: Ecogel	**Batch No.:** 06248

AITEC TECHNICIAN: Print Name **D. ROTHERY** (As per Mike Wood) Signature	**Certification:** ACCP Level II ☐ CGSB 48.9712 Level 2 ☐ SNT-TC-1A Level II ☑
CLIENT REPRESENTATIVE FINAL ACCEPTANCE: Print Name	Signature Date

HEAD OFFICE
389 Davis Road, Oakville, Ontario L6J 2X2
Telephone: (905) 845-9542 * Fax (905) 845-9551

Page 1 of 1

007 UT R1