REVIEW OF STS ASARCO CHIMNEY STRUCTURAL INVESTIGATION

818 FT. TALL REINFORCED CONCRETE CHIMNEY

ASARCO SMELTING PLANT

EL PASO, TEXAS

Prepared by Chimney Consultants Inc.
November 20, 2012

Introduction

The 818 ft. tall ASARCO Smelting Plant chimney located in El Paso, Texas was constructed in 1966 by the M.W. Kellogg Company. A recent structural investigation was performed by HKN Engineers to assess the chimney's structural capacity and its ability to meet the strength requirements of ACI 307-08.

We have reviewed HKN's investigation and have the following comments:

1) Across-wind loading per ACI 307-08 Section 4.2.3 has not been properly addressed.

2) Circumferential bending due to radial wind pressure per ACI 307-08 Section 4.2.4 has not been considered.

3) The impact of the existing reinforcing steel splice lengths on the computed capacity has not been considered.

Discussion & Findings

Across-wind

HKN has incorrectly determined that the chimney is not sensitive to across-wind load. ACI 307-08 Section R4.2.3 provides direction for assessing across-wind loads when the outside shell diameter at one third of the height is not less than 1.6 times the top outside diameter. Across-wind load does need to be addressed.

Circumferential Bending

HKN has not addressed circumferential bending, which for the ASARCO chimney is critical since it contains only one curtain of reinforcing steel throughout the upper 600 ft. of the structure. Our investigation has determined that the upper 600 ft of the chimney shell does not meet the strength requirements for circumferential bending in accordance with ACI 307-08. The demand/capacity ratio ranges from 2.38 to 3.74 over this region. In essence, the upper 600 ft of the chimney possess only 27% to 42% of the strength required to resist circumferential bending due to wind load.

Splice Length

The bending capacity of the concrete chimney shell and lining is a function of the reinforcing steel size and spacing. In addition, when computing the bending capacity of the existing structure, the splice length of the existing reinforcing steel needs to be considered and the capacity of the structure should be reduced in those regions where the existing splice length does not meet current design code requirements. Based on our findings, the computed axial bending capacity throughout the lower 688 ft. of the chimney shell is reduced by approximately 20% when taking into account the insufficient splice length. In addition, the computed axial bending capacity throughout a total of 550 vertical feet of the chimney lining should also be reduced to account for insufficient splice length.

Conclusions

Across-wind loads need to be considered.

The lack of sufficient circumferential bending capacity is a serious structural deficiency and it should be noted that catastrophic failure of a reinforced concrete chimney resulting from insufficient circumferential bending capacity is not unprecedented.

The existing reinforcing steel splice lengths need to be accounted for when determining capacity.

Calculations

Circumferential Bending:

Wind speed = 90 mph 3 sec. gust in accordance with ACI 307-08
I = 1.15
f'c = 4000 psi
fy = 40000 psi

Definition of terms used in calculations:

OD = Outside diameter of concrete shell (ft)

Thk = Thickness of concrete shell wall (in)

HORIZ Outside H (c/c spc in.) = c/c spacing of outside face horizontal rebar (in)

HORIZ Outside H bar size = Bar size of outside face horizontal rebar (#)

HORIZ Inside H (c/c spc in.) = c/c spacing of inside face horizontal rebar (in)

HORIZ Inside H bar size = Bar size of inside face horizontal rebar (#)

$\underline{p}(z)$ = as defined by ACI 307-08 Eq. (4-5)

Gr(z) = as defined by ACI 307-08 Eq. (4-32)

pr(z) = as defined by ACI 307-08 Eq. (4-31)

Mi(z) = circumferential wind moment as defined by ACI 307-08 Eq. (4-29)

Mo(z) = circumferential wind moment as defined by ACI 307-08 Eq. (4-30)

1.4 Mi(z) = factored circumferential wind moment producing tension on inside face

1.4 Mo(z) = factored circumferential wind moment producing tension on outside face

M(ti) Capacity = bending capacity with tension on inside face

M(to) Capacity = bending capacity with tension on outside face

M(ti) Dem/Cap = demand / capacity for circumferential bending with tension on inside face

M(to) Dem/ Cap = demand / capacity for circumferential bending with tension on outside face

Chimney geometry & circumferential reinforcing size and spacing.

Elevation (ft)	OD (ft)	Thk (in)	HORIZ. Outside H (c/c spc in.)	HORIZ. Outside H bar size	HORIZ. Inside H (c/c spc in.)	HORIZ. Inside H bar size
818	31.25	9.00	6.00	3	-	-
787	32.43	9.00	6.00	3	-	-
762	33.39	9.00	6.00	3	-	-
738	34.31	9.00	6.00	3	-	-
713	35.26	9.00	6.00	3	-	-
688	36.22	9.00	5.50	3	-	-
664	37.13	9.13	5.50	3	-	-
639	38.09	9.25	5.50	3	-	-
615	39.01	9.38	5.50	3	-	-
590	39.96	9.50	5.50	3	-	-
565	40.92	9.50	5.50	3	-	-
541	41.83	9.63	5.50	3	-	-
516	42.79	9.75	5.50	3	-	-
492	43.70	9.88	5.50	3	-	-
467	44.66	10.00	5.50	3	-	-
443	45.58	10.25	7.50	4	-	-
418	46.53	10.50	7.50	4	-	-
393	47.49	11.00	7.50	4	-	-
369	48.40	12.00	7.50	4	-	-
344	49.36	12.50	7.50	4	-	-
320	50.28	13.50	6.00	4	-	-
295	51.23	15.00	6.00	4	-	-
270	52.19	16.00	6.00	4	-	-
246	53.10	17.00	5.50	4	-	-
221	54.06	17.50	5.50	4	-	-
197	54.97	18.50	5.00	4	12.00	4
172	55.93	19.00	5.00	4	12.00	4
148	56.85	20.00	5.00	4	12.00	4
123	57.80	21.00	6.00	5	12.00	4
98	58.76	21.50	6.00	5	12.00	4
74	59.67	26.00	6.00	6	12.00	4
49	60.63	36.00	6.00	6	12.00	4
25	61.54	36.00	6.00	6	12.00	4
0	62.50	36.00	6.00	6	12.00	4

Calculation of circumferential bending moments due to radial wind pressure.

Elevation (ft)	p(z) (psf)	Gr(z)	pr(z) (psf)	Mi(z) (ft-lb/ft)	Mo(z) (ft-lb/ft)
818	25.84	1.67	64.73	4667	4064
787	25.54	1.68	64.48	5016	4369
762	25.28	1.69	42.84	3537	3081
738	25.04	1.71	42.70	3726	3246
713	24.77	1.72	42.55	3927	3421
688	24.50	1.73	42.39	4132	3599
664	24.23	1.74	42.22	4329	3771
639	23.95	1.76	42.05	4538	3952
615	23.67	1.77	41.87	4741	4129
590	23.37	1.78	41.67	4955	4316
565	23.06	1.80	41.47	5174	4506
541	22.75	1.81	41.26	5383	4689
516	22.42	1.83	41.03	5603	4880
492	22.10	1.85	40.80	5814	5064
467	21.75	1.86	40.54	6035	5257
443	21.39	1.88	40.28	6244	5438
418	21.02	1.90	39.99	6461	5627
393	20.62	1.92	39.68	6670	5809
369	20.22	1.95	39.36	6855	5970
344	19.79	1.97	39.00	7057	6146
320	19.36	2.00	38.63	7232	6299
295	18.88	2.02	38.21	7397	6443
270	18.37	2.05	37.75	7565	6588
246	17.85	2.09	37.26	7713	6718
221	17.27	2.12	36.69	7867	6852
197	16.67	2.16	36.08	7983	6953
172	15.99	2.21	35.36	8093	7048
148	15.26	2.26	34.55	8153	7101
123	14.42	2.33	33.57	8173	7118
98	13.44	2.41	32.36	8138	7088
74	12.33	2.50	30.88	7914	6893
49	10.86	2.65	28.75	7400	6446
25	8.83	2.88	25.43	6756	5884

Note that pr(z) is increased by 50% for a distance 1.5d(h) from the top

Circumferential bending Demand / Capacity using 1.4W per ACI 307-08 Section 5.3.2.

Elevation (ft)	1.4 Mi(z) (ft-lb/ft)	1.4 Mo(z) (ft-lb/ft)	M(ti) Capacity (ft-lb/ft)	M(to) Capacity (ft-lb/ft)	M(ti) Dem/Cap	M(to) Dem/Cap
818	6533	5690	2078	3726	3.14	1.53
787	7023	6117	2078	3726	3.38	1.64
762	4952	4313	2078	3726	2.38	1.16
738	5217	4544	2078	3726	2.51	1.22
713	5498	4789	2078	3726	2.65	1.29
688	5785	5038	2259	4057	2.56	1.24
664	6061	5279	2259	4147	2.68	1.27
639	6353	5533	2259	4237	2.81	1.31
615	6637	5781	2260	4327	2.94	1.34
590	6937	6042	2255	4415	3.08	1.37
565	7244	6309	2255	4415	3.21	1.43
541	7537	6564	2260	4507	3.33	1.46
516	7844	6832	2260	4597	3.47	1.49
492	8140	7090	2260	4687	3.60	1.51
467	8449	7359	2260	4777	3.74	1.54
443	8742	7614	2974	6572	2.94	1.16
418	9045	7878	2974	6812	3.04	1.16
393	9338	8133	2975	7292	3.14	1.12
369	9597	8359	2975	8252	3.23	1.01
344	9879	8605	2976	8732	3.32	0.99
320	10125	8819	3672	12067	2.76	0.73
295	10356	9020	3673	13867	2.82	0.65
270	10590	9224	3674	15067	2.88	0.61
246	10798	9405	3984	17722	2.71	0.53
221	11013	9592	3984	18377	2.76	0.52
197	11176	9734	13150	23230	0.85	0.42
172	11330	9868	13450	23950	0.84	0.41
148	11415	9942	14050	25390	0.81	0.39
123	11442	9966	15706	33976	0.73	0.29
98	11393	9923	16006	34906	0.71	0.28
74	11080	9650	20515	60295	0.54	0.16
49	10361	9024	26515	86695	0.39	0.10
25	9459	8238	26515	86695	0.36	0.10

Sample calculation of circumferential bending capacity at elevation 713 ft in accordance with ACI 307-08 Appendix A pages 28 ~ 29.

Circumferential Bending Capacity - ACI 307-08 | Elevation 713 ft.

Strength reduction factor (phi)	**0.90**	
Thermal load factor	**1.2**	
Temperature differential Tx (F deg)	**0**	
Fc (psi)	**4000**	
Shell wall thickness (inches)	**9.00**	
CL distance outside steel to outside face of conc	**3.25**	
Outside steel Fy (psi)	**40000**	
As outside (in\2 / ft of height)	**0.22**	
Inside steel Fy (psi)	**40000**	
As inside (in\2 / ft of height)	**0**	
Sum V = 0 eq A-6	**0.0018**	
a (Tension Outside)	**0.0239652**	***a (Ten. Outside) check OK***
Phi Mn = Mu (ft-lb/ft) Tension Outside	**3724**	
Sum V = 0 eq A-6	**0.0018**	
a (Tension Inside)	**0.0239652**	***a (Ten. Inside) check OK***
Phi Mn = Mu (ft-lb/ft) Tension Inside	**2074**	
Coefficient of Exp	0.0000065	
Es (psi)	29000000	
Ec (psi)	3604997	
B1	0.85	
n	8.0444	
Y1	0.0000	
Y2	0.6389	
p'	0.002037	
c1	-0.01639	
c2	0.00027	
c3	0.02094	
c'	0.12924	
Fstc (psi)	0	
F"ctc (psi)	0	
fy'c for outside steel (psi)	40000	
fy'c for inside steel (psi)	40000	
fc"c (psi)	4000	

a (Tension Outside)	0.0239652	
fcs eq A-1	-1027289	compression steel - inside
fcs (must not be > fy'c)	-40000	compression steel - inside
Pcs eq A-3	0	compression steel (lb)
fts eq A-2	1884435	tension steel - outside
fts (must not be > fy'c)	40000	tension steel - outside
Pts eq A-4	733	tension steel (lb)
Pcb eq A-5	733	compression block (lb)
Sum V = 0 eq A-6	0.0018	
Mn	4138	
Mu (Outside) = Phi Mn (ft-lb/ft)	3724	
a (Tension inside)	0.0239652	
fcs eq A-1	-1027289	compression steel - outside
fcs (must not be > fy'c)	-40000	compression steel - outside
Pcs eq A-3	-733	compression steel (lb)
fts eq A-2	1884435	tension steel - inside
fts (must not be > fy'c)	40000	tension steel - inside
Pts eq A-4	0	tension steel (lb)
Pcb eq A-5	733	compression block (lb)
Sum V = 0 eq A-6	0.0018	
Mn	2304	
Mu (Inside) = Phi Mn (ft-lb/ft)	2074	

Splice Length:

Per M.W. Kellogg Company Drw. No. 6127-9ED, the splice lengths are designated as follows:

Bar Size	Splice (in)
3	15
4	15
5	19
6	23
7	27
8	30
9	34
10	39
11	43

Vertical reinforcement splice lengths in accordance with ACI 307-08 are as follows:

ACI 318-05

Fy (psi)	60000
Fc (psi)	4000

VERTICAL Bar Size	Concrete Cover to edge of bar (in)	Minimum c/c bar spacing (in)	**VERTICAL** Development (inch)	**VERTICAL** Splice (inch)
4	2.50	8.00	12.00	15.60
5	2.50	8.00	14.23	18.50
6	2.50	8.00	17.08	22.20
7	2.50	8.00	24.90	32.37
8	2.50	8.00	28.46	37.00
9	2.50	8.00	32.10	41.73
10	2.50	8.00	36.61	47.59
11	2.50	8.00	44.14	57.38

Ratio of existing splice to required splice:

Bar Size	Existing Splice (in)	Required Splice (in)	Existing/ Required
3	15	15.60	0.962
4	15	15.60	0.962
5	19	18.50	1.027
6	23	22.20	1.036
7	27	32.37	0.834
8	30	37.00	0.811
9	34	41.73	0.815
10	39	47.59	0.819
11	43	57.38	0.749