Construction and Maintenance Management Inc.	BY: Rolando Ionta	DATE: dd-mm-yy
	CHK'D: Bogdan Mazurczyk	DATE: dd-mm-yy
	Project No. YY-XXX	
	Description: Blast Furnace- Small Bell Lift Chain	
	Eyebolt Failure Analysis	
	This report e-mailed to Client staff on dd/mm/yy	

Tape No. 13 dd/mm/yy

Tape No. 14 dd/mm/yy; 4:23:32

Purpose of Project:

Client requested that CMM perform a failure analysis of the Small Bell Lifting Chain Eyebolt. The failure analysis is to encompass a review of the entire small and large bell operating system determine what could have caused this type of catastrophic failure.

Data Provided by Client:

The following data/information was provided by Client during the meeting of mm/dd/yy and follow-up phone conversations and site visits.

1- Both the north and south small bell eyebolts recently failed on Saturday, mm/dd/yy.

2- The subject eyebolts, are of the new design per drawing XXXXX, were installed in December of yy.

3- The relief valve was reported to be stuck in the closed position during this failure.

5- The two broken eyebolts were given to Rolando Ionta for further inspection and evaluation.

6- There is no specific pattern to the failures. The previous similar failure occurred about four or five years ago.

7- The lifting chain link components have not failed in any of the reported failures.

8- The "horse head" shaped "SMALL BELL BEAM QUADRANT" steel casting connecting the lift chain to the lift beam has been torn off at the bolts on past similar eyebolt failures.

9- Both the original and new design eyebolt have failed at the same location. The common failure point is at the top of the bottom nut at the root of the threads.

10- The Client described the normal operation and sequence of the Equalizer Valve, the Relief Valve and Lifting Mechanism to Rolando. Major information is as follows:

- a- Operation of the Equalizer Valve, Relief Valve, Large Bell and the Small Bell Lifting Lifting Mechanism is completely automatic and controlled through a PLC.
- b- For the large bell to be opened and/or closed, the gas seal must pressurized or "equalized" with the same pressure in the top of the furnace. This equalizing pressure is approximately 7 PSIG.
- c- For the small bell to be opened and/or closed, the gas seal must first be vented by the relief valve.
- d- The area above the small bell is open to atmosphere and therefore cannot be pressurized.
- e- The small bell cycles five to six times for every cycle of the large bell.

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f- The small bell upper support is visually leveled. The lifting chain bottom nuts are then adjusted to suspend the small bell and rod assembly on two lifting chains.
Please note that with this type of visual leveling and manual setting of the nuts, it is extremely to difficult to obtain equal loading on the support chain components since this lifting chain assembly is not of a self equalizing design. This can result in one of the lift chain assemblies carrying most or all of the load until it literally stretches to distribute the load to the other lift chain assembly.

11- Actual known weights of the small bell suspended components were not readily available from the Client, therefore it was agreed to obtain the loading/weight data from the available drawings.

12- The Client's drawings XXXXX and XXXXX were reviewed during the mm/dd/yy meeting. Several additional drawings were pulled and reviewed for this failure analysis. A drawing list of all the drawings reviewed/used for this failure analysis is included in this report.

13- The Client, arranged for and supplied the metallurgical analysis to confirm the composition of the eyebolt samples.

General Procedure for the Failure Analysis:

The following general procedure was followed in conducting this failure analysis. Please note that this analysis report relies heavily on video capture photographs in support of the presented observations, calculations and conclusions.

1- Pull and review the applicable drawings for the small bell and large bell.

2- Visually inspect the two broken eyebolts in CMM's office to deduce the nature or type of failure exhibited in each.

3- Have the subject eyebolts cleaned and repeat the visual inspection to confirm the prior observations.

4- Have the subject failed eyebolts tested to confirm metallurgical composition and hardness.

5- Interview Client's personnel to obtain the operating and maintenance conditions, procedures and and observations of the general large and small bell system. Rolando Ionta personally interviewed the following personnel in conducting this failure analysis:

Mr. X
Mr. Y
Mr. Z

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The information provided by these key personnel is denoted above and in the photographs included in this report.

6- From the available information on the drawings, review/calculate the loading on the Lifting Chain Components under "Normal Operation" and under any possible adverse "Upset Condition".

7- Compare the results of the calculations with the observed failed components to isolate the root cause of this catastrophic failure.

8- Please note that as of the date of this report, the metallurgical analysis was not available.

Copies of this report e-mailed to the following:

Construction and Maintenance Management Inc.

BY: Rolando Ionta	DATE: dd-mm-yy
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Project No. YY-XXX	
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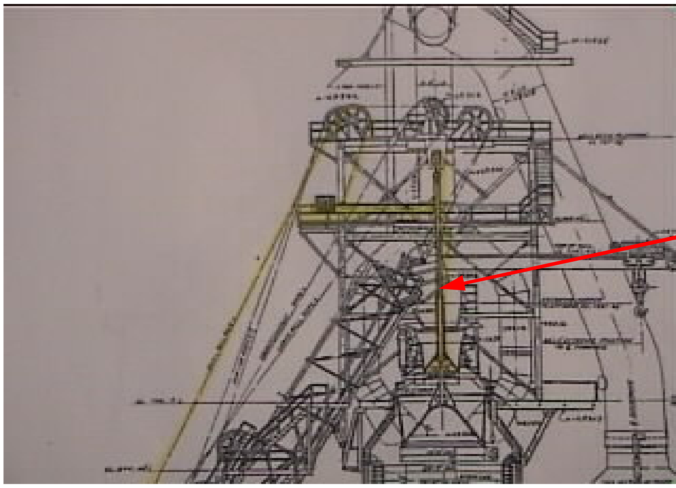

PHOTO No. 1

Partial view of Section A-A on Drawing XXX. Small and Large Bell are actuated by wire ropes from a hoist in the Skip Hoist Room.

Small Bell is highlighted in yellow.

Small Bell Eyebolts failed on Saturday, mm/dd/yy.

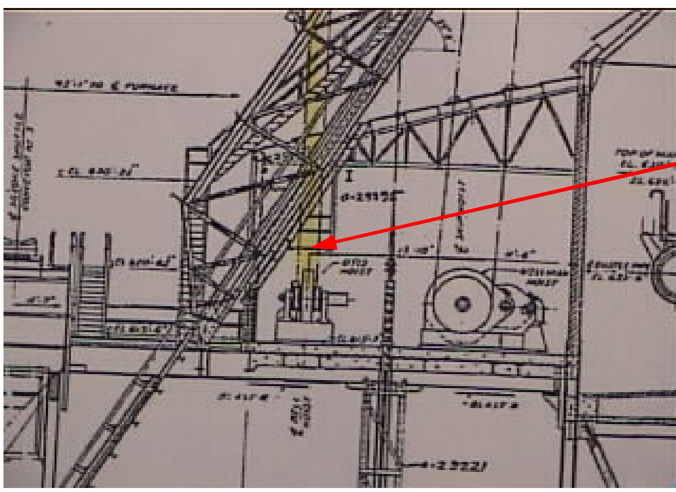

PHOTO No. 2

Partial view of Section A-A on Drawing XXX. Small and Large Bell are actuated by wire ropes from a hoist in the Skip Hoist Room.

Small Bell ropes are highlighted in yellow.

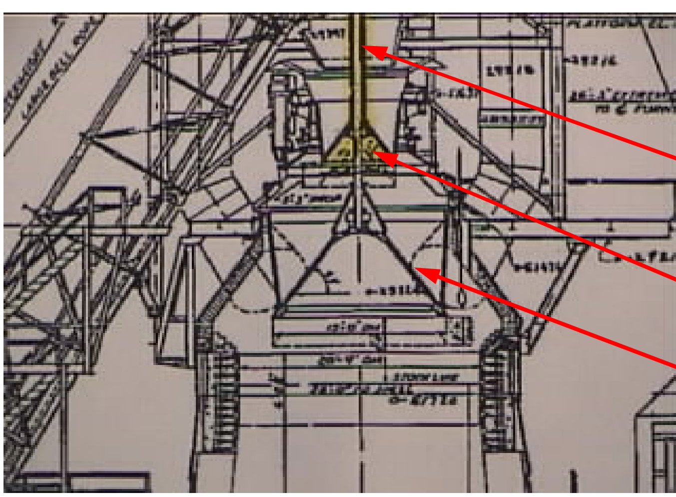

PHOTO No. 3

Closer view of Section A-A on Drawing XXX.

Bell Rod- Large Bell Rod operates within the small bell rod.

Small Bell is highlighted in yellow.

Large Bell.

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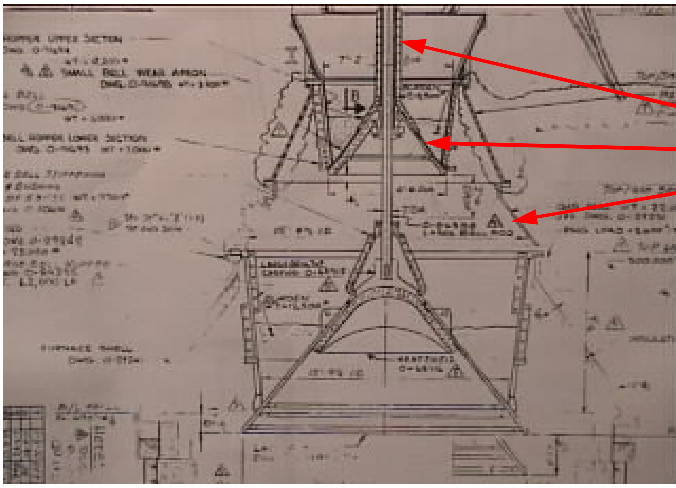

PHOTO No. 4

Partial view of Drawing XXX.
Small Bell Rod.
Small Bell.
Gas Seal- space between small and large bell. This space must be equalized to operate large bell. The equalizing pressure is 7 PSIG. This space must be relieved/vented to operate the small bell.
Small Bell cycles 5-6 times per large bell cycle.

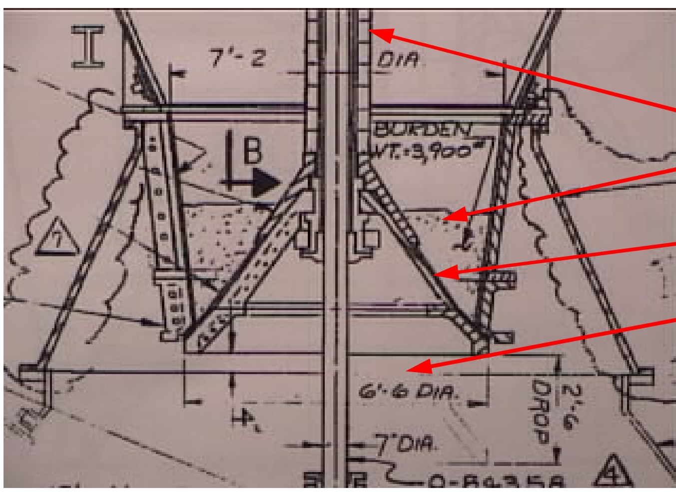

PHOTO No. 5

Partial view of Drawing XXX.
Small Bell Rod.
Typical Burden Load= 3,900 Lbs.
Maximum Burden, full hopper= 22,000 Lbs.
Small Bell.
6'-6" (78") Small Bell diameter.
At 7 PSIG equalizing pressure, Small Bell with Burden can be supported with lifting beam in open position.

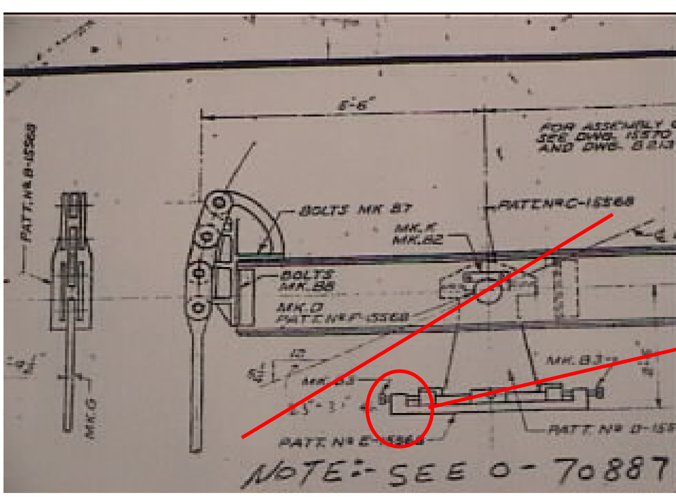

PHOTO No. 6

Partial view of Drawing XXX.
Normal actuation of lifting beam yields 2-3" of vertical motion at approx. 23.6^{O} beam pivot.
Lift beam will bottom on support if driven down by free falling small bell.
Lift beam will bottom at approx. 30^{O} beam pivot yielding approx. 34 1/2" of vertical travel of the small bell assembly.

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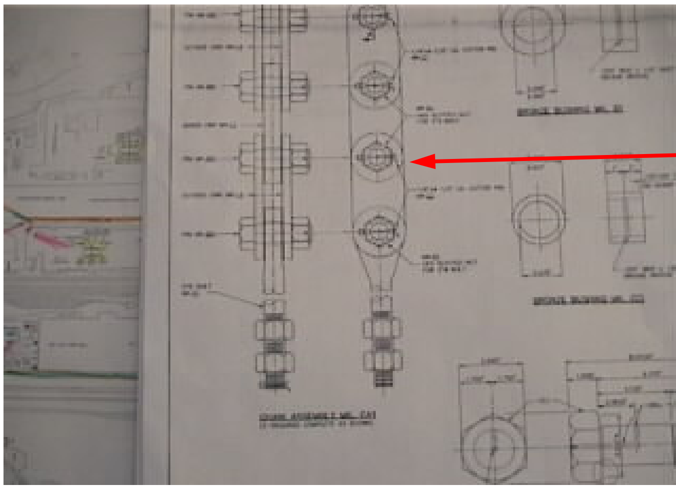

PHOTO No. 7

Partial view of Drawing XXX.

Lift Chain assembly is attached to the lifting beam shown in Photo 6 above.

See Photo 8 for view where lift chain attaches to the Small Bell Support.

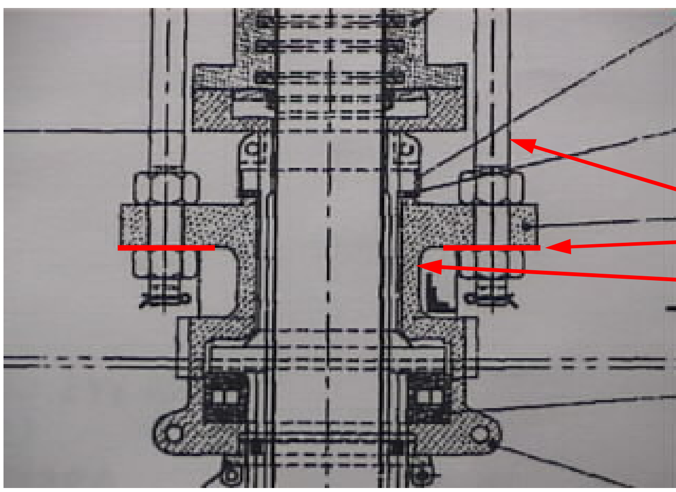

PHOTO No. 8

Partial view of Drawing XXX.
This is the connection of the lifting chain assembly to the Small Bell Upper Support.
Failed Eyebolt MK-E1
Eyebolt Failure Planes.
Small Bell Upper Support.

The assembly is visually leveled and adjusted making equalizing of the load very difficult.
Design is not self equalizing.

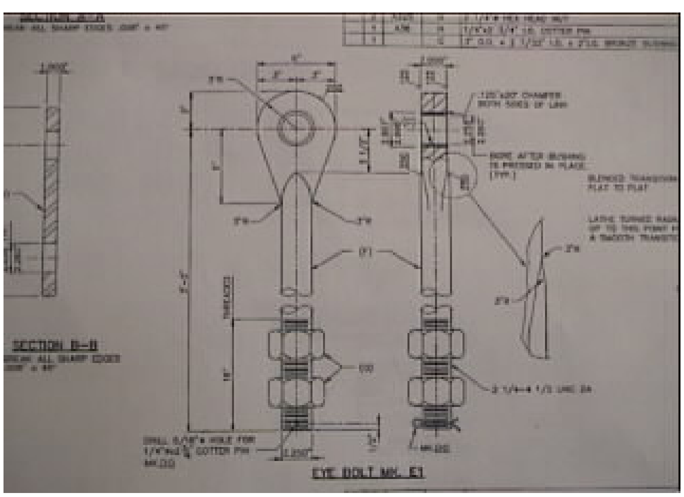

PHOTO No. 9

View of Eye Bolt MK-E1 on Drawing XXX.

Except for the fracture, the two failed eyebolts were per dimensions on drawing.

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PHOTO No. 10

View looking at the failed eyebolts from the mm/dd/yy Failure.
North Eyebolt with fractured mating part.
South Eyebolt- mating part not found.

North eyebolt measured 18 3/4" from center of eye to fracture.

South eyebolt measured 19 1/4" from center of eye to fracture.

PHOTO No. 11

Close-up view of the south eyebolt fracture surface. Observations are as follows:
1- Very rough failure surface across entire root diameter.
2- Shear Lip.
3- No beach (Fatigue) marks present.
4- No signs of necking.
This is typical of a sudden overload failure of a brittle material which indicates that this is a very tough material as specified.

PHOTO No. 12

Close-up view of the north eyebolt fracture surface. Observations are as follows:
1- Very rough failure surface across entire root diameter.
2- Shear Lip.
3- No beach (Fatigue) marks present.
4- No signs of necking.
This is typical of a sudden overload failure of a brittle material which indicates that this is a very tough material as specified.

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PHOTO No. 13

Close-up view of the mating part of the north eyebolt fracture surface. Observations are as follows:
1- Failure surface is a direct match with that of the north eyebolt shown in photo 12 above.
2- No abnormal signs on the nut.
3- Washer surface of all three nuts are very corroded. This may be an indicator of poor seating which would also indicate one eyebolt was subjected to entire load.

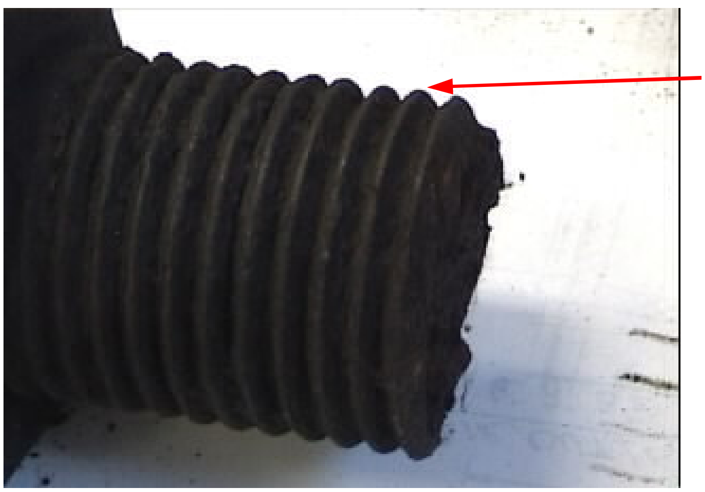

PHOTO No. 14

Close-up view of the outside diameter of the threads at the failure plane.
Observations are as follows:
1- No sign of necking.
2- No sign of any stretched threads.

This is typical of an overload failure of a brittle material which indicates that this is a very tough material as specified.

PHOTO No. 15

Both of the failed eyebolts were re-inspected after cleaning. There were no deficiencies observed except for the fractures in the threads. The eyebolts were straight indicating no major side or bending forces.

Both eyebolts were then sent to Client LAB for hardness testing and metallurgical analysis.

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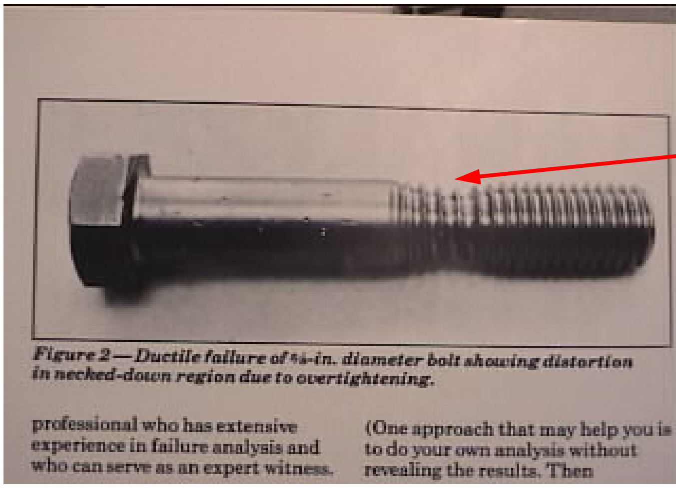

PHOTO No. 16

Photo of reference information for diagnosing bolt failures.
This photo depicts sudden overload of a ductile material which results in **necking** or yielding of the material.

This is not what was observed on the two subject eyebolts. Therefore, the two subject eyebolts are not ductile but brittle as is typical of high strength materials.

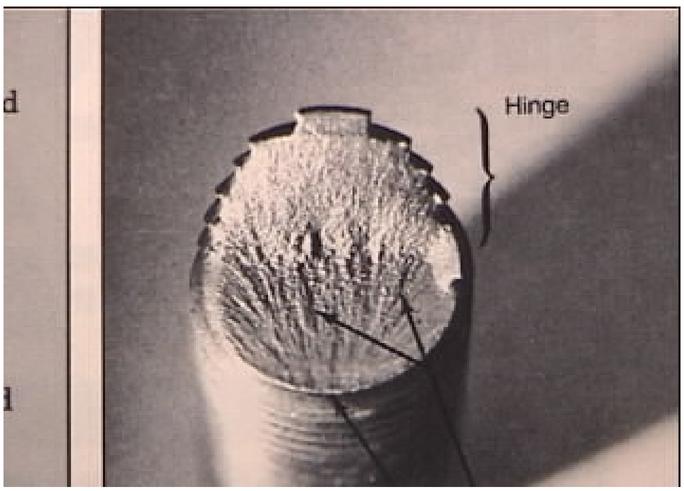

PHOTO No. 17

Photo of reference information for diagnosing bolt failures.
This photo depicts sudden overload of a brittle material.

This is similar to the failure observed on the two subject eyebolts. Therefore, the two subject eyebolts are not ductile but brittle as is typical of high strength materials.

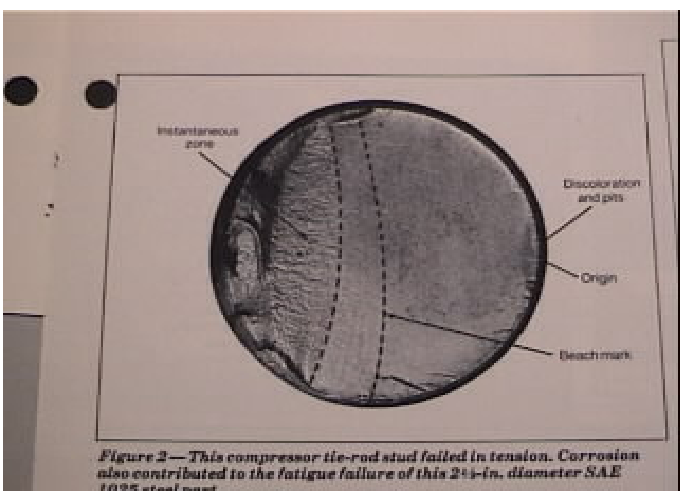

PHOTO No. 18

Photo of reference information for diagnosing bolt failures.
This photo depicts a fatigue type of failure.

This is not what was observed on the two subject eyebolts. There were no beach or fatigue lines on the two failed eyebolts, but, rather, one large instantaneous failure zone was present depicting a sudden overload.

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	Description: Blast Furnace- Small Bell Lift Chain	
	Eyebolt Failure Analysis	
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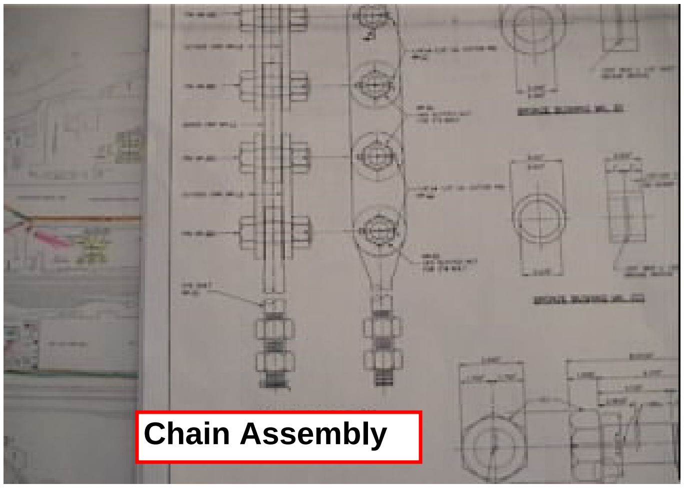
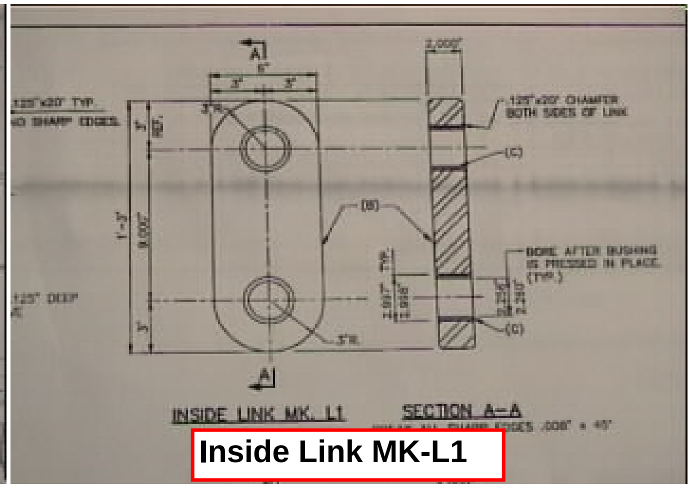
Calculations:

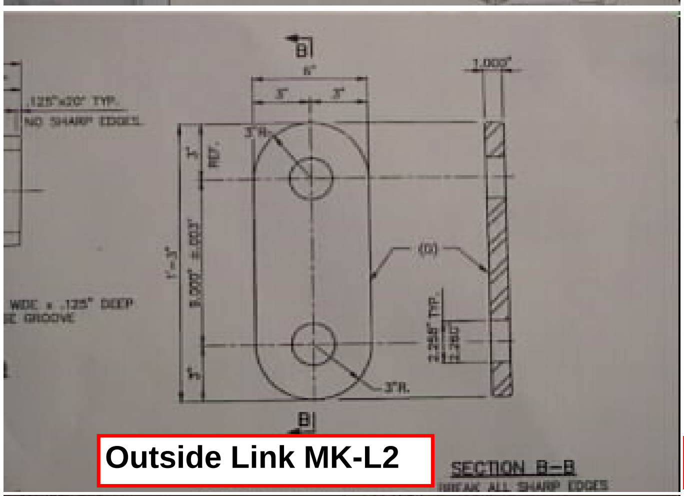
1- Check breaking strength of lifting chain components to determine weakest link.



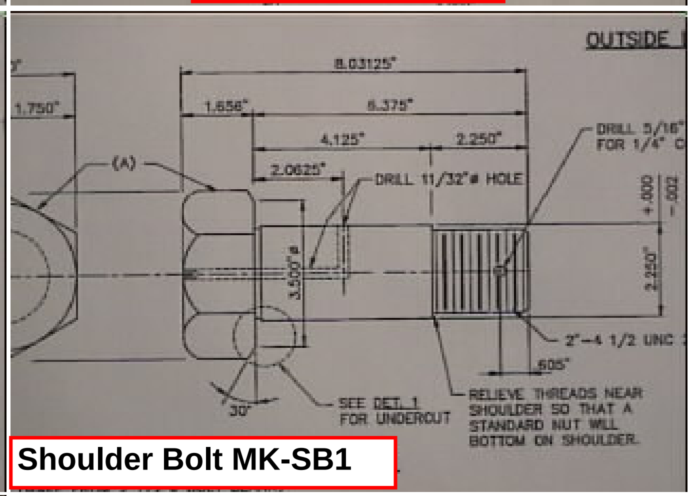
Chain Assembly



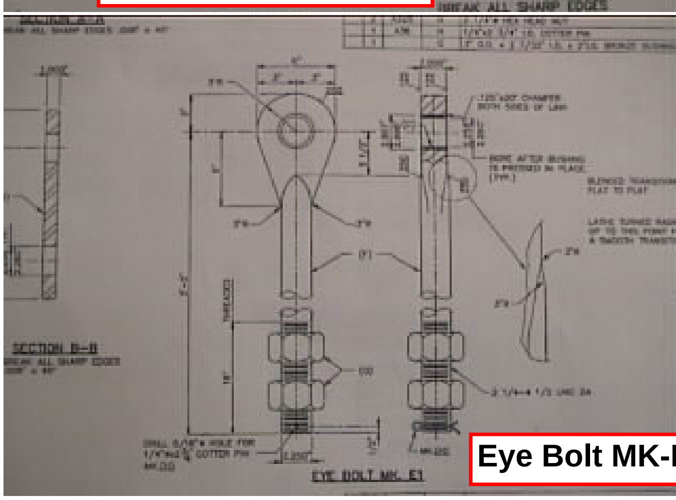
Inside Link MK-L1



Outside Link MK-L2



Shoulder Bolt MK-SB1



Eye Bolt MK-E1

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	CHK'D: Bogdan Mazurczyk	DATE: dd-mm-yy
	Project No. YY-XXX	
	Description: Blast Furnace- Small Bell Lift Chain	
	Eyebolt Failure Analysis	
	This report e-mailed to Client staff on dd/mm/yy	

Calculations:

1- Check breaking strength of lifting chain components to determine weakest link.

Item Description	Lift Chain Assembly - Dwg. 0-XXX			
	Inside Link	Outside Link	Shoulder Bolt	Eye Bolt
	MK - L1	MK - L2	MK - SB1	MK - E1
1- Specified Material	T1 TYPE B	T1 TYPE B	4141 HT	4340 HT
a- Tensile Strength - KSI	110	110	150	140
b- Yield Strength - KSI	100	100	130	120
c- Shear Strength (75% Ult) - KSI	83	83	113	105
2- Failure Plane Dimensions				
a- Chain Links:				
1- Link thickness- inches	2.00	1.00	N/A	N/A
2- Link Width- inches	6.00	6.00	N/A	N/A
3- Link Bush. Bore - inches	2.25	2.25	N/A	N/A
4- No. of Links supporting Load	1	2	N/A	N/A
5- Stress Concentration Factor	2.26	2.26	N/A	N/A
6- Calc. Tensile Area- in^2	7.50	7.50	N/A	N/A
7- Calc. Shear Area- in^2	7.50	7.50	N/A	N/A
8- Calc. Bearing Area- In^2 (90^O)	2.25	2.25	N/A	N/A
b- Shoulder & Eye Bolts				
1- Nominal Body Dia. - inches	N/A	N/A	2.25	2.25
2- Threads per Inch	N/A	N/A	N/A	4 1/2
3- Eye Outside Dia. - inches	N/A	N/A	N/A	6.00
4- Eye Bushing Bore - inches	N/A	N/A	N/A	2.938
5- Eye Thickness- inches	N/A	N/A	N/A	2.00
6- Effective body Length- inches	N/A	N/A	N/A	4.00
7- Effective Thread Length- inches	N/A	N/A	N/A	9.00
8- Thread Stress Concentration	N/A	N/A	1.00	3.00
9- Bolt Body Tensile/Shear Area-In^2	N/A	N/A	3.98	3.98
10- Thread Tensile Area- In^2	N/A	N/A	N/A	3.25

Construction and Maintenance Management Inc.

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Project No. YY-XXX			
Description: Blast Furnace- Small Bell Lift Chain			
Eyebolt Failure Analysis			
This report e-mailed to Client staff on dd/mm/yy			

1- Check breaking strength of lifting chain components to determine weakest link.

Item Description	Lift Chain Assembly - Dwg. 0-XXX			
	Inside Link	Outside Link	Shoulder Bolt	Eye Bolt
	MK - L1	MK - L2	MK - SB1	MK - E1
b- Shoulder & Eye Bolts- continued				
11- Calc. Eye Tensile Area- In^2	N/A	N/A	N/A	**6.13**
12- Calc. Eye Shear Area- In^2	N/A	N/A	N/A	**6.13**
13- Calc. Eye Bearing Area- In^2 (90^o)	N/A	N/A	N/A	**2.94**
14- Thread Sec. Spring rate Lbs/In.	N/A	N/A	N/A	**10,825,632**
15- Body Sec. Spring rate Lbs/In.	N/A	N/A	N/A	**29,820,587**
16- Composite Spring rate Lbs/in.	N/A	N/A	N/A	**7,942,355**
3- Component Breaking Loads:				
a- Chain Links:				
1- Tension - Kips	**365.04**	**365.04**	N/A	N/A
2- Shear - Kips	**618.75**	**618.75**	N/A	N/A
3- Bearing - Kips	**247.50**	**247.50**	N/A	N/A
b- Shoulder Bolt				
1- Shear in Body - Kips	N/A	N/A	**1,033.78**	N/A
2- Bearing in Body - Kips	N/A	N/A	**337.50**	N/A
c- Eye Bolt				
1- Tension in Eye- Kips	N/A	N/A	N/A	**857.50**
2- Shear in Eye - Kips	N/A	N/A	N/A	**643.13**
3- Bearing Eye - Kips	N/A	N/A	N/A	**411.25**
4- Tension to Yield Threads - Kips	Stress Concentration Included			**129.91**
5- Tension to Break Threads - Kips	Stress Concentration Included			**151.56**
6- Tension to Yield Threads - Kips	Stress Concentration Excluded			**389.72**
7- Tension to Break Threads - Kips	Stress Concentration Excluded			**454.68**
8- Deflection to Yield- inches	N/A	N/A	N/A	**0.049**
9- Energy Capacity at Yield- Lb Inches		N/A	N/A	**389,723**
10- Deflection to Fracture- Inches	N/A	N/A	N/A	**0.057**
11- Energy to Fracture- Lb inches	N/A	N/A	N/A	**454,677**
Breaking Strength- Kips (Ten&Shear)	**365.04**	**365.04**	**1,033.78**	**151.56**

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From the above analysis of the lifting chain components, the Eye Bolt MK- E1 is by far the weakest component in this mechanism with the weakest point being at the root of the threads.

Please note that stress concentration factors can vary significantly depending on the exact geometry of the thread profile. Stress concentration factors for threads are typically in the range of 2 to 4 and sometimes can be significantly higher. For this analysis, a stress concentration factor of 3 was used which is a typical average value.

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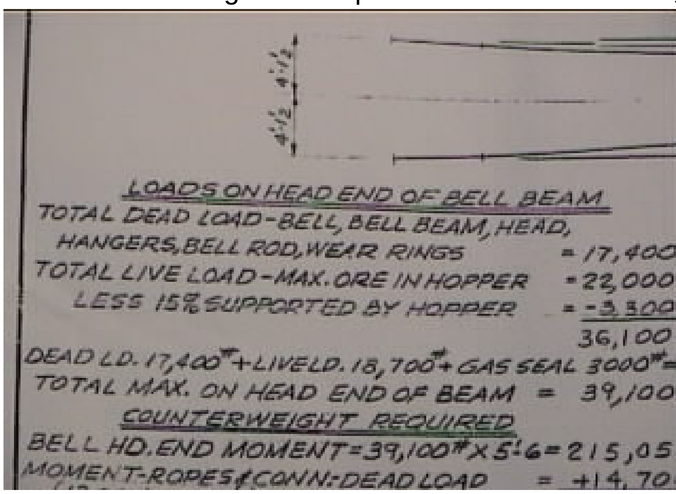
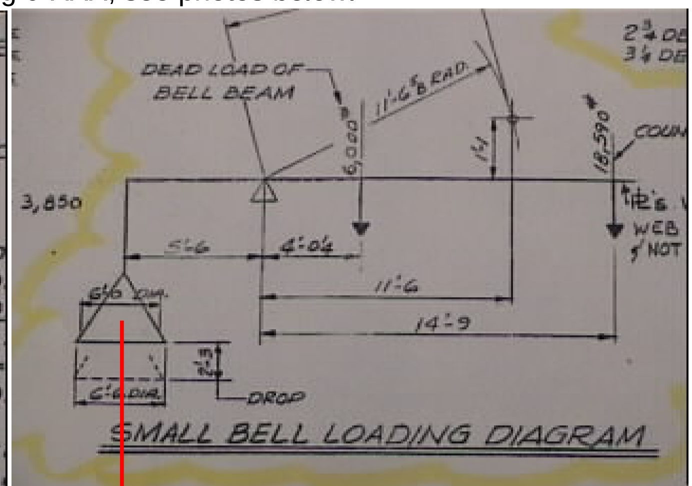
2- Check Small Bell Loading:

Small Bell loading data is specified on Client Drawing 0-XXX, see photos below.





P = see calculations below

Critical Small Bell Loading Data is as follows:

Total dead load of Small Bell =	17,400	Lbs.	
Typical Burden Load on Small Bell =	3,900	Lbs.	per dwg 0-84353.
Maximum Burden @ full hopper =	18,700	Lbs.	per dwg 0-84582.

Total maximum static/steady load =	**17,400**	**+**	**18,700**	**=**	**36,100**	**Lbs.**
Typical load subject to free fall =	**17,400**	**+**	**3,900**	**=**	**21,300**	**Lbs.**

Small Bell Diameter at Gas Seal = 78 inches = **4,778 In^2.**

Equalizing pressure = 7 PSIG

Force at bottom of top bell due to equalizing pressure = **4,778 In^2. X 7 PSIG**

= **33,449 Lbs.**

33,449 Lbs. Due to Equalizing Pressure >> 21,300 Lbs. Bell & Typical Burden.

Therefore, Small Bell with Typical Burden counteracted by equalizing pressure.

This means that the small bell with a typical burden load will be supported by the equalizing pressure of 7 PSIG if the relief valve remained closed while the lifting beam was actuated to open the small bell.

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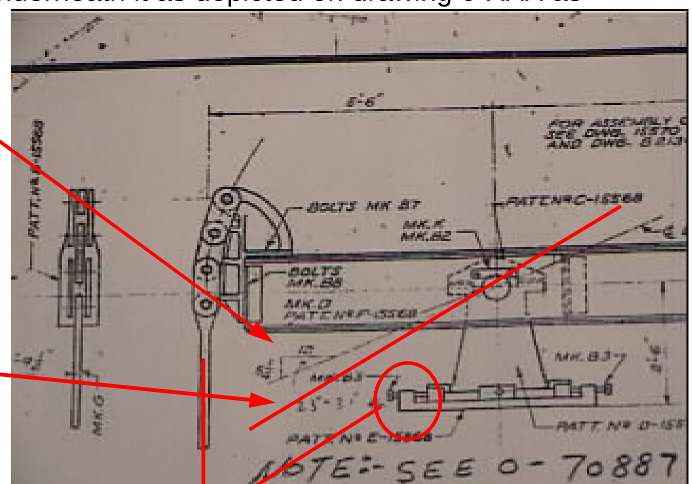
2- Check Small Bell Loading (continued):

Calculate the energy developed by the small bell free falling the distance resulting from the lift beam bottoming out on the bracket/support underneath it as depicted on drawing 0-XXX as shown below.



The 5 1/4 to 12 slope shown on the dwg. equates to the 2'-3" drop specified on the dwgs.
However, should the small bell rod free fall, the beam can pivot up to a maximum angle of approximately 30^{O} per the layout shown.

At approximately 30^{O} the vertical free fall drop is calculated to be:

Max Drop= PI x radius x angle/180

= **PI X 66 X 30 /180**

Max Drop = 34.56 inches

Small Bell Load	=	**17,400 Lbs.**	Bell only.
	=	**21,300 Lbs.**	Bell+Typ Burden
	=	**36,100 Lbs.**	Max Static

Calculate the energy in the free fall of the small bell.

Free fall total effective weight, Small Bell with no Burden =	**17,400 Lbs.**
Typical Burden Load =	**3,900 Lbs.**
Free fall total effective weight, Small Bell + Typical Burden=	**21,300 Lbs.**

Energy due to free falling from maximum available height of **34.56** inches is:

Energy = Weight x Height

Energy of Small Bell with no burden=	**17,400**	**X**	**34.56**	**=**	**601,301 Lb Inches**
Energy of Small Bell with typical burden=	**21,300**	**X**	**34.56**	**=**	**736,075 Lb Inches**

Energy due to free falling from normal operating height of **27.00** inches is:

Energy = Weight x Height

Energy of Small Bell with no burden=	**17,400**	**X**	**27.00**	**=**	**469,800 Lb Inches**
Energy of Small Bell with typical burden=	**21,300**	**X**	**27.00**	**=**	**575,100 Lb Inches**

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2- Check Small Bell Loading (continued):

Maximum nominal load on one (1) eyebolt = **36,100 Lbs.**

Eyebolt Yield Strength with Stress Concentration = **129,908 Lbs.** Line c-4 from Page 3.

129,908 >> 36,100 Therefore, Eyebolt is AMPLE FOR NORMAL LOADING.

From the previous lifting chain component analysis the energy capacity of the eyebolt is:

Energy Capacity at Yield = **389,723 Lb Inches**

Energy Capacity at Fracture = **454,677 Lb Inches**

Energy of Small Bell with no burden= **469,800 Lb Inches at drop of 27.00** Inches

469,800 Lb. In. due to Small Bell Drop >> 389,723 Lb. In. Eyebolt Yield Capacity

Therefore, Small Bell with No Burden Will CAUSE YIELDING OF EYEBOLT.

469,800 Lb. In. due to Small Bell Drop >> 454,677 Lb. In. Eyebolt Fracture Capacity

Therefore, Small Bell with No Burden WILL CAUSE FRACTURE OF EYEBOLT.

Calculate the required minimum drop to start yielding & fracturing of the threads:

Energy = Weight x Height

Height = Energy/Weight

Minimum Height to cause yielding = **389,723 / 17,400 = 22.40 Inches**

Minimum Height to cause failure = **454,677 / 17,400 = 26.13 Inches**

The **22.40** inches of drop required to start yielding of the eyebolt is within the **27.00** inches of available drop due to actuation of the lifting beam mechanism.

Therefore, although the eyebolt design is ample for normal loading and operating conditions, any fault or upset condition that would result in a free falling situation of the small bell, even with no burden, can result in a failure of the eyebolt due to the energy developed by the free fall. This is based on ONE (1) eyebolt being subjected to the entire small bell assembly weight which is very possible since this small bell mechanism is not of a self equalizing design. This is very possible should one of the two nuts become loose during operation.

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Conclusions:

After inspection of the subject failed two (2) eyebolts, review of information from Client personnel, review of Client drawings and the attached analysis/calculations, the following conclusions have been drawn:

1- The design of the Small Bell Lifting Chain Assembly is not of an equalizing design.

2- The visual leveling and adjusting of the Lifting Chain Assembly makes it very difficult to achieve equal load distribution on the two eyebolts. One eyebolt will be subjected to the majority of the load. With any misalignment during installation or operation, one eyebolt will be subjected to the entire load of the small bell, bell rod and associated burden load.

3- One (1) eyebolt is of ample strength to support the load due to the small bell assembly with even the burden of a full (22,000 Lbs.) hopper under normal operating conditions.

4- The equalizing pressure of 7 PSIG in the gas seal is ample to support the weight of the small bell assembly and the typical burden of 3,900 pounds.

5- The geometry of the lift beam and lifting chain assembly allows for a normal vertical travel 2'-3" (27"). The beam will bottom out at the pivot support if driven by the small bell and results in a total available vertical travel of 34 1/2".

6- Should the lifting beam mechanism be activated to open the small bell while the gas seal was under equalizing pressure, the small bell would be held up in the closed position due to the equalizing pressure. With the lifting beam actuated to the open position during this time, a free falling condition would exist once the equalizing pressure is relieved.

7- A free fall of the small bell, with no burden, falling a distance of approximately 24 1/2" will develop sufficient energy to start yielding of the eyebolt with one eyebolt subjected to the entire load. A free fall height of 26 1/8" will develop sufficient energy to instantaneously fracture the eyebolt based on one eyebolt being subjected to the entire load.

8- The required free fall heights required to cause yielding and fracture as specified in item 7 are within the vertical travel available during an upset condition resulting in the small bell being held up by the equalizing pressure while the lifting beam is being actuated to open.

9- The sequence of events/faults required for this rare upset condition was not identified during this study. This may be best addressed by the appropriate Client personnel.

10- The metallurgical analysis results will be forwarded once they are received.

Please contact Rolando Ionta at 216-485-3704 if you have any questions concerning this report.