

Fatigue Life Prediction and Variability of New and Existing Welded CHS Y-Joints

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The design and analysis methods for ancillary highway structures have recently become the focus of many research efforts as a result of unsatisfactory in-service performance (Chavez, Gilani, and Whittaker, 1997; Dexter and Ricker, 2002; Gilani and Whittaker, 2000a; Gilani and Whittaker, 2000b; Gilani, Chavez, and Whittaker, 1997; Kaczinski, Dexter, and Van Dien, 1998). One structure type receiving significant attention is the overhead welded highway sign support truss (both full span and cantilevered span). These structures are prevalent throughout the United States and typical full-span truss configurations used are shown in Figure 1.

Many of these structures contain circular hollow shapes (CHS) and connections that employ circumferential fillet welds. There have been many recent reports of cracking in these structures in the vicinity of the welded connections (Dexter and Ricker, 2002). A first step in understanding the cause of these cracks is to quantify connection fatigue life performance and the variability in that performance. The goal of the present effort is to contribute to the process of understanding the fatigue life variability of welded connections composed of CHS typical of those used in ancillary highway sign support structures. This statistical data can then be used to generate rational fatigue life predictions and quantify the variability in the fatigue lives for these structures using accepted procedures (Moses, Schilling, and Raju, 1987).

Relatively little research has been conducted in the specific area of transportation sign support structures when compared to other structure configurations, even though they are



(a)



(b)

Fig. 1. Typical sign support structures containing welded connections and round HSS shapes: (a) Type 1 aluminum supported sign and tri-chord truss; and (b) variable message sign (VMS) or changeable message sign (CMS) and four-chord box truss.

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found throughout the entire transportation network. Much of the present knowledge in the area of welded CHS connections typically found in these structures has been contributed by the offshore structure industry. Analytical efforts related to CHS connections are numerous and have spanned nearly two decades. The advent of finite element analysis as a widely available tool facilitated these efforts and they continue today. There have been numerous analytical and numerical efforts devoted to welded tubular connections (Chiew, Soh, and Wu, 1999; Chiew, Soh, and Wu, 2000; Karamanos, Romeijn, and Wardenier, 1999; Karamanos, 2000; Lee, 1999; Lee and Wilmschurst, 1996; Lee and Wilmschurst, 1997; Noordhoek and de Back, 1987; Snijder, Gijbbers, Dijkstra, and ter Avest, 1987; Soh and Soh 1993). The present research effort concentrates on experimental work and fatigue life variability, and this focus will remain for the literature review and synthesis to follow.

A large amount of experimental research in fatigue performance of welded CHS connections has been carried out. It has primarily focused on connection details that are used in the design of offshore structures. The elastic stress distribution in the chord wall of CHS T-joints commonly found in offshore structures was the objective of one of the first investigations carried out in the United States (Brown, 1966). Similar investigations for Y-joints were also conducted (Chen, 1966). Experimental programs investigating the in-plane static behavior of T-, Y-, and K-joints have also been undertaken (Beale and Toprac, 1967). The behavior of CHS T-joints subjected to fatigue loading with different stress ranges and different weld profiles — convex (as-welded surface) or concave (ground smooth surface) — has been evaluated (Natarajan and Toprac, 1968). This effort also sought to establish stress-life ($S-N$) curves for crack initiation in these joints. Investigations into the fatigue failure mechanism of welded tubular joints using fracture mechanics theory and experimental investigation data for crack initiation and propagation have also been conducted (Becker, Bouwkamp, and Gerberich, 1970).

Stress analyses and fatigue tests have been performed on overlapping K-joints (Moe, 1987), and detailed evaluation of strain gage readings measured during a fatigue test of a tubular Y-joint has been undertaken (Camisetti, 1987). The fatigue testing of overlapping YT-joints has been conducted and application of $S-N$ curves developed for nonoverlapping connections for predicting the fatigue life of overlapping joints has been validated (La Lani and Forsyth, 1987). The impact of residual stresses on the initiation and fatigue crack growth in welded tubular joints has also been studied (Glinka, Dharmavasan, and Dover, 1987), and the effects of seawater submersion on the fatigue performance of K-joint specimens with random loading have been quantified (Schmale and Kreiskorte, 1987). European experimental fatigue testing results have been compared to analytical

estimates generated for T-, Y-, K-, and X-joints (van Delft, Noordhoek, and DaRe, 1987), and the effect of material fracture toughness on the fatigue life of welded HSS joints has been assessed (van Den Brink and ter Avest, 1987).

The Comité International pour le Développement et l'Etude de la Construction Tubulaire (CIDECT) design guides for HSS (Rondal, Wurder, Dutta, Wardenier, and Yeomans, 1992; Wardenier, Dutta, Yeomans, Packer, and Bucak, 1995; Wardenier, Kurobane, Packer, Dutta, and Yeomans, 1991; Zhao, Herion, Packer, Pthli, Sedlacek, Wardenier, Weynand, van Winderde, and Yeomans, 2001) and the text by Marshall (Marshall, 1992) are currently the most comprehensive sources for fatigue life prediction and static strength of welded CHS joints. These documents pull together the vast quantity of research conducted prior to 1999 and provide design recommendations for joint strength and stress-life curves using a number of methodologies (for example, the classification method and the hot-spot stress method). There have been several significant efforts related to the fatigue strength of welded HSS joints conducted since the publication of these documents. The behavior of welded T-joints composed of CHS and rectangular hollow shapes (RHS) has been experimentally quantified, and the use of the hot-spot stress methodology for fatigue life and static strength of these joints has been evaluated (Bian and Lim, 2003). Simplified stress concentration factor formulas for fatigue life predictions have also been proposed and evaluated (van Wingerde, Packer, and Wardenier, 2001). An extensive evaluation of the fatigue life of CHS joints and their use in bridge structures has also recently been completed (Schumacher, 2003).

The extensive information related to CHS joints found in previous research efforts appears to omit information highly important to fully understanding the variability in the expected fatigue life of a sign support structure. Fatigue detail categories have been recommended (AASHTO, 2001; Zhao et al., 2001), but the statistical distributions that model fatigue life variability have remained undefined. If fatigue life estimates (either the initial expected fatigue life or the remaining fatigue life given pre-existing service) are to be generated using established procedures (Moses et al., 1987), quantifying the fatigue life variability is a must. Furthermore, if reliability-based fatigue life estimates are to be generated, this information will be required.

The present paper outlines an experimental program undertaken to quantify fatigue-life variability of the *ET* fatigue detail category for welded CHS connections commonly found in sign support structures. The program included fatigue testing of existing and fabricated Y-joint specimens composed of CHS, detailed material characterization, and comparison of experimentally determined fatigue lives with a variety of analytical methodologies. Further details of the experimental portion of the study are available elsewhere (Peronto, 2003). The results of the research effort serve as

Table 1. Welding Parameters Used in Specimen Preparation (Peronto, 2003)					
Electrode (1)	Wire Diameter (2)	Voltage (3)	Amperage (4)	Wire Feed (5)	Shielding Gas (6)
E70S6	0.035 in.	24 V	190 A	636 in./min	75%—Argon
					25%—CO ₂

the foundation for quantifying the expected service life for overhead sign support structures in relation to the fatigue limit state of the welded connections. Without statistical information related to the expected fatigue lives of the welded joints provided by the present effort, reliability-based design procedures that consider the fatigue limit state cannot be developed. The present data have been used as the basis for a procedure for predicting the service lives of full-span overhead sign support trusses (Foley, Ginal, Peronto, and Fournelle, 2004; Ginal, 2003).

SPECIMEN FABRICATION AND FATIGUE-TEST FIXTURING

Three groups of specimens were fabricated, fixtured, and tested. The first group, denoted NS, consisted of 12 joint specimens fabricated from ASTM A513 DOM (drawn over mandrel) material. Three of the NS specimens included “back-grinding” to alleviate the need for filler weld metal around the circumference of the brace member. The difference in brace “fit” is shown in Figure 2. The second group, denoted ES, was composed of eight specimens that were cut from a decommissioned Wisconsin Department of Transportation (WisDOT) sign support structure. The structure went into service in 1962 and was decommissioned in 2002. The

service life was therefore a little over 40 years. The final specimen group was a replacement for the NS group. The A513 DOM material used in the NS specimens is not allowed for sign support structures (AASHTO, 2001). Therefore, a third group of specimens, denoted NSx, was fabricated to provide data for specimens composed of specification-compliant material (ASTM A53 or A500).

The authors are aware of several instances (AWSTech, 2004; SEASINT, 2000) where the ASTM A513 DOM material was requested as a substitution for ASTM A53 or A500 material. The pricing pressures and material availability in recent history related to structural steel may result in suppliers requesting substitutions for which the structural engineer has little documented evidence to support refusal. Such a substitution might be A513 DOM material (commonly used in mechanical engineering applications; for example, motorcycle frame design, automotive chassis design) for A500 or A53 CHS. Therefore, testing on both the NSx and NS specimens was carried out to make definitive recommendations in this regard and provide the structural engineer with experimental evidence supporting the need for A500 and A53 material in structures subjected to fatigue loading. The welding parameters for the NS and NSx specimens are given in Table 1. The dimensions of the specimen brace and chord



(a)



(b)

Fig. 2. Saddle connectivity: (a) back-ground or fish-mouth specimen; (b) non-back-ground or straight-cut specimen (Peronto, 2003).

Table 2. Fatigue-Test Specimen Dimensions (Peronto, 2003)					
Specimen Group (1)	Specimen I.D. (2)	Chord Member		Brace Member	
		O.D. (in.) (3)	t_w (in.) (4)	O.D. (in.) (5)	t_w (in.) (6)
NS	1	4.50	0.194	1.66	0.131
	2	4.50	0.190	1.66	0.130
	3	4.50	0.193	1.65	0.129
	4	4.50	0.194	1.66	0.128
	5	4.50	0.195	1.68	0.128
	6	4.50	0.194	1.66	0.138
	7 (B.G.)*	4.50	0.192	1.65	0.130
	8 (B.G.)*	4.50	0.194	1.65	0.130
	9	4.50	0.196	1.65	0.135
	10	4.50	0.198	1.65	0.130
	11	4.50	0.194	1.65	0.129
	12 (B.G.)*	4.50	0.195	1.65	0.130
ES	1	5.625	0.284	1.91	0.149
	2	5.625	0.289	1.90	0.152
	3	5.625	0.281	1.93	0.153
	4	5.625	0.275	1.90	0.156
	5	5.625	0.290	1.92	0.157
	6	5.625	0.275	1.89	0.160
	7	5.625	0.290	1.89	0.158
	8	5.625	0.285	1.91	0.160
NSx	1	4.50	0.237	1.66	0.140
	2	4.50	0.237	1.66	0.140
	3	4.50	0.237	1.66	0.140
	4	4.50	0.237	1.66	0.140
	5	4.50	0.237	1.66	0.140
	6	4.50	0.237	1.66	0.140
* B.G. indicates that the specimen has been fabricated using back-grinding.					

members are given in Table 2. It should be noted that the specimens are full size and typical of those found in welded highway sign support structures. Therefore, it is expected that no “size effect” is present in the results.

An experimental fixture was designed and constructed to facilitate fatigue testing in an existing MTS 810 load frame with controller. Figures 3 and 4 illustrate the test fixture used to test the Y-joint specimens. The NS and NSx setups had slightly different fixturing with respect to the actuator side as shown. Further details regarding the experimental setup are available (Peronto, 2003).

MATERIAL CHARACTERIZATION

The material from which the fatigue specimens were fabricated was characterized using chemical composition analysis, microscopic examination, Rockwell B testing and tensile testing. Samples were taken from the chord and brace members and were machined into ASTM compliant tension test specimens (ASTM, 1999a). The specimens were machined such that the axis of the specimen was parallel to the direction of rolling and (for the chord members) perpendicular to the axis of the cyclical loading applied to the

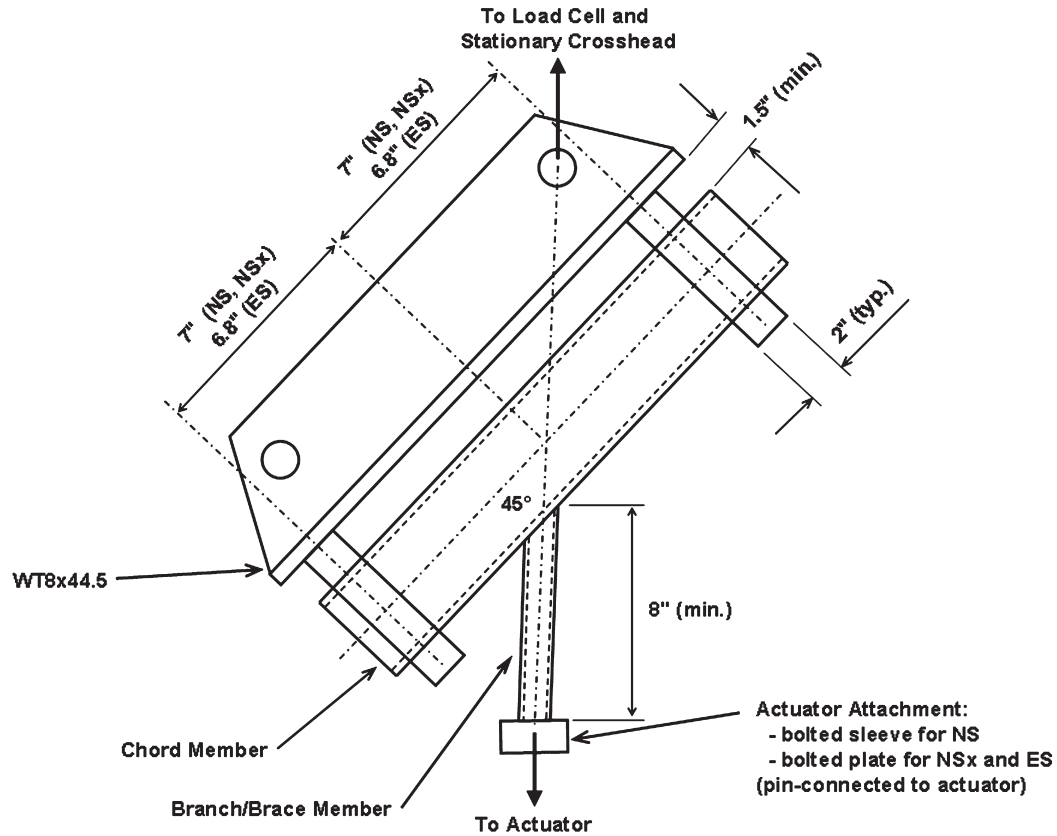


Fig. 3. Schematic for experimental fatigue testing.



(a)



(b)

Fig. 4. Typical specimen support fixture in MTS machine: (a) ES and NSx specimen fixturing (ES shown); (b) NS fixturing.

brace. Four tensile test specimens for chord material were generated for the NS joints, three for the NSx joints, and three for the ES joints.

An extensometer was mounted to the specimens and modulus of elasticity data were obtained. The experimental data indicated that the materials had modulus values in the expected range (28,000–29,000 ksi) for structural steels (Peronto, 2003). Unfortunately, an extensometer capable of providing full stress-strain response data was not available. Therefore, the tension testing conducted resulted in graphical

display of applied stress (engineering stress) versus displacement of the testing machine cross-head. While this cannot allow stress-strain data to be generated, it certainly allows yield stress, ultimate tensile stress, and percent elongation at rupture to be determined. These were felt to be sufficient to characterize the materials. Figures 5 through 7 illustrate the tensile testing data generated for all specimens.

The stress-extension behavior of the ES material had a well-defined yield plateau typical of hot-rolled, mild-carbon structural steel. The yield plateau was utilized to define the yield stress for the material by selecting the lower yield point. The NS and NSx materials had stress-extension behavior that exhibited no well-defined yield stress. An approximate yield stress for these materials was determined visually using the stress-elongation curves. Figures 5 and 7 illustrate the approximate yield stress chosen for these materials. The lack of an extensometer for the testing precluded use of the 0.2% offset or other technique for defining the yield stress (ASTM, 2004).

Table 3 provides the average percent elongations, yield stress and ultimate stress for the tensile tests conducted for each specimen group. There is a significant difference in percent elongation in the NS material when compared to the NSx and ES materials. The ramifications of this lack of ductility in the material will be related to the fatigue life of joints composed of NS material as well as the material's microstructure. The minimum yield strength and minimum ultimate tensile strength requirements for ASTM A500 (Gr. B and C), A53 (Gr. B and C), and the various versions of A513 material are also provided in Table 3. The NSx and ES specimen groups both demonstrate yield stress, ultimate stress, and ductility similar to that required for ASTM A500

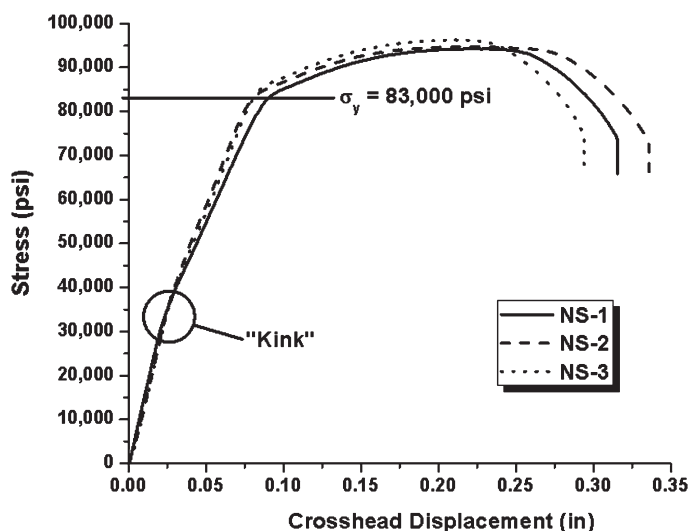


Fig. 5. Stress-extension behavior of material comprising NS specimen group.

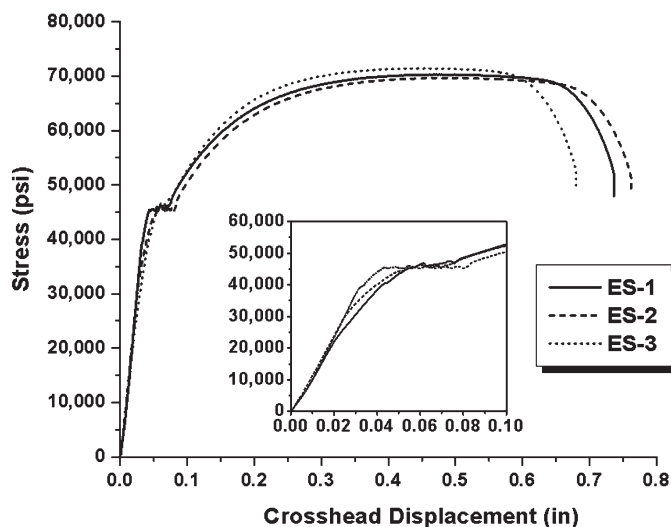


Fig. 6. Stress-extension behavior for material comprising ES specimen group.

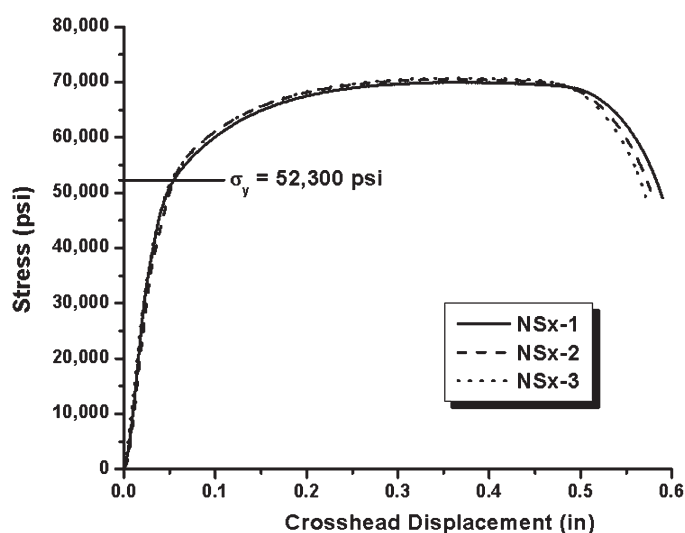


Fig. 7. Stress-extension behavior for material comprising NSx specimen group.

Table 3. ASTM Minimum Tensile Test Data Requirements and Properties Determined via Tensile Testing (Peronto, 2003)				
ASTM Designation or Specimen Designation (1)		F_y (ksi) (2)	F_u (ksi) (3)	Percent Elongation (4)
A53	A53 Gr. B	35	60	n/a
A500	A500 Gr. B	42	58	23
	A500 Gr. C	46	62	21
A513 (AISI 1026)	Sink Drawn	55	70	7
	Mandrel Drawn	70	80	5
	Mandrel Drawn Stress-Relieved	65	75	10
Present	NS	83.0 [†]	95.2	10.6
	NSx	52.3 [†]	70.4	26.0
	ES (avg.)	45.4	70.5	26.8
[†] Indicates value obtained by rational visualization of Figures 5 and 7 for NS and NSx materials, respectively.				

Table 4. Material Chemistries (percentage of total weight with balance being iron) for NSx and ES Specimen Material (Peronto, 2003)							
Element (1)	ASTM	NSx		ES		ASTM	
	A53 Gr. B Type S & E (2)	Chord (1022) (3)	Brace (1010) (4)	Chord (1026) (5)	Brace (1022) (6)	A500 Gr. B (7)	A500 Gr. C (8)
Si	n/a	0.02	0.03	0.02	0.13	n/a	n/a
S	0.045	0.006	0.004	0.027	0.019	0.045	0.045
P	0.05	0.014	0.017	0.007	0.011	0.045	0.045
Mn	1.20	0.70	0.56	0.76	0.71	1.40	1.40
C	0.30	0.22	0.07	0.26	0.23	0.30	0.27
Cr	0.40	0.01	0.07	0.07	0.04	n/a	n/a
Ni	0.40	0.01	0.06	0.05	0.02	n/a	n/a
Mo	0.15	< 0.01	0.01	0.02	< 0.01	n/a	n/a
Cu	0.40	0.02	0.10	0.08	0.04	0.18	0.18
V	0.08	< 0.005	< 0.005	< 0.005	< 0.005	n/a	n/a
Pb	n/a	< 0.01	< 0.01	< 0.01	< 0.01	n/a	n/a
Al	n/a	0.047	< 0.033	0.028	0.021	n/a	n/a
Ti	n/a	< 0.005	< 0.005	n/a	n/a	n/a	n/a

Table 5. Material Chemistries (percentage of total weight with balance being iron) for NS Specimen Material (Peronto, 2003)						
Element (1)	ASTM	NS		ASTM		
	A513 (1026) (2)	Chord (1026) (3)	Brace (1008) (4)	A53 Gr. B Type S & E (5)	A500 Gr. B (6)	A500 Gr. C (7)
Si	n/a	0.03	0.01	n/a	n/a	n/a
S	< 0.035	0.007	0.007	0.045	0.045	0.045
P	< 0.035	0.012	0.016	0.05	0.045	0.045
Mn	0.60 – 0.90	0.71	0.43	1.20	1.40	1.40
C	0.22 – 0.28	0.24	0.08	0.30	0.30	0.27
Cr	n/a	0.03	0.03	0.40	n/a	n/a
Ni	n/a	0.02	0.01	0.40	n/a	n/a
Mo	n/a	< 0.01	< 0.01	0.15	n/a	n/a
Cu	n/a	0.02	0.02	0.40	0.18	0.18
V	n/a	< 0.005	< 0.005	0.08	n/a	n/a
Pb	n/a	< 0.01	< 0.01	n/a	n/a	n/a
Al	n/a	0.042	0.06	n/a	n/a	n/a
Ti	n/a	n/a	n/a	n/a	n/a	n/a

Gr. B and C materials. The yield stress, ultimate tensile stress and ductility values determined for the NS material via testing indicate that it meets requirements for A513 mandrel-drawn (DOM) material. The ductility magnitudes seen in the test results indicate that it may be stress-relieved. The F_y/F_u ratios are 0.50 for the NS specimens, 0.66 for the NSx specimens, and 0.64 for the ES specimens.

Rockwell B hardness tests were also conducted for the chord, brace, and the weld materials. Measured Rockwell B data were typical for mild-carbon steels and weld electrode material. The weld material, brace material, and chord material showed consistent values in the range of 77 to 91 (Peronto, 2003). Several of the joints (NS and ES) were examined for weld penetration into the base material at the fillet welds. The study indicated that the joints examined had very good weld penetration into the base metal without undercutting (Peronto, 2003).

Chemical composition analysis for all materials was conducted. Tables 4 and 5 contain the material chemistry data for the NS, NSx, and ES specimens. Based upon chemical composition, the NSx, ES, and NS material certainly appears to satisfy the ASTM A53 and A500 chemical composition requirements. However, the ductility of the NS material is lacking. Therefore, the importance of ductility requirements in material specification is reinforced. It should be noted that the values contained in the table are percentages of total

weight with the balance being iron. As a result, only the alloying element percentages are reported.

The material characterization continued with examination of the material's microstructure. Three regions were examined for each of the specimens (NS, NSx, and ES): the chord material, brace material, and material in the heat affected zone (HAZ). Microstructures typical for all materials are shown in Figures 8 through 10. Darker regions in the figures are pearlite and the lighter regions are proeutectoid ferrite. A greater percentage of pearlite in the field of view relative to the ferrite indicates greater carbon content. The amounts of pearlite in the chord and brace material are consistent with the carbon contents of the components given in Tables 4 and 5. Comparison of the 500x material microstructures for the ES and NSx material illustrates the significant difference for the two materials' microstructures and is the reason for the difference in the stress-elongation response shown in Figures 6 and 7.

The ES and NSx microstructures exhibit a relatively uniformly distributed (regular) mixture of pearlite and ferrite; therefore, the material ductility is at the levels demanded for structural engineering purposes. However, the material in the NS specimens is heavily banded (refer to Figure 8). The proeutectoid ferrite and the pearlite form well-defined layers parallel to the rolling direction and the longitudinal direction of the chord. This banding results from the micro-segregation

of alloy elements, especially carbon, during solidification of the steel at its initial stage in production. This extreme banding can result in anisotropic behavior in the steel and can have an adverse affect on the material's ductility and fatigue life. The banding can also lead to micro-cracking in the base material during weld cooling.

The bilinear response in the elastic portion of the stress-elongation curve seen in Figure 5 is very interesting and appears to be related to the banding exhibited in the NS material microstructure. Several tension tests with an extensometer were conducted to verify that this kink indeed existed in the stress-elongation response. It was initially thought that this might be slip in the grips of the testing machine. However, it may be argued that the banded microstructure could be leading the NS material to behave as a laminated composite material with a secondary elastic stiffness becoming prevalent after initial yield. The formation of this kink and its impact on the material's behavior is under further study but is outside the scope of the present research effort because the NS material does not satisfy design specification requirements (AASHTO, 2001).

Overall, extreme banding in microstructure can lead to premature fatigue failure. This effect was clearly observed in the fatigue performance of the NS group of specimens to be discussed in the next section. Further discussions of the effects of material banding in steel microstructures are available (ASM, 1996; ASM, 2002; Khalid, Farooque, ul Haq, and Khan, 1999; Ramanathan and Foley, 2001; Van Aken, 2001).

FATIGUE TESTING

Fatigue testing of all specimens was conducted by loading the brace member axially in cyclical tension. The experimental fixturing was previously described and is shown in Figures 3 and 4. The loading applied had constant amplitude, the frequency varied from 1 to 2 Hz, and the procedure followed established protocols (ASTM, 1998; ASTM, 1999b; ASTM, 2002). Failure of a specimen during the testing was defined as one of two scenarios (Peronto, 2003): separation of the brace member from the chord by 0.5 in.; or the instant when the specimen could not support the maximum loading in the loading range (5% tolerance on this magnitude).

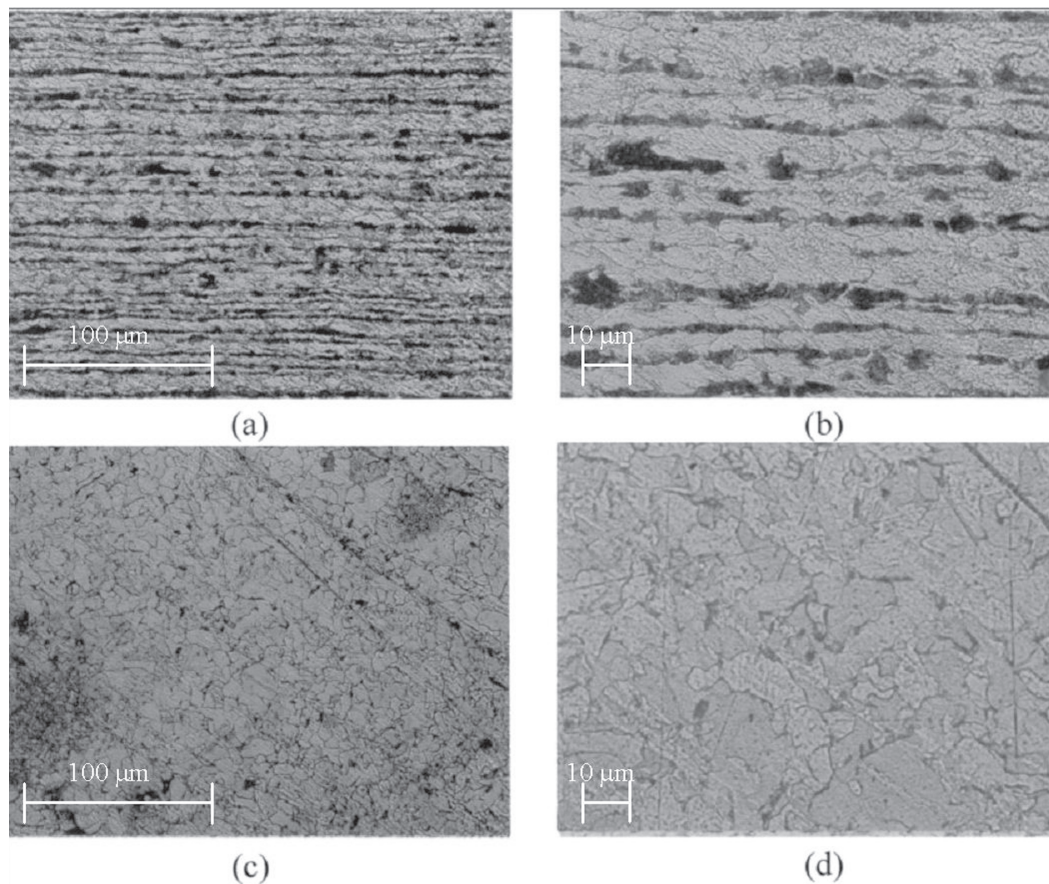


Figure 8: NS microstructure: (a) 200x chord, (b) 500x chord, (c) 200x brace, (d) 500x brace (Peronto, 2003).

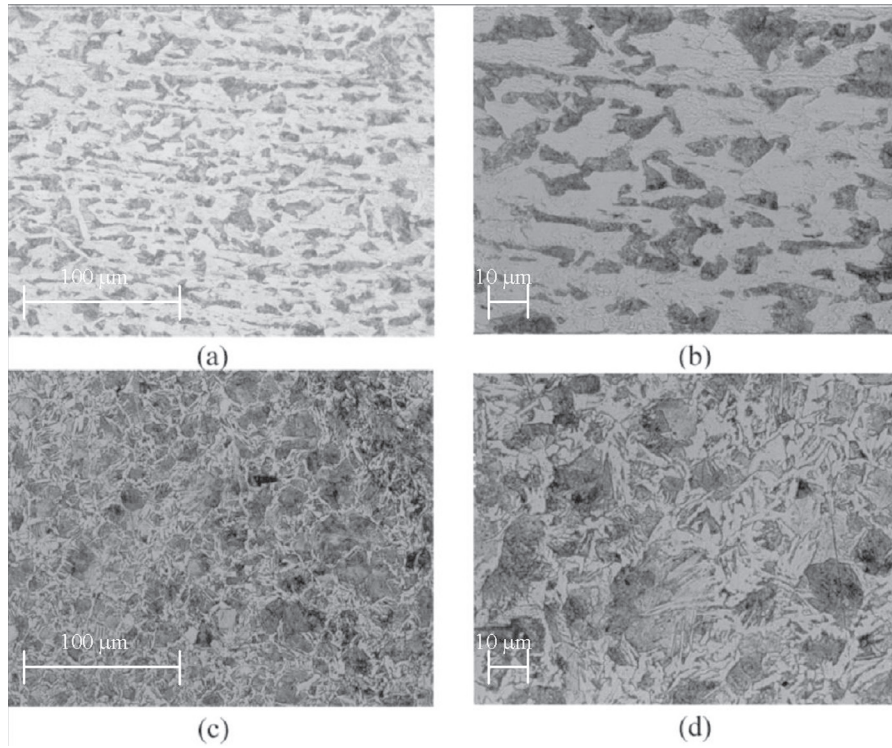


Fig. 9. ES microstructure: (a) 200x chord, (b) 500x chord, (c) 200x brace, (d) 500x brace (Peronto, 2003).

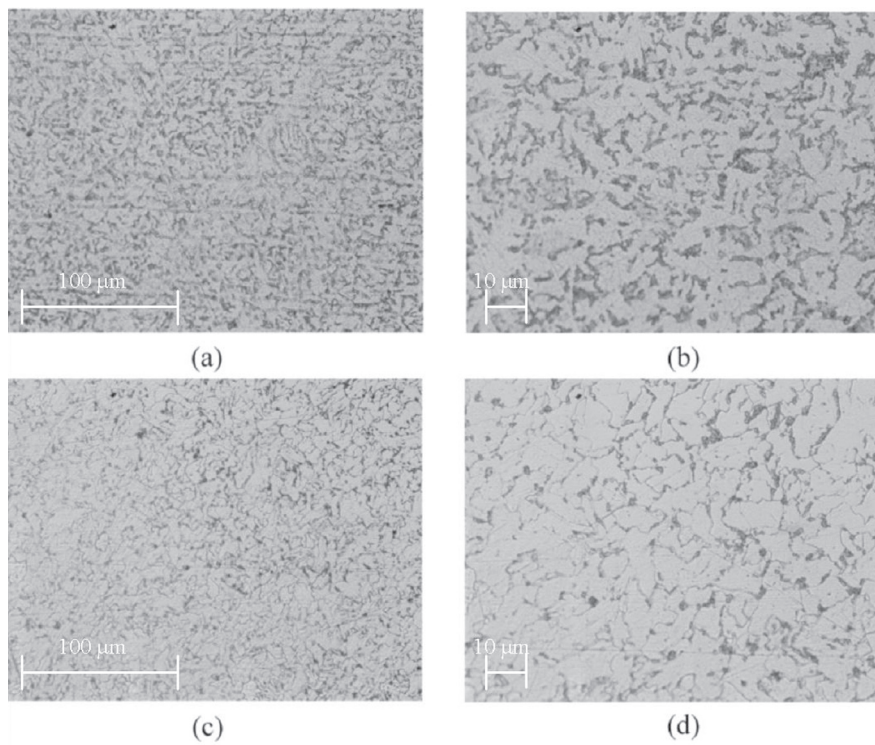


Fig. 10. NSx microstructure: (a) 200x chord, (b) 500x chord, (c) 200x brace, (d) 500x brace (Peronto, 2003).

Table 6. Fatigue Testing Statistics for Specimens Tested				
Parameter (1)		NS (2)	NSx (3)	ES (4)
S_r (ksi)		19.1	17.9	14.0
μ (cycles)		18,224	55,785	128,979
σ (cycles)		2,410	14,260	35,374
COV		0.132	0.256	0.274
median (cycles)		18,862	56,572	144,569
$\mu_{\ln N}$		0.352	0.477	0.492
$\sigma_{\ln N}$		9.748	10.815	11.646
N	95%	9,595	22,710	50,850
	70%	13,502	36,070	81,970
	50%	17,120	49,760	114,240
A	95%	0.668×10^8	1.302×10^8	1.395×10^8
	70%	0.941×10^8	2.069×10^8	2.249×10^8
	50%	1.193×10^8	2.854×10^8	3.135×10^8

Many of the NS and ES specimens were outfitted with strain gauges (four total) mounted around the circumference of the brace member in 90° intervals (Peronto, 2003). These gauges were utilized to quantify the stress-range gradient across the brace member diameter resulting from the specimen fixturing and to validate the load magnitudes set in the load-frame controller. The strain gauges were mounted at a distance of at least one brace diameter from the fillet weld. The average measured strain readings around the circumference of the brace member, the measured elastic modulus for the material, and the measured cross-sectional area of the brace member were used to check the load ranges imparted by the MTS controller. The load range indicated by the MTS controller was compared to the load range computed using the measured strain, elastic modulus, and cross-sectional areas. In all cases, the expected load range computed from measured data closely correlated with the load ranges reported by the MTS controller. The stress ranges, S_r , used in the NS, NSx, and ES material testing are given in Table 6.

The failure modes of the NS, NSx, and ES specimens varied slightly. All specimens in the NS group had failure defined by loading tolerance. As expected, a crack initiated at the weld toe at the crown position on the chord and failure occurred with the crack extending at least one-half the brace member circumference (see Figure 11). The failures of the NSx and ES specimens were significantly different. Tearing of the brace member from the chord was present in these

specimens prior to triggering the cyclic loading termination criteria. It was difficult to ascertain exactly which criteria resulted in the controller stopping the test for the ES and NSx specimens. However, the 0.5 in. separation criteria certainly could have been active when the controller shut down the load cycling. The failure of the NSx and ES specimens indicate that the material was significantly tougher than that of the NS specimens. This is exhibited by the tearing of the brace member away from the chord member in the NSx and ES group (see Figure 11). It should be noted that the failure process for several specimens from the NSx and ES group was observed. The number of cycles expended during tearing was minimal. Typical in-service failures for these structures (refer to Figure 12) have been similar to those seen in the experiments.

The fracture surface of an ES specimen was examined using a scanning electron microscope (Peronto, 2003). Fatigue crack striations were observed on the fracture surface, indicating that this material did indeed support fatigue crack growth. The material testing performed for the NSx and ES specimens indicated significant toughness and that stable growth of fatigue cracks would be possible.

The experimental fatigue-testing data obtained for all specimens is given in Figure 13. The 95% confidence fatigue-life curve corresponding to the detail category for this welded connection (AASHTO, 2001) is also shown in the figure as AASHTO (2001). All specimen data fall

outside this predictive equation (AASHTO, 2001). It should be noted that the NS experimental data for fatigue life are very low when compared to the ES and NSx results. The reason for this is the extreme banding in the material's microstructure. It appears that the stress-life curve (AASHTO, 2001) sufficiently captured the lower boundary of the fatigue-life data for the NS specimens. The impact of the material microstructure on the fatigue life is apparent. ASTM A513 DOM material should not be allowed for sign support structures, or structures subjected to fatigue loading. It should be noted, however, that back-grinding did not appear to have an impact on the fatigue life of the NS specimens (Peronto, 2003), confirming previous findings.

FATIGUE-LIFE VARIABILITY ANALYSIS

Determining an adequate statistical model for the *ET* detail category connection, typical of welded CHS joints, is of paramount importance to predict fatigue life and its variability for welded CHS sign support structures. Quantifying fatigue-life variability is currently not possible using specifications for design (AASHTO, 2001). The culmination of the experimental effort undertaken in this study was generation of statistical information needed to quantify fatigue-life variability of welded CHS joints suitable for use in fatigue-life estimation methodologies (Moses et al., 1987).



(a)



(b)



(c)

Fig. 11. Typical specimen failures: (a) NS material specimens, (b) ES material specimens, (c) NSx material specimens.

The present study utilizes an experimental stress range, S_r , and examines the statistical variation in the number of cycles to failure at that stress range. This process is schematically shown in Figure 14. Target stress ranges, S_r^1 and S_r^2 , are defined. There will be variation in the number of cycles to failure at each of these stress ranges, and each statistical distribution will have its own N_1^{95} and N_2^{95} values that define the number of cycles to failure that are exceeded by 95% of all data at the given stress range. It should be noted that if the constant amplitude fatigue limit (CAFL) was being studied, the variability in stress range (rather than number of cycles

to failure) would be more appropriate. The reason is that a fatigue life of 2,000,000 cycles may be defined as “infinite,” but there would likely be a variety of stress ranges resulting in 2,000,000 or more cycles to failure. The technique used in the present study ignores uncertainty in the target stress range. This is felt to be a minor issue as the same experimental fixturing and test-frame was used for all NSx and ES specimens.

Linear stress life curves with 95% confidence levels can be defined for each set of experimental data (for example, NSx and ES specimens). Each line has a common slope in



Fig. 12. Typical cracking observed during sign support structure service life.

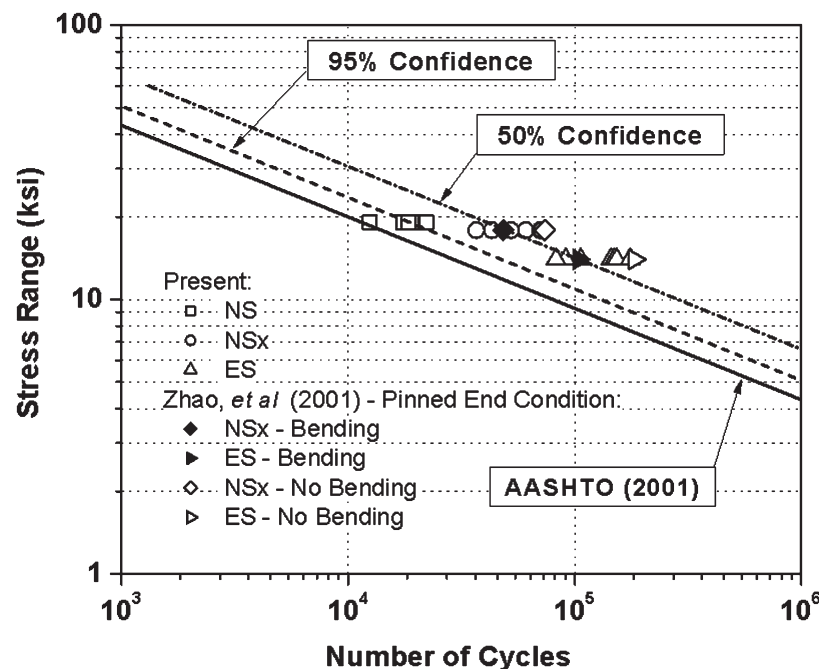


Fig. 13. S-N experimental data, CIDECT-8 (Zhao et al., 2001) prediction (fixed-end chord) and current design S-N curves (AASHTO, 2001).

log-space as indicated in Figure 14 and two ordinate intercepts are defined. If the intercepts, A_1^{95} and A_2^{95} , are “close” to one another, then one value may be used to define a linear relationship corresponding to 95% confidence-level fatigue lives. If these values are not “close” to one another, or multiple stress ranges (for example, more than the two considered in the present study) were utilized, one could consider a statistical distribution in A^{95} with a 95% confident value being that used for design.

It was determined that the variability in the number of cycles to failure at each stress range for all specimens was adequately modeled using a log-normal cumulative distribution function through plotting sample experimental data on probability paper (Peronto, 2003). Given that the sample data followed the log-normal model, the probability that a number of stress cycles to failure, N , will exceed a defined (design) value, N_D , can be computed using (Nowak and Collins, 2000)

$$P[N \geq N_D] = 1.0 - \Phi \left[\frac{\ln N_D - \mu_{\ln N}}{\sigma_{\ln N}} \right] \quad (1)$$

where

$\mu_{\ln N}$ and $\sigma_{\ln N}$ = the mean and standard deviation in the natural log of the number of cycles to failure
 ϕ = the normal cumulative distribution function

Equation 1 is used to establish cycle counts that correspond to user-defined confidence levels. Using the data in Table 6 for the NSx specimens and Equation 1 as an example, the probability that the number of cycles to failure will exceed 22,710 is

$$P[N \geq 22,710] = 0.95$$

This allows one to state that there is 95% confidence that the number of cycles to failure for the NSx specimens at a stress range equal to 17.9 ksi will be at least 22,710 cycles.

The log-normal statistical model also allows S - N diagrams for other confidence levels to be established. Linear model parameters for 95, 70, and 50% (median) confidence levels are given in Table 6. These alternate confidence levels allow the engineer to “put a number” on situations where the 95% confidence fatigue life disagrees with reality. For example, the 95% confidence level prediction would allow the engineer to say with 95% confidence that the fatigue life would be at least “x” cycles. However, it may also be valuable to be able to say one is 50% confident that the fatigue life would be at least “y” cycles. This allows the structural engineer to qualify situations when in-field performance does not match experimental prediction or simulation, and to tailor inspection intervals based upon confidence levels for fatigue life. Furthermore, if design values are set at 95% confidence (as currently done), then this also provides for inspection cycles for fracture-critical elements.

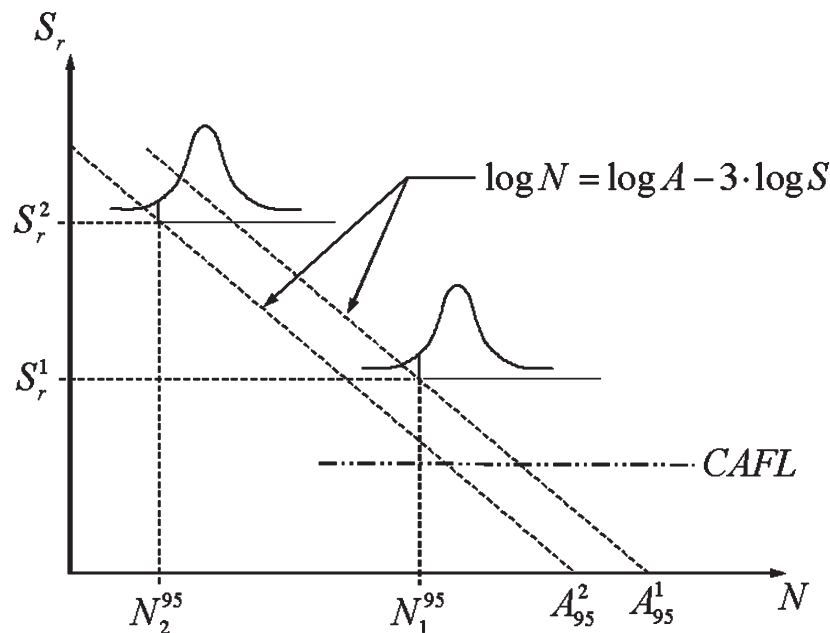


Fig. 14. Schematic of the approach used to establish stress-life curves for fatigue-life estimation in regions outside the CAFL.

The region in stress-life space that is of interest in the present study corresponds to stress ranges that are above the constant amplitude fatigue limit (CAFL). Using the 95% confidence level number of cycles to failure, the relationship between stress range and fatigue life can be written as

$$\log N^{95} = \log A^{95} - 3 \log S_r \quad (2)$$

where

A^{95} = x-axis intercept corresponding to the 95% confidence number of cycles to failure at the defined constant amplitude stress range with a slope of 3

Table 6 indicates that the 95% confidence A -value for the NSx and ES specimens were 1.302×10^8 and 1.395×10^8 , respectively. A conservative lower A -value (1.3×10^8) was used to define a design stress-life curve for the NSx and ES specimens.

It is important to note that there is approximately 7% difference between A^{95} values for the NSx and ES specimens. These values imply greater fatigue life for the older material for all stress ranges. This is in spite of the fact that the ES material had 40 years of service prior to testing. The ES specimens were coated in thick layers of paint throughout the service life, where newer sign support structures are likely galvanized to minimize in-service maintenance. The NS and NSx specimens were not galvanized for the present study.

The experimental results for all three specimen groups are shown in Figure 13. The 95% and 50% confidence fatigue-life curves for the NSx and ES specimens are also shown in the figure. The 95% confidence fatigue life curve based upon the experimental results is significantly beyond the 95% curve used in the current specifications (AASHTO, 2001). It should be noted, however, that only two specimen groups consisting of Y-joint specimens and the corresponding fatigue tests are being used to define the 95% confidence stress-life curve in the present study.

COMPARISON TO PREDICTIVE EQUATIONS

As previously mentioned, the CIDECT design guides for hollow structural shapes (HSS) (Rondal et al., 1992; Wardenier et al., 1995; Wardenier et al., 1991; Zhao et al., 2001) and the text by Marshall (Marshall, 1992) are currently the most comprehensive sources for fatigue-life prediction methodologies and static strength computations for welded CHS joints. The steel design manual (AISC, 2001) includes specifications and commentary on design using HSS, and a separate specification devoted to HSS is available (AISC, 2000), but fatigue is not considered. The present section outlines a comparative study between fatigue-life predictions

made using the CIDECT-8 procedure and the experimental results for the NSx and ES specimens. The NS material was not considered in this comparison.

Fatigue lives for the ES and NSx specimens were computed using the CIDECT-8 procedure (Zhao et al., 2001). The experimental fixturing suggested the following analysis for bending and axial stress in the specimens. The two clamps shown in Figure 4 supply end conditions for the chord member that are likely somewhere in between the two extremes of pinned and fixed. The cyclical loading applied to the brace member through the actuator was resolved into components parallel and perpendicular to the chord. The perpendicular component was assumed to cause bending on a span of 14 in. or 13.6 in., depending on the specimen (refer to Figure 3). The parallel component was assumed to be split equally between the two chord segments, leading to the support clamps with tension force being applied to the upper segment of the chord member. The tensile stresses in the chord due to bending moment supplied through the brace member and the direct tensile stresses resulting from the loading configuration are additive at the crown of the chord member.

Two conditions of bending in the brace member were considered: bending and no bending. Table 6 contains the direct tension stress ranges. The magnitude of the ES specimen tension stress ranges resulting from bending was very close to 3.8 ksi for each of the specimens that were instrumented. The NSx specimens contained identical fixturing to that of the ES specimens (for example, perpendicular plate connection to the actuator), and therefore, the same bending stress ranges were used for the NSx specimens. The CIDECT-8 procedure makes provisions for considering bending stresses in the brace, and these procedures were followed in the present computations. An example MathCAD (MEEI, 2003) worksheet typical of that used for these computations is given in the Appendix (ES material, bending present in the brace, pinned chord end conditions).

Table 7 contains the fatigue life predictions for the NSx and ES specimens computed using the CIDECT-8 procedure (Zhao et al., 2001) as implemented in the MathCAD (MEEI, 2003) worksheet found in the Appendix. The presence of bending in the brace and the chord end conditions has a significant impact on the fatigue life of the welded CHS joint. The fatigue lives found in Table 7 ignore partial safety factors that likely would need to be applied for real structures. Figure 13 contains fatigue life predictions of the CIDECT-8 procedure for pinned-end chords with and without bending in the brace. The pinned-end condition reflected the experimental data more closely than the fixed-end conditions. The predictions for the fatigue lives of the specimens fall nicely within the experimental results obtained.

When bending is considered in the brace, the fatigue-life prediction falls near the median number of cycles to failure

Table 7. CIDECT-8 (Zhao et al., 2001) Fatigue-Life Predictions for Various End Conditions and Presence of Bending in the Brace Member		
Chord End Condition and Brace Bending Condition (1)	Fatigue Life	
	NSx (2)	ES (3)
Fixed:		
No Bending	121,600	255,900
Bending	73,790	137,700
Pinned:		
No Bending	73,790	183,700
Bending	48,420	104,500

(50% confidence line). When brace bending is ignored, the CIDECT-8 prediction falls at the upper end of the experimentally determined cycles to failure. Altering the end conditions on the chord to the fixed condition results in a right-ward shift in the CIDECT-8 prediction to a location where the no bending condition falls at the upper end of the experimental results and the bending condition falls to the right of the experimental data obtained.

The CIDECT-8 procedure (Zhao et al., 2001) provides very reasonable predictions of the number of loading cycles to failure for the NSx and ES specimens tested. CIDECT-8 predictions for the NS material specimens were not computed. As described previously, the banding in the microstructure of this material should disallow its use for joints subjected to fatigue loading. The procedure provides fatigue-life predictions that fall very close to the median number of cycles to failure obtained experimentally when pinned end conditions for the chord members and brace member bending were included in the predictive equations. The CIDECT-8 procedure also correctly predicted the location for crack initiation (the crown of the chord member) for all specimens.

CONCLUSIONS

There are several conclusions and recommendations that can be made in light of the completed study. The experimental data illustrate that banding in a CHS material's microstructure can cause bilinear behavior in the elastic region of the material's stress-strain response and a marked decrease in material ductility. The detrimental impact of the material microstructure on the fatigue life has also been confirmed. A513 DOM material should not be allowed for sign support structures or structures subjected to fatigue loading that

contain welded CHS joints. Furthermore, material specifications for these CHS should include chemical composition requirements and minimum percentage elongation requirements. Back-grinding appears to have no impact on the fatigue life of the welded CHS joints tested, thus confirming past research findings.

The fatigue-life variability at any stress range above the CAFL can be modeled using a log-normal cumulative distribution function. The 95% confidence-level ordinate intercept used in design specifications (AASHTO, 2001) for welded CHS joints appears to be conservative. The fatigue lives of the ES material joints tested fall well above the 95% confidence level lines (AASHTO, 2001; Peronto, 2003) and are comparable to the NSx material results. This would indicate that the 40-year service life of the sign support structure from which these specimens were obtained had little or no damage induced during its service life. The structure from which the ES specimens were cut was painted with a very viscous paint colloquially referred to as "red lead." Sign support structures are presently galvanized to minimize field maintenance. It would be very interesting to evaluate the impact of the galvanizing process on the fatigue lives of welded CHS joints.

The CIDECT-8 methodology appears to be capable of predicting the median fatigue lives for the welded CHS joints studied. It should be noted that it may be prudent to adjust the CIDECT-8 predictions with partial safety factors to 95% confidence levels when design recommendations are made. These partial safety factors should be generated for a variety of confidence levels where some could be used for design, and others would be suitable for understanding in-service fatigue performance.

ACKNOWLEDGMENTS

This research was funded by the Wisconsin Department of Transportation (Contract: 0092-00-0016) and the U.S. Department of Transportation in the interest of information exchange. The material or information reported is the result of research done under the auspices of the Department and Wisconsin Highway Research Program. The content reflects the views of the authors. WisDOT and FHWA (US DOT) assumes no liability for its contents or use thereof. This publication does not constitute a standard specification or regulation of the Department or FHWA.

The authors would also like to acknowledge the help of AISC member, Construction Supply and Erection of Germantown, Wisconsin (Michael Henke). The authors would also like to thank Justin Ocel of the University of Minnesota for his fruitful discussion regarding the CIDECT-8 fatigue-life computations and the idea for carrying out these computations in MathCAD. The continual encouragement and support of the late Professor Robert Dexter of the University of Minnesota is also gratefully acknowledged. Finally, the authors would like to thank the reviewers for the many constructive comments that have resulted in a much improved manuscript.

APPENDIX

CIDECT 8 Procedure for Fatigue Life Evaluation

Fatigue Life Estimate Using CIDECT 8 Procedure - ES Specimens

Computations follow "Hot Spot Stress Method" procedure outlined in:

Zhao, X.-L., Herion, S., Packer, J.A., Puthli, R.S., Sedlacek, G., Wardenier, J., Weynand, K., van Wingerde, A.M., Yeomans, N.F., *Design Guide for Circular and Rectangular Hollow Section Welded Joints Under Fatigue Loading*, Construction with Hollow Sections, CIDECT 8, TUV-Verlag, Koln, Germany, 2001.

Define Specimen Dimensions and Brace Stress Range (all units: lbs, inches, and degrees U.N.O.).

Chord outer diameter and thickness

$$d_{oc} := 5.625$$

$$t_c := 0.284$$

Angle made by brace relative to chord

$$\theta := 45.0$$

$$\theta_{rad} := \theta \cdot \frac{\pi}{180} \text{ float, 3} \rightarrow .785$$

Axial Stress range in brace member and out-of-plane bending stress in brace member:

$$S_{r_ax_b} := 14000.0 \quad \text{psi}$$

$$S_{r_ipb_b} := 3800.00 \quad \text{psi}$$

Brace outer diameter and thickness

$$d_{ob} := 1.91$$

$$t_b := 0.156$$

Length of chord member - distance between supports

$$L := 13.6$$

Compute Range of Force in Brace Member

$$d_{ib} := d_{ob} - 2 \cdot t_b$$

$$A_{brace} := \frac{\pi \cdot (d_{ob}^2 - d_{ib}^2)}{4}$$

$$P_{brace} := S_{r_ax_b} \cdot A_{brace} \text{ float, 4} \rightarrow 1.20410^4$$

Compute Range of Axial Force in Chord and Range of Bending Moment in Chord

Horizontal and vertical components of brace force range

$$P_{\text{horiz}} := P_{\text{brace}} \cdot \cos(\theta_{\text{rad}}) \text{ float}, 6 \rightarrow 8516.95$$

$$P_{\text{vert}} := P_{\text{brace}} \cdot \sin(\theta_{\text{rad}}) \text{ float}, 6 \rightarrow 8510.18$$

Axial force in the chord member

$$P_{\text{chord}} := \frac{1}{2} \cdot P_{\text{horiz}} \text{ float}, 4 \rightarrow 4258. \quad \text{Assumes 1/2 of the horizontal component carried to each support}$$

Bending Moment in the chord member (change subscript according to end-condition desired)

$$M_{\text{chord}} := \frac{P_{\text{vert}} \cdot L}{4} \text{ float}, 4 \rightarrow 2.893 \cdot 10^4 \quad \text{Assumes pinned-end conditions}$$

$$M_{\text{chord1}} := \frac{P_{\text{vert}} \cdot L}{8} \text{ float}, 4 \rightarrow 1.447 \cdot 10^4 \quad \text{Assumes fixed-end conditions}$$

Compute Stress Ranges in Chord and Brace

$$S_{r_ax_ch} := \frac{P_{\text{chord}}}{\frac{\pi}{4} \left[d_{oc}^2 - (d_{oc} - 2 \cdot t_c)^2 \right]} \text{ float}, 4 \rightarrow 893.5$$

$$S_{r_mom_ch} := \frac{M_{\text{chord}} \cdot \frac{d_{oc}}{2}}{\frac{\pi}{64} \left[d_{oc}^4 - (d_{oc} - 2 \cdot t_c)^4 \right]} \text{ float}, 4 \rightarrow 4775.$$

Non-Dimensional Parameters for SCF Computations

$$\begin{array}{llll} \gamma := \frac{d_{oc}}{2 \cdot t_c} & \tau := \frac{t_b}{t_c} & \alpha := \frac{2 \cdot L}{d_{oc}} & \beta := \frac{d_{ob}}{d_{oc}} \\ \gamma = 9.903 & \tau = 0.549 & \alpha = 4.836 & \beta = 0.34 \end{array}$$

Check parameters for validity

$$ANS_1 := \text{if}(0.2 \leq \beta \leq 1.0, \text{"Yes"}, \text{"No"}) \rightarrow \text{"Yes"}$$

$$ANS_2 := \text{if}(15 \leq 2 \cdot \gamma \leq 64, \text{"Yes"}, \text{"No"}) \rightarrow \text{"Yes"}$$

$$ANS_3 := \text{if}(0.2 \leq \tau \leq 1.0, \text{"Yes"}, \text{"No"}) \rightarrow \text{"Yes"}$$

$$ANS_4 := \text{if}(4 \leq \alpha \leq 40, \text{"Yes"}, \text{"No"}) \rightarrow \text{"Yes"}$$

$$ANS_5 := \text{if}(30 \leq \theta \leq 90, \text{"Yes"}, \text{"No"}) \rightarrow \text{"Yes"}$$

If answers to ALL queries at the left are "Yes", then the SCF formula are within the range of validity.

$$C := 1.00 \quad \begin{array}{ll} C = 0.50 & \text{for fixed chord supports} \\ C = 1.00 & \text{for pinned chord supports} \\ C = 0.70 & \text{otherwise} \end{array}$$

$$C_1 := 2.0(C - 0.5) \text{ float}, 4 \rightarrow 1.000$$

$$C_2 := \frac{C}{2} \text{ float}, 4 \rightarrow .5000$$

$$C_3 := \frac{C}{5} \text{ float}, 4 \rightarrow .2000$$

Define the SCF's with General Chord Fixity Equations

Assume uniplanar loading

$$T_5 := \left[\gamma \cdot \tau^{1.1} \cdot \left[1.11 - 3 \cdot (\beta - 0.52)^2 \right] \cdot \sin(\theta_{\text{rad}})^{1.6} \right] + C_1 \cdot (0.8\alpha - 6) \cdot \tau \cdot \beta^2 \cdot (1 - \beta^2)^{0.5} \cdot \sin(2 \cdot \theta_{\text{rad}})^2$$

$$T_6 := \left[\gamma^{0.2} \cdot \tau \cdot \left[2.65 + 5 \cdot (\beta - 0.65)^2 \right] \right] + \tau \cdot \beta \cdot (C_2 \cdot \alpha - 3) \cdot \sin(\theta_{\text{rad}})$$

$$T_7 := 3 + \gamma^{1.2} \cdot (0.12e^{-4 \cdot \beta} + 0.011\beta^2 - 0.045) + \beta \cdot \tau \cdot (C_3 \cdot \alpha - 1.2)$$

$$T_3 := 1.3 + \gamma \cdot \tau^{0.52} \cdot \alpha^{0.1} \cdot \left[0.187 - 1.25\beta^{1.1} \cdot (\beta - 0.96) \right] \cdot \sin(\theta_{\text{rad}})^{2.7 - 0.01 \cdot \alpha}$$

$$F_2 := \text{if} \left[\alpha < 12, 1 - (1.43\beta - 0.97\beta^2 - 0.03) \cdot \gamma^{0.04} \cdot e^{(-0.71 \cdot \gamma^{-1.38} \cdot \alpha^{2.5})}, 1.0 \right]$$

$$T_8 := 1.45\beta \cdot \tau^{0.85} \cdot \gamma^{(1 - 0.68 \cdot \beta)} \cdot \sin(\theta_{\text{rad}})^{0.70}$$

$$T_9 := 1.0 + 0.65\beta \cdot \tau^{0.40} \cdot \gamma^{(1.09 - 0.77 \cdot \beta)} \cdot \sin(\theta_{\text{rad}})^{(0.06 \cdot \gamma - 1.16)}$$

$$\text{SCF}_{\text{ax_ch_saddle}} := T_5 \cdot F_2 \text{ float}, 4 \rightarrow 2.620$$

$$\text{SCF}_{\text{ax_b_saddle}} := T_3 \cdot F_2 \text{ float}, 4 \rightarrow 2.512$$

$$\text{SCF}_{\text{ax_ch_crown}} := T_6 \text{ float}, 4 \rightarrow 2.644$$

$$\text{SCF}_{\text{ax_b_crown}} := T_7 \text{ float}, 4 \rightarrow 2.755$$

$$\text{SCF}_{\text{ipb_ch_saddle}} := 0$$

$$\text{SCF}_{\text{ipb_b_saddle}} := 0$$

$$\text{SCF}_{\text{ipb_ch_crown}} := T_8 \text{ float}, 4 \rightarrow 1.354$$

$$\text{SCF}_{\text{ipb_b_crown}} := T_9 \text{ float}, 4 \rightarrow 2.413$$

Calculate Hot Spot Stress Ranges at All Relavent Locations

$$S_{\text{rhs_ch_saddle}} := \text{SCF}_{\text{ax_b_saddle}} \cdot S_{\text{r_ax_b}} + \text{SCF}_{\text{ipb_b_saddle}} \cdot S_{\text{r_ipb_b}} + \text{SCF}_{\text{ax_ch_saddle}} \cdot S_{\text{r_ax_ch}} + \text{SCF}_{\text{ipb_ch_saddle}} \cdot S_{\text{r_mom_ch}}$$

$$S_{\text{rhs_ch_crown}} := \text{SCF}_{\text{ax_b_crown}} \cdot S_{\text{r_ax_b}} + \text{SCF}_{\text{ipb_b_crown}} \cdot S_{\text{r_ipb_b}} + \text{SCF}_{\text{ax_ch_crown}} \cdot S_{\text{r_ax_ch}} + \text{SCF}_{\text{ipb_ch_crown}} \cdot S_{\text{r_mom_ch}}$$

$$S_{\text{rhs_b_saddle}} := \text{SCF}_{\text{ax_b_saddle}} \cdot S_{\text{r_ax_b}} + \text{SCF}_{\text{ipb_b_saddle}} \cdot S_{\text{r_ipb_b}}$$

$$S_{\text{rhs_b_crown}} := \text{SCF}_{\text{ax_b_crown}} \cdot S_{\text{r_ax_b}} + \text{SCF}_{\text{ipb_b_crown}} \cdot S_{\text{r_ipb_b}}$$

Convert Stress Ranges to MPa to be Consistent with CIDECT Formula

$$S_{rhs_ch_saddle} := S_{rhs_ch_saddle} \cdot \left(\frac{1}{25.4^2} \right) \cdot \left(\frac{4.445}{1} \right) \text{float}, 5 \rightarrow 258.43$$

$$S_{rhs_ch_crown} := S_{rhs_ch_crown} \cdot \left(\frac{1}{25.4^2} \right) \cdot \left(\frac{4.445}{1} \right) \text{float}, 5 \rightarrow 389.73$$

$$S_{rhs_b_saddle} := S_{rhs_b_saddle} \cdot \left(\frac{1}{25.4^2} \right) \cdot \left(\frac{4.445}{1} \right) \text{float}, 5 \rightarrow 242.30$$

$$S_{rhs_b_crown} := S_{rhs_b_crown} \cdot \left(\frac{1}{25.4^2} \right) \cdot \left(\frac{4.445}{1} \right) \text{float}, 5 \rightarrow 328.91$$

Convert Brace and Chord Thickness to mm

$$t_c := t_c \cdot 25.4 \text{float}, 5 \rightarrow 7.2136$$

$$t_b := t_b \cdot 25.4 \text{float}, 5 \rightarrow 3.9624$$

Compute Number of Cycles to Failure Assuming Constant Amplitude Loading

$$N_{ch_saddle} := 10^{\frac{12.476 - 3 \cdot \log(S_{rhs_ch_saddle})}{1 - 0.18 \cdot \log\left(\frac{16}{t_c}\right)}} \text{float}, 4 \rightarrow 3.90810^5$$

$$N_{ch_crown} := 10^{\frac{12.476 - 3 \cdot \log(S_{rhs_ch_crown})}{1 - 0.18 \cdot \log\left(\frac{16}{t_c}\right)}} \text{float}, 4 \rightarrow 1.04510^5$$

$$N_{b_saddle} := 10^{\frac{12.476 - 3 \cdot \log(S_{rhs_b_saddle})}{1 - 0.18 \cdot \log\left(\frac{16}{t_b}\right)}} \text{float}, 4 \rightarrow 9.52810^5$$

$$N_{b_crown} := 10^{\frac{12.476 - 3 \cdot \log(S_{rhs_b_crown})}{1 - 0.18 \cdot \log\left(\frac{16}{t_b}\right)}} \text{float}, 4 \rightarrow 3.38810^5$$

Choose the minimum number of cycles from group above

$$N := \min(N_{ch_saddle}, N_{ch_crown}, N_{b_saddle}, N_{b_crown})$$

$$N \rightarrow 1.045 \cdot 10^5$$

REFERENCES

- AASHTO (2001), *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals, 4th Edition*, American Association of State Highway and Transportation Officials, Washington, DC.
- AISC (2000), *Load and Resistance Factor Design Specifications for Steel Hollow Structural Sections*, American Institute of Steel Construction, Inc., Chicago, IL.
- AISC (2001), *Manual of Steel Construction, Load and Resistance Factor Design*, 3rd Edition, American Institute of Steel Construction, Inc., Chicago, IL.
- ASM (1996), *Fatigue and Fracture*, American Society for Metals International, Materials Park, OH.
- ASM (2002), *Failure Analysis and Prevention*, American Society for Metals International, Materials Park, OH.
- ASTM (1998), *Standard Practice for Verification of Constant Amplitude Dynamic Forces in Axial Fatigue Testing System*, E 467-98a, ASTM, West Conshohocken, PA.
- ASTM (1999a), *Standard Practice for Tensile Testing*, E 8-96a, ASTM, West Conshohocken, PA.
- ASTM (1999b), *Standard Practice for Verification of Specimen Alignment Under Tensile Loading*, E 1012-99, ASTM, West Conshohocken, PA.
- ASTM (2002), *Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Testing of Metallic Materials*, E 466-06, ASTM, West Conshohocken, PA.
- ASTM (2004), *Standard Test Methods for Tension Testing of Metallic Materials*, E8-04, ASTM International, West Conshohocken, PA.
- AWSTech (2004), "General Technical Forum," American Welding Society, Miami, FL.
- Beale, L.A. and Toprac, A.A. (1967), "Analysis of In-Plane T, Y, and K Welded Tubular Connections," University of Texas SFRL & Welding Research Council.
- Becker, J.M., Bouwkamp, J.G., and Gerberich, William W. (1970), "Fatigue Failure of Welded Tubular Joints," *Second Annual Offshore Technology Conference*, Houston, Texas, p. 36.
- Bian, L.-C. and Lim, J.-K. (2003), "Fatigue Strength and Stress Concentration Factors of CHS-to-RHS T-Joints," *Journal of Constructional Steel Research*, Vol. 59, No. 5, pp. 627–640.
- Brown, R.C. (1966), "An Experimental Investigation of T-Joints," Master's Thesis, University of Texas, Austin, TX.
- Camisetti, C. (1987), *Strain Gauge Measurements During a Fatigue Test of a Y Offshore Tubular Joint*, Elsevier, Delft, The Netherlands.
- Chavez, J.W., Gilani, A.S., and Whittaker, A.S. (1997), "Fatigue-Life Evaluation of Changeable Message Sign Structures, Volume 2—Retrofitted Structures," *Report No. UCB/EERC-97/10*, Earthquake Engineering Research Center, University of California, Berkeley, CA.
- Chen, J. (1966), "Stresses in Steel Tubular Y-Joints," Master's Thesis, University of Texas, Austin, TX.
- Chiew, S.-P., Soh, C.-K., and Wu, N.-W. (1999), "Experimental and Numerical Stress Analysis of Tubular XT-Joint," *Journal of Structural Engineering*, Vol. 125, No. 11, pp. 1239–1248.
- Chiew, S.-P., Soh, C.-K., and Wu, N.-W. (2000), "Experimental and Numerical SCF Studies of Multiplanar Tubular XX-Joint," *Journal of Structural Engineering*, Vol. ST11, pp. 1331–1118.
- Dexter, R.J. and Ricker, M.J. (2002), *Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports*, NCHRP Report 469, Transportation Research Board—National Research Council, Washington, DC.
- Foley, C.M., Ginal, S.J., Peronto, J.L., and Fournelle, R.A. (2004), "Structural Analysis of Sign Bridge Structures and Luminaire Supports," *WHRP 04-03*, Wisconsin Highway Research Program, Madison, WI.
- Gilani, A. and Whittaker, A. (2000a), "Fatigue-Life Evaluation of Steel Post Structures. I: Background and Analysis," *Journal of Structural Engineering*, Vol. 126, No. 3, pp. 322–330.
- Gilani, A. and Whittaker, A. (2000b), "Fatigue-Life Evaluation of Steel Post Structures. II: Experimentation," *Journal of Structural Engineering*, Vol. 126, No. 3, pp. 331–340.

- Gilani, A.S., Chavez, J.W., and Whittaker, A.S. (1997), "Fatigue-Life Evaluation of Changeable Message Sign Structures, Volume 1—As Built Structures," *Report No. UCB/EERC-97/10*, Earthquake Engineering Research Center, University of California, Berkeley, CA.
- Ginal, S.J. (2003), "Fatigue Performance of Full-Span Sign Support Structures Considering Truck-Induced Gust and Natural Wind Pressures," MS Thesis, Marquette University, Milwaukee, WI.
- Glinka, G., Dharmavasan, S., and Dover, W.D. (1987), *An Analysis of the Effect of Residual Stress on the Initiation and Fatigue Crack Growth in Tubular Welded Joints*, Elsevier, Delft, The Netherlands.
- Kaczinski, M.R., Dexter, R.J., and Van Dien, J.P. (1998), "Fatigue Resistance Design of Cantilevered Signal, Sign and Light Supports," *NCHRP Report 412—Project 10-38*, ATLSS Engineering Research Center, Bethlehem, PA.
- Karamanos, S.A., Romeijn, A., and Wardenier, J. (2000), "Stress Concentrations in Tubular DT-Joints for Fatigue Design," *Journal of Structural Engineering*, Vol. ST11, pp. 1320–1330.
- Karamanos, S.A., Romeijn, A., and Wardenier, J. (1999), "Stress Concentrations in Multi-Planar Welded CHS XX-Connections," *Journal of Constructional Steel Research*, Vol. 50, pp. 259–282.
- Khalid, F.A., Farooque, M., ul Haq, A., and Khan, A.Q. (1999), "Role of Ferrite/Pearlite Banded Structure and Segregation on Mechanical Properties of Microalloyed Hot Rolled Steel," *Material Science and Technology*, Vol. 15, No. 10.
- La Lani, M. and Forsyth, P. (1987), "The Fatigue Behavior of Overlapping Joints," *3rd International ECSC Offshore Conference on Steel in Marine Structures (SIMS '87)*, Delft, The Netherlands, Elsevier.
- Lee, M.M.K. (1999), "Strength, Stress and Fracture Analyses of Offshore Tubular Joints Using Finite Elements," *Journal of Constructional Steel Research*, Vol. 51, pp. 265–286.
- Lee, M.M.K. and Wilmschurst, S.R. (1996), "Parametric Study of Strength of Tubular Multiplanar KK-Joints," *Journal of Structural Engineering*, Vol. ST8, pp. 893–904.
- Lee, M.M.K. and Wilmschurst, S.R. (1997), "Strength of Multiplanar Tubular KK-Joints Under Antisymmetrical Axial Loading," *Journal of Structural Engineering*, Vol. ST6, pp. 755–764.
- Marshall, P.W. (1992), *Design of Welded Tubular Connections: Basis and Use of AWS Code Provisions*, Elsevier, Amsterdam.
- MEEI (2003), *MathCAD*, Mathsoft Engineering & Education, Inc., Cambridge, MA.
- Moe, E.T. (1987), *Stress Analysis and Fatigue Tests on Overlapped K-Joints*, Elsevier, Delft, The Netherlands.
- Moses, F., Schilling, C.G., and Raju, K.S. (1987), "Fatigue Evaluation Procedures for Steel Bridges," *NCHRP Report 299*, National Cooperative Highway Research Program, Washington, DC.
- Natarajan, M. and Toprac, A.A. (1968), "The Fatigue Strength of Tubular T-Joints," University of Texas, Austin, TX.
- Noordhoek, C. and de Back, J. (1987), *Steel in Marine Structures*, Elsevier, Delft, The Netherlands.
- Nowak, A.S. and Collins, K.R. (2000), *Reliability of Structures*, McGraw-Hill.
- Peronto, J.L. (2003), "High-Cycle Constant Amplitude Fatigue Life Variability of Welded Round HSS Y-Joints," MS Thesis, Marquette University, Milwaukee, WI.
- Ramanathan, R. and Foley, R.P. (2001), "Effect of Prior Microstructure on Austenite Decomposition and Associated Distortion," Illinois Institute of Technology, Chicago, IL.
- Rondal, J., Wurker, K.-G., Dutta, D., Wardenier, J., and Yeomans, N. (1992), *Structural Stability of Hollow Sections*, Verlag TUV Rheinland, Koln, Germany.
- Schmale, E. and Kreiskorte, H. (1987), "Random Load Tests on Model Scale and Full Scale K-Joints in Sea Water Test Facilities and Strain Measurements," *3rd International ECSC Offshore Conference on Steel in Marine Structures (SIMS '87)*, Delft, The Netherlands, Elsevier.
- Schumacher, A. (2003), "Fatigue Behavior of Welded Circular Hollow Section Joints in Bridges," Doctor of Science Thesis, Ecole Polytechnique, Lausanne, Switzerland.
- SEAINT (2000), "Mail Archive for April–June 2000: ASTM A513 Tubing," Structural Engineers Association International.
- Snijder, H.H., Gijsbers, F.B.J., Dijkstra, O.D., and ter Avest, F.J. (1987), "Probabilistic Fracture Mechanics Approach of Fatigue and Brittle Fracture in Tubular Joints," *3rd International ECSC Offshore Conference on Steel in Marine Structures (SIMS'87)*, Delft, The Netherlands, Elsevier.
- Soh, A.-K. and Soh, C.-K. (1993), "Hot Spot Stresses of Tubular Joints Subjected to Combined Loadings," *Journal of Structural Engineering*, Vol. 119, No. 2, pp. 654–661.
- Van Aken, D. (2001), "Engineering Concepts: Segregation and Banding in Steel," *Industrial Heating*.
- van Delft, D.R.V., Noordhoek, C., and DaRe, M.L. (1987), "The Results of the European Fatigue Tests on Welded Tubular Joints Compared with SCF Formulas and Design Lines," *3rd International ECSC Offshore Conference on Steel in Marine Structures (SIMS '87)*, Elsevier Delft, The Netherlands.

- van Den Brink, S.H. and ter Avest, F.J. (1987), *Assesment of the Fracture Toughness Properties of Material in Welded Tubular Joints*, Elsevier, Delft, The Netherlands.
- van Wingerde, A.M., Packer, J.A., and Wardenier, J. (2001), "Simplified SCF Formulae and Graphs for CHS and RHS K- and KK-Connections," *Journal of Constructional Steel Research*, Vol. 57, No. 3, pp. 221–252.
- Wardenier, J., Dutta, D., Yeomans, N., Packer, J.A., and Bucak, O. (1995), *CIDECT 6: Design Guide for Structural Hollow Sections in Mechanical Applications*, Verlag TUV Rheinland, Koln, Germany.
- Wardenier, J., Kurobane, Y., Packer, J.A., Dutta, D., and Yeomans, N. (1991), *Design Guide for Circular Hollow Section (CHS) Joints Under Predominantly Static Loading*, Verlag TUV Rheinland, Koln, Germany.
- Zhao, X.-L., Herion, S., Packer, J.A., Puthli, R.S., Sedlacek, G., Wardenier, J., Weynand, K., van Winderde, A.M., and Yeomans, N.F. (2001), *CIDECT 8: Design Guide for Circular and Rectangular Hollow Section Welded Joints Under Fatigue Loading*, TUV-Verlag, Koln, Germany.

