HMS

HEAVY MOVABLE STRUCTURES, INC.

FIFTH BIENNIAL SYMPOSIUM

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Holiday Inn Surfside
Clearwater Beach, Florida

SESSION WORKSHOP PRESENTATIONS

"SPEED REDUCER: FAILURE INVESTIGATION AND ANALYSIS"

by BILL DOHERTY, P.E.
Doherty & Associates, Inc.

Speed Reducer: Failure Investigation and Analysis

by

Bill Doherty, P.E.
DOHERTY & ASSOCIATES, INC.

This paper is an abridgement of the original investigation and final report written by the author (dated June 15, 1990). He was also responsible for the on-site testing reflected in the report. The project involved was Florida Department of Transportation Bridges: FDOT #87170-3529 & 87170-3530, Sunny Isles Boulevard.

The rationale, observations and conclusions contained in the original report and this paper are those of the author. No final conclusions were ever published by the Department. The author has since retired from the Department of Transportation.

INVESTIGATION

In 1990, the Florida Department of Transportation was midway in the construction of two multi-lane bascule bridges on SR-826 in North Miami Beach to replace the aging single set of two lane spans built in 1927.

On January 20, 1990, the westbound northeast span's speed reducer failed. Inspection revealed the input motoring pinion had failed and was inoperable.

These northern spans (i.e., west bound vehicles) were opened to the public on February 10, 1988. The two southern spans (i.e., east bound) were in a final checkout phase.

TASK: Establish the most likely cause of failure and other possible options which impacted the bridge machinery.

The scope of the field investigation was limited to the site and all the records available from the General Contractor. All plant and shop reviews were handled by others.

General Approach:

The field investigation involved three stages:

(1) collect, review and analyze all available data;

(2) develop and establish the most likely mode(s) of failure; and,

(3) conduct tests which may validate modes of failure.

The third stage utilized the Department's Materials Testing Laboratory Bridge Balancing crew from Gainesville, Florida. under the technical direction of the Tallahassee Structures Design Office, Mechanical/ Electrical Section.

Background and Data Reviews:

The Department of Transportation owns approximately 140 movable bridges. This pair of multi-lane double leaf bascule bridges route both east and west bound traffic accessing the north and south beach areas. Construction commenced on July 9, 1986 replacing the existing two lane double leaf bascule built in 1927.

This was the first time the Department experienced this type of failure in any of its movable bridges. Speed reducers are utilized in all movable bridges except for hydraulic systems employing cylinders. Present population (approx.350) of speed reducers vary in size and rating. There have been only a half a dozen reducer failures in the past ten years, but none in this manner. Generally, it has been bearings, not gears.

Design of the Sunny Isles replacement bridges commenced in 1978, shelved due to funding, until they were re-designed in 1984 incorporating newer technologies. One of the improvements was a softer start system for the machinery. This was accomplished utilizing hydraulic versus electric drive motors on the input shaft of the speed reducer.

Various discussions and changes transpired during the shop print submittal stage of construction. These vacillations are reflected in the project correspondence. Final approved shop prints called for a Falk (i.e., Falk Corporation) fluid drive system interfacing with a Brad Foote (i.e., Brad Foote Gear Works, Inc.) speed reducer.

Although the opening/closing operation is controlled by a programmable computer (PC), it did NOT control the acceleration of the hydraulic drive system. The acceleration of the input shaft, from 0 - 870 rpm, was controlled by potentiometer in the motor control center.

SPEED REDUCER DATA REVIEW:

In order to expedite repairs and return traffic flow over the causeway, the Department agreed to a manufacturer's recommendation to change the input set of helical herringbone gears to a set of spur gears.

The matrices in (Appendix C.) Figures #1 and #2 (Helical Herringbone Speed Reducer and Modified Spur Speed Reducer) summarize the basic tooth loads and stress calculations for each type of input gears. The matrices were compiled using the manufacturer's data and the design horsepower rating. The equations employed are listed in the AASHTO 1978 Movable Bridge Specifications.

In general, all tooth loads values were at an acceptable level (row #23). The material stress indicated for the differential stage are confusing and seems some considerations had been left out. All other stages appear to be able to handle the 40 hp design load for opening/closing the bascule spans.

The matrices, Appendices, Figures #1 & #2, Rows #30 through #42, relate to fatigue limits of the input shaft. The contract specifications limited the fatigue stress to 38.5 KSI in accordance with AGMA requirements. The cyclical stress ratios (row #30 divided by the total design load amplitude, row #34) for all pinion gears are below 1.0, where the driven gears are above (row #36). This does not seem to be detrimental.

FACT: Each bridge span is always at the same tooth position at the start of an opening or closing cycle. The same set of teeth on the input pinion/gear set are subject to an initial starting stress. The set on opening and the set on closing may be one in the same or could be different.

The material used in the manufacture of the input pinion is AISI 4340 alloy steel (Appendix D.). Specific characteristics related to this material are indicated in Appendix D, tables #1 & #2. A particular characteristic of this material is its ability to become less ductile through cyclic stressing. A fact acknowledged in this case by the metallurgical analysis on file with the Department.

RATIONALE FOR SEQUENCE OF FAILURE:

The following sequence of failure is based on observations, facts and reasoning utilizing data collected and pictures taken during disassembly of the failed speed reducer.

Operationally, all indications at the bridge control console were normal during the opening/closing cycle that Saturday evening (January 20, 1990). Upon closing the northeast span's speed reducer failed when the span was approximately 3 feet from the fully down position.

From photos, it can be inferred the NE span's input pinion teeth deteriorated in two different time periods. This inference is supported by the fact that only half of the pinion shaft is discolored. The discoloring is due to the heat of shearing the remaining pinion teeth resulting in plastic flow of the driven gear. The discolored side of the helical pinion is on the end of the shaft toward the hydraulic motor and flexible input coupling. This discoloration was the final disintegration of the pinion shaft.

The herringbone side without discoloration disintegrated without generating any heat, but over some time period prior to the discoloration of the opposite end. There was a gradual loss of pinion teeth over some unspecified period. The loss had to have occurred some time between installation and the shaft failure, approximately 24 months.

What caused the domino effect of the tooth loss?

There had to be an uneven loading across the face of the helical herringbone pinion. This inference is substantiated via the deterioration found in progress on the NW span's pinion. Some portions of the input pinion's teeth were missing on the side opposite the motoring coupling.

This gradual disintegration of teeth on one side of the helical input pinion also indicates there was always a shift in the loading due to a twisting action of the pinion shaft prior to failure. Whether it was continuous or only at the start of a cycle does not matter: a herringbone helical gear is designed for only uniform loads, without any angular distortion.

It was concluded that the initial erosive action of the pinion teeth gradually diminished the tooth carrying capacity without discoloration.

What caused this angular twisting action?

The end of the shaft opposite the hydraulic motor coupling contained a large auxiliary spur gear to gain mechanical advantage during emergency operations (loss of electrical power) to the hydraulic power supply. The auxiliary gear adds an inertia load to the pinion shaft during start transients.

The hydraulic system start transients developed sufficient torsional loading to cause repeated cyclic stress on the input pinion, if the rate of acceleration (ramp) was not set properly. The contract specifications required the ramp (acceleration) time for the input shaft was 15 seconds. The field tests of all spans were measured at 2.0 seconds. This high acceleration rate was NOT without added strain on the input shaft (ref. Appendix B-3 & B-6).

Therefore, since an excessive angular displacement and loading existed within the length of the herringbone helical gear, the impact of the loading had to have been detrimental to the teeth.

HYPOTHESIS

The input pinion's angular (torsion) deflection and high acceleration strain were the prime considerations in a null hypothesis which states: "the diameter to length ratio of the pinion shaft is insufficient to resist the torsion and resulting angular deflection" within the gear face length. Thus, consuming the total allowable backlash, and permitting the gear teeth to develop an impact and odd loading sequence.

Tests measurements indicated the amount of angular deflection of the input pinion shaft under load was sufficient to shift the load from one side of the helical gear to the other.

The repeated torsional loads occurred only during start transients. The start transients dampened out after the input pinion approached full speed, balancing the load across the input gear face.

Eventually, these torsional loads disintegrated the teeth via a domino effect until there was insufficient tooth surface to carry the load. Thus, through repeated starting transients, the teeth failed due to the material's fatigue limits being exceeded.

MODE OF FAILURE

Therefore, it is concluded; the mode of failure of the input pinion/gear set was "fatigue". This conclusion is supported by test results.

DISCUSSION OF TESTS

Procedures were developed to test the speed reducer in the field. The site was instrumented for measuring both static and dynamic conditions.

Static Test Results

Measurement taken on the southeast span's speed reducer helical input pinion ...(i.e., with applied loads 165 to 300 ft-lbs) would twist (Appendix A-1,A-2) sufficiently to shift the gear teeth load from the near-side of the driven gear to the far-side of the driven gear, reducing the face width contact area increasing the stress concentration per tooth.

The total contact area between the gears is reduced to the 2" face width of the far side of the driven gear teeth. This location is approximately where the (NW) pinion's failure gives an "apple bite" appearance. Any deflection or twist across the face of the driven gear produces an unequal loading.

The method employed to obtain the torsional deflection data utilized a torque wrench on the input pinion shaft via the emergency auxiliary input shaft.

Movement of a reference marked on a yard stick, bonded to the head of a bolt attached to the center tap of the input shaft, was recorded for both clockwise and counterclockwise rotation. The measurement arm (mark) was set at 29.56" from the shaft center to amplify the shaft rotation.

Appendix A, Table A-1, & Figure A-2 represents torsional deflection at the pitch circle of the input pinion covering the face width of the driven gear. The upper and lower AGMA limits represent the allowable range of backlash. The solid line represents the calculated torsion (Figures A-1 & 2, columns I & J) of a solid AISI 4340 steel 2.0" dia. shaft 7" long. The asterisk dotted line are the data from the initial rotation (i.e., clockwise). The line with no symbol are data from the counterclockwise rotation. The "step" in data are attributed to either (1) the flexing in the steelflex coupling or (2) the lack of removing the take-up in the backlash before starting the measurement or a combination of both.

The loads were applied to the auxiliary shaft which transferred it to the spur gear (14.5 ratio) keyed to the input pinion. Both the hydraulic brake on the motor side of the steelflex coupling and the driven gear were engaged. The total length of shaft under test was 40.6". It is assumed that all torsional deflection occurred in the smallest diameter nearest the load application (at the 1.9136" pitch dia. along the 7" of teeth engagement).

Five ft-lbs increments were applied for a total of 30 ft-lbs observed on the torque wrench gauge. This resulted in a range of input pinion loads of 0-435 ft-lbs. Design load is 40 hp or 240 ft-lbs at 870 rpm.

After the measurements were taken, the wrench and its attachments were sent for a calibration check in the LECO labs in Jacksonville, Florida. (data in Appendix B).

Dynamic Test Results

All design calculations were adequate for size of the speed reducer loads. Tests revealed; full motor speed was obtained (approx. 900 RPM) in 1 to 2 seconds, whether opening or closing, thus placing higher than normal torque transients cycles on the input pinion. The input acceleration RATE of loading or "acceleration ramp" did NOT meet specifications. This acceleration rate is set by the manufacturer.

Specifications indicates 0 - 870 rpm should take 15 seconds. Measurements reflected it only takes 1 to 2 seconds (Figure B-3 & B-6). The total time of opening or closing is NOT in accordance with specifications. Stress calculations submitted by the manufacturer did NOT reflect full stress reversal capability, nor did the submittal(s) address, adhere, acknowledge or take exception to the contract requirements or limits. The attached calculations, which doubles the stress obtained using AASHTO tooth load equations, reflects a lack of full stress reversal capability; an out-of-spec condition (Appendix C, Figure 1 & 2, rows 38 & 40; Appendix B-2, B-5, Input Strain).

APPENDICES

These appendices contain data and references which assisted in establishing the mode of failure. The following list and limited description identify the information in each.

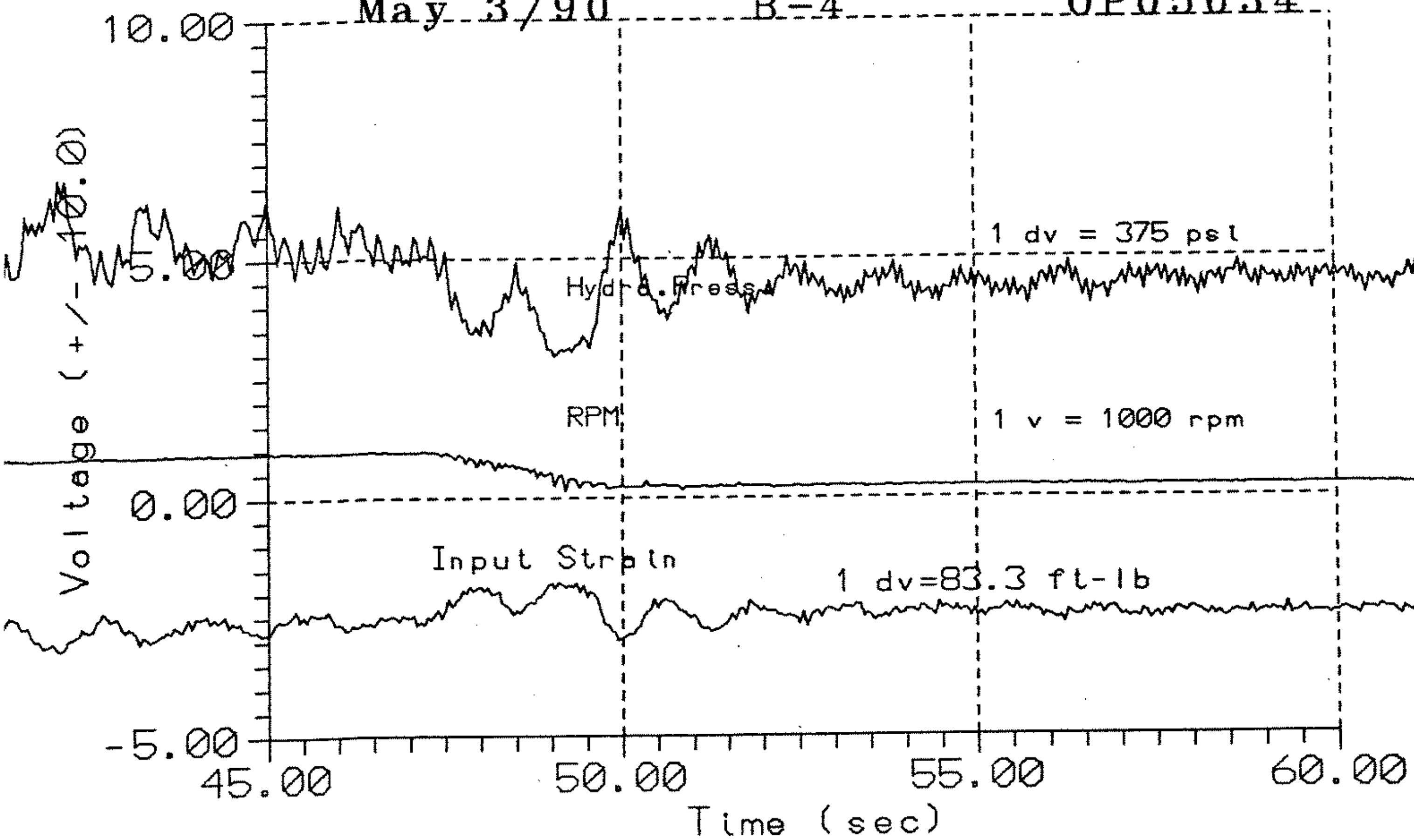
A. 1. Calculations of Axial Torsion on Input Pinion Gear
   2. Curves of Axial Twist from Static Torque Test
   3. Sketch of Shaft

B. 1. Calibration Curve Input Strain Gauge for Torque Wrench Values.
   2. Opening Cycle - Related Parameters
   3. Expanded View of Opening Cycle-Beginning
   4. Expanded View of Opening Cycle-End
   5. Closing Cycle - Related Parameters
   6. Expanded View of Closing Cycle-Beginning
   7. Expanded View of Closing Cycle-End

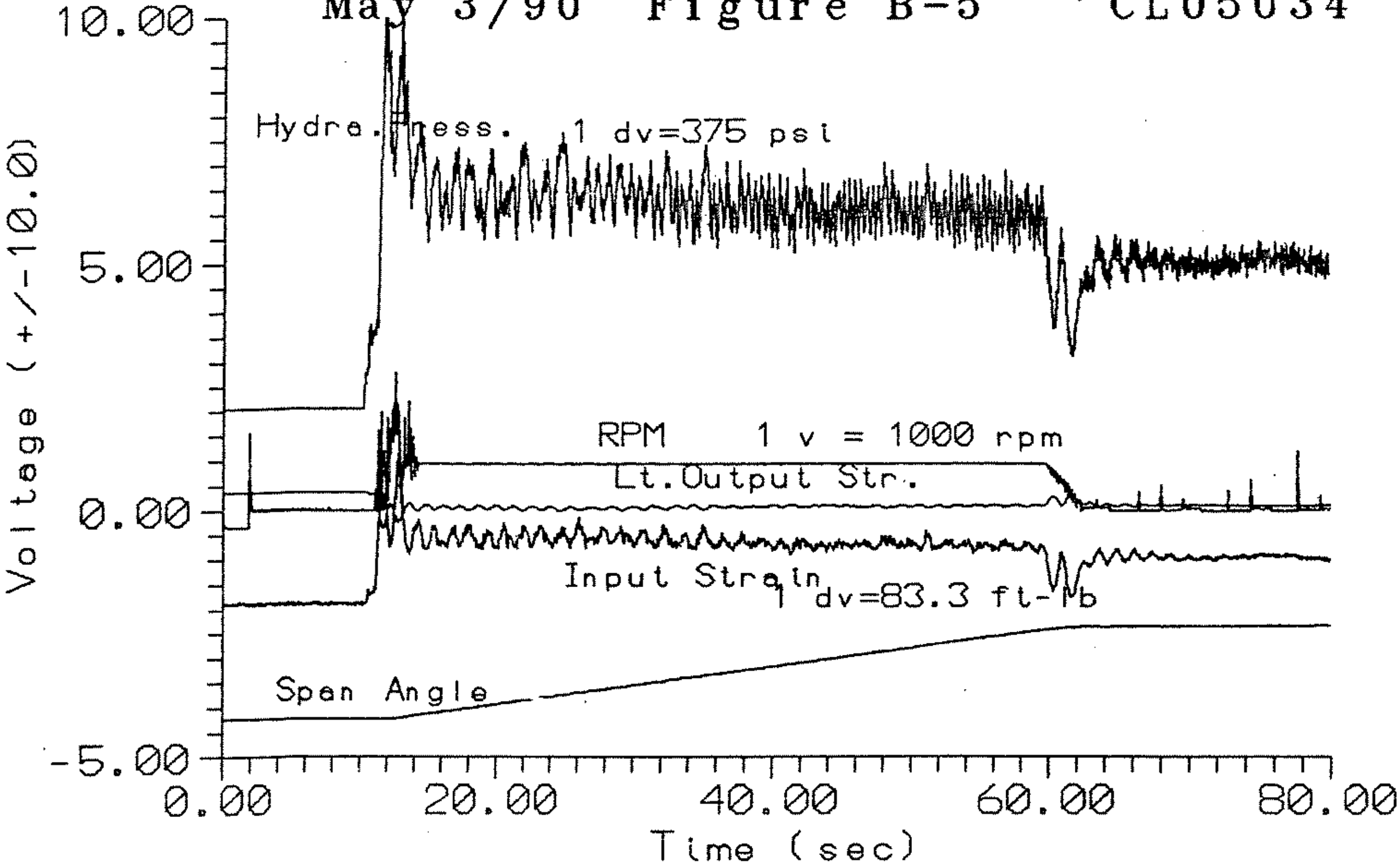
C. Bridge Machinery & Performance Evaluation Statement
   Figure 1. Helical Herringbone Speed Reducer Calculations per AASHTO
   Figure 2. Modified Spur Speed Reducer Calculations per AASHTO

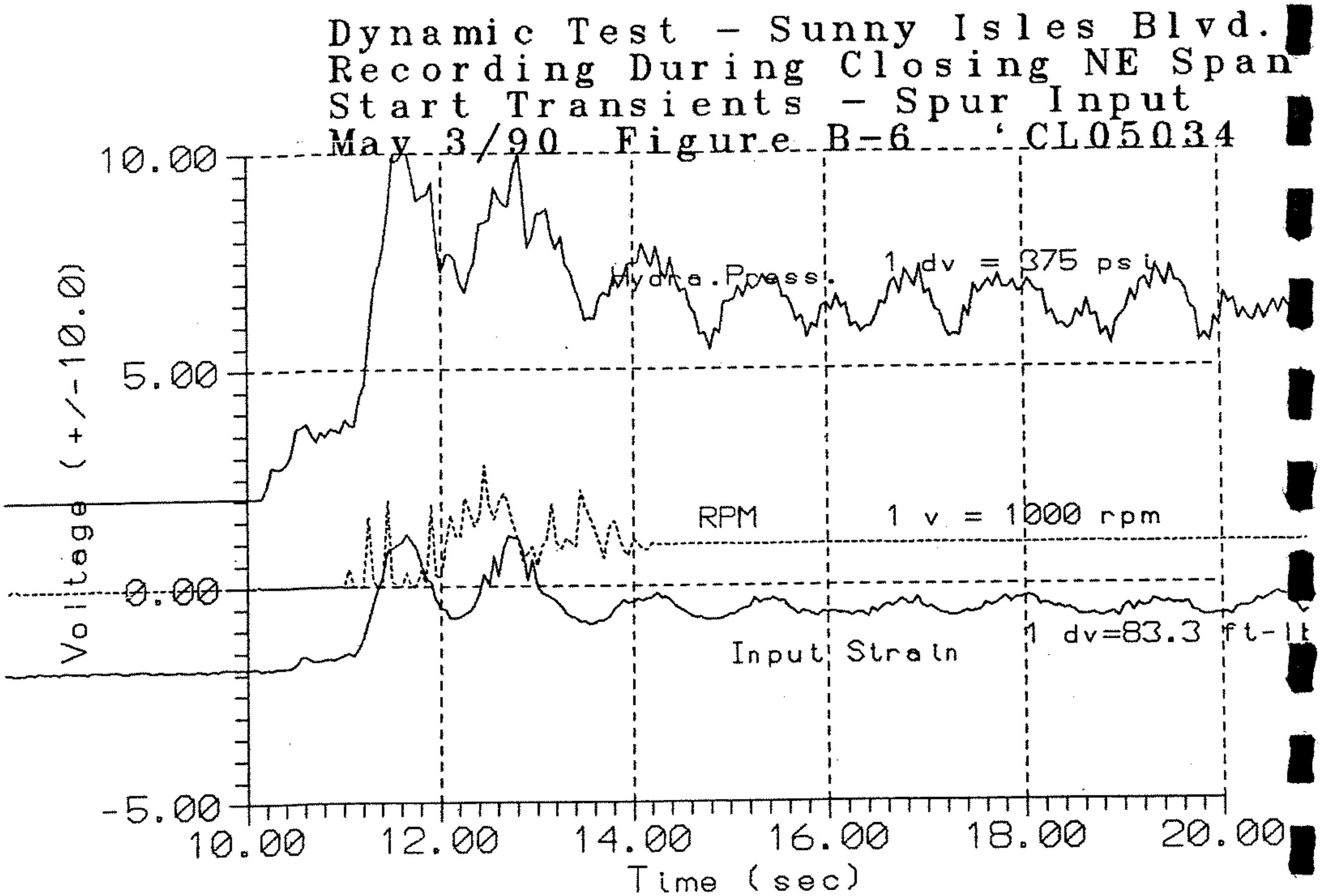
D. Reference (not included in this paper) ASM Handbook, Tenth Ed. covering Fatigue Resistance of Steels, as related to AISI 4340 Steel, Figures 3 & 4., Page 675. and Tables 1 & 2, Monotonic Stress-Strain Properties of Selected Materials.

Dynamic Test - Sunny Isles Blvd.
Profile - Opening NE Span (20/s)
Start Transients - Spur Input
May 3/90 B-4 OP05034

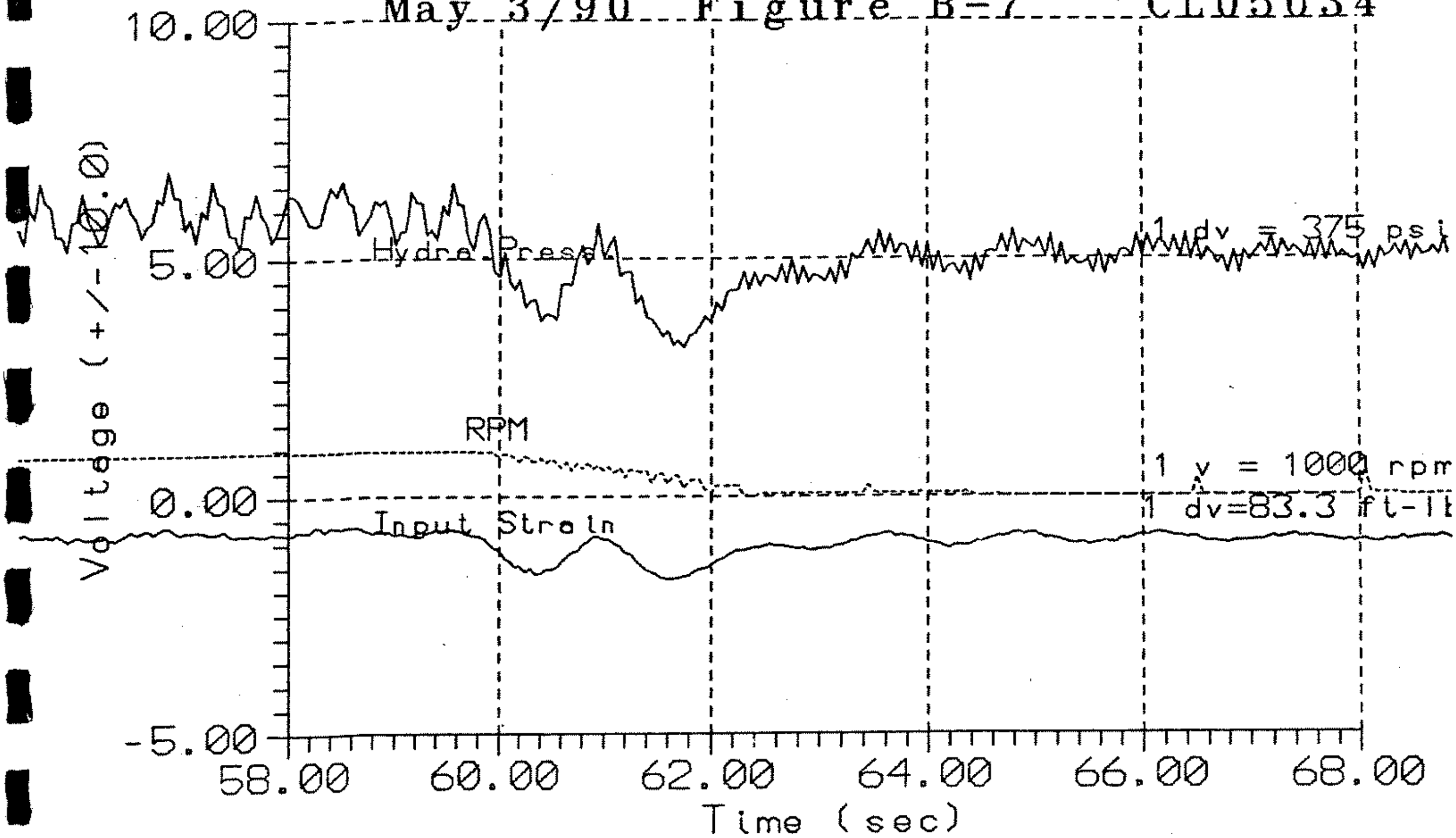


Dynamic Test - Sunny Isles Blvd.
Recording During Closing NE Span
Start Transients - Spur Input
May 3/90 Figure B-5 'CL05034




Dynamic Test - Sunny Isles Blvd.
Recording During Closing NE Span
Start Transients - Spur Input
May 3/90 Figure B-6 'CL05034
10.00
5.00
0.00
-5.00
Voltage (+/-10.0)
Hydra.Press. 1 dv = 375 psi
RPM 1 v = 1000 rpm
1 dv=83.3 ft-lb
Input Strain
10.00
12.00
14.00
16.00
18.00
20.00
Time (sec)

Dynamic Test - Sunny Isles Blvd.
Recording During Closing NE Span
Start Transients - Spur Input
May 3/90 Figure B-7 'CL05034



A	B	C	D	E	F	G	H	I
1								
2						Bill Doherty, P.E.		
3	April 9,1990		FIGURE 1.			Mech/Elect. Section		
4	Rev./EOR Telecon 4/20/90					Florida Dept. of Transp.		
5	Gear Box Analysis - Initial Helical Gear @ 870 rpm							
6	Started Oper. to Failure-Dates		Jan.20,88	Jan,20,90		Laboratory Results:		
7	Sunny Isles Blvd. Gear Box Analysis					Walsh Construction Co.		
8	due to Northeast Span's Gear Failure					Pinion Shaft Analysis		
9						Report=Ult.Str.=168,000 psi		
10	Ltr. from Brad Foote Gear Works, Inc. - Data rec'vd 2/12/90 A-W Ltd.					Yield Str. = 154,000 psi		
11	Started Operations	Jan.20,88						
12	Failure on	Jan.20,90				Oper.Time of 1 Open'g/Closing Cycle		
13	Estimated Bridge Open'gs/Day =		30	Accum.Total=	21,900	Minutes =	5.00	
14	=============	========	========	========	========	========	========	========
15	Description / Stage & Totals		1	diff	2	3	4	Output
16	Input Torque(In-lbs)	2,892.00	1.00					
17	@ tooth	(ft-lbs)	241.00	760.96	760.96	3,424.31	14,440.31	47,205.37
18	Act.Full Load (lbs @ P.Cir.)		3,023	1,522	5,287	13,832	32,165	
19	Tooth Load							
20	@ 300% of Output Torque		9,068	4,566	15,860	41,496	96,495	
21	=============	========	========	========	========	========	========	========
22	Allowable-Pinion Tooth(AASHTO)		3,617	1,024	6,854	21,322	48,485	
23	Ratio-Allowable/Actual Pinion		1.20	0.67	1.30	1.54	1.51	
24	Ratio-Allowable/300% Pinion		0.40	0.22	0.43	0.51	0.50	
25	Allowable-Gear Tooth(AASHTO)		4,995	1,024	9,097	26,962	58,412	
26	Ratio-Allowable/Actual Gear		1.65	0.67	1.72	1.95	1.82	
27	Ratio-Allowable/300% Gear		1.65	0.67	1.72	1.95	1.82	
28								
29	=============	========	========	========	========	========	========	========
30	Stress, KSI							
31	B.Foote-2/9/90 Pinion		52,500	18,000	52,500	65,000	65,000	
32	B.Foote-2/9/90 Gear		49,440	18,000	49,440	65,000	65,000	
33	FDOT Fatigue Design Stress Limit							
34	SP.Para.5.4,Pg.13,d & f) ->		38,500	38,500	38,500	38,500	38,500	
45								
36	Tooth Stresses & Life Cycles							
37	Full Load Stress Cycles							
38	Pinion, T.Amplitude, KSI ->		87,752	53,500	80,987	84,334	86,242	
39	Stress Ratio (design/ampl.)		0.44	0.72	0.48	0.46	0.45	
40	Gear, T.Amplitude, KSI ->		63,537	53,500	61,022	66,691	71,586	
41	Stress Ratio (design/ampl.)		0.61	0.72	0.63	0.58	0.54	
42	Design Service Life (yrs)		30					
43	Total No of Open'g/Clsg		328,500					
44	Design Cycle Life,millions		714.49	113.14	113.14	25.14	5.96	
45	Todate							
46	Pinions Cycles-millions		47.63	7.54	7.54	1.68	0.40	
47	Gears Cycles-millions		7.54	7.54	1.68	0.40	0.12	
48	=============	========	========	========	========	========	========	========
49	Input rpm		870.00	137.77	137.77	30.61	7.26	
50	Ratio		6.32	1.00	4.50	4.22	3.27	391.09
51	Output rpm		137.77	137.77	30.61	7.26	2.22	
52	Pitch dia.(pinion)"		1.91	6.00	3.45	5.94	10.77	
53	Cir.P dia." Pinion		0.32	0.52	0.54	0.81	1.30	
54	Pitch dia.(gear)"		12.00	6.00	15.55	25.06	35.23	
55	Cir. Pitch dia."gear		0.31	0.52	0.54	0.81	1.30	
56	# of teeth (p)		19.00	36.00	20.00	23.00	26.00	
57	# of teeth (g)		120.00	36.00	90.00	97.00	85.00	
58	Hel./Spiral Angle		34.00	30.00	15.22	14.59	15.16	
59	PA angle		20.00	20.00	25.00	20.00	20.00	
60	Axial Thrust, lbs		2,038.75	878.68	1,436.62	3,601.00	8,712.50	
61	fpm		435.85	216.40	124.59	47.62	20.48	
62	face width		4.00	1.25	3.50	5.25	7.00	
63	=============	========	========	========	========	========	========	========
64	Estimated Composite Windup - Holding Output Shaft							
65	Allow.Backlash	clearance	0.020	0.010	0.025	0.030	0.035	
66	Pitch dia.(pinion)	dia-p	1.91	6.00	3.45	5.94	10.77	
67	(gear)	dia-g	12.00	6.00	15.55	25.06	35.23	
68	Ratio "		7.4223	1.1603	0.1832	0.0375	0.0065	
69	Accum (degrees)		49.7268	10.3623	2.1475	0.3722	0.0000	
70								

FIGURE C - 1

A	B	C	D	E	F	G	H	I
1								
2						Bill Doherty, P.E.		
3	April 9,1990		FIGURE 2.			Mech/Elect. Section		
4	Rev./EOR Telecon 4/20/90					Florida Dept. of Transp.		
5	Gear Box Analysis - Modified Spur Gear @ 870 rpm							
6	Started Oper. to Failure-Dates		Jan.20,88	Jan,20,90		Laboratory Results:		
7	Sunny Isles Blvd. Gear Box Analysis					Walsh Construction Co.		
8	due to Northeast Span's Gear Failure					Pinion Shaft Analysis		
9						Report=Ult.Str.=168,000 psi		
10	Ltr. from Brad Foote Gear Works, Inc. - Data rec'vd 2/12/90 A-W Ltd.					Yield Str. = 154,000 psi		
11	Started Operations	Jan.20,88						
12	Failure on	Jan.20,90				Oper.Time of 1 Open'g/Closing Cycle		
13	Estimated Bridge Open'gs/Day =		30	Accum.Total=	21,900	Minutes =	5.00	
14	=============	========	========	========	========	========	========	========
15	Description / Stage & Totals		1	diff	2	3	4	Output
16	Input Torque(in-lbs)	2,892.00	1.00					
17	@ tooth	(ft-lbs)	241.00	760.96	760.96	3,424.31	14,440.31	47,205.37
18	Act.Full Load (lbs @ P.Cir.)		3,023	1,522	5,287	13,832	32,165	
19	Tooth Load							
20	@ 300% of Output Torque		9,068	4,566	15,860	41,496	96,495	
21	=============	========	========	========	========	========	========	========
22	Allowable-Pinion Tooth(AASHTO)		6,543	1,024	6,854	21,322	48,485	
23	Ratio-Allowable/Actual Pinion		2.16	0.67	1.30	1.54	1.51	
24	Ratio-Allowable/300% Pinion		0.72	0.22	0.43	0.51	0.50	
25	Allowable-Gear Tooth(AASHTO)		8,964	1,024	9,097	26,962	58,412	
26	Ratio-Allowable/Actual Gear		2.97	0.67	1.72	1.95	1.82	
27	Ratio-Allowable/300% Gear		2.97	0.67	1.72	1.95	1.82	
29	=============	========	========	========	========	========	========	========
30	Stress, KSI							
31	B.Foote-2/9/90 Pinion		52,500	18,000	52,500	65,000	65,000	
32	B.Foote-2/9/90 Gear		49,440	18,000	49,440	65,000	65,000	
33	FDOT Fatigue Design Stress Limit							
34	SP.Para.5.4,Pg.13,d & f) ->		36,500	36,500	36,500	36,500	36,500	
36	Tooth Stresses & Life Cycles							
37	Full Load Stress Cycles							
38	Pinion, T.Amplitude, KSI ->		46,508	53,500	80,967	84,334	86,242	
39	Stress Ratio (design/ampl.)		0.79	0.72	0.48	0.46	0.45	
40	Gear, T.Amplitude, KSI ->		35,404	53,500	61,022	66,691	71,586	
41	Stress Ratio (design/ampl.)		1.09	0.72	0.63	0.58	0.54	
42	Design Service Life (yrs)		30					
43	Total No of Open'g/Clsg		328,500					
44	Design Cycle Life,millions		714.49	113.14	113.14	25.14	5.96	
45	Todate							
46	Pinions Cycles-millions		47.63	7.54	7.54	1.68	0.40	
47	Gears Cycles-millions		7.54	7.54	1.68	0.40	0.12	
48	=============	========	========	========	========	========	========	========
49	Input rpm		870.00	137.77	137.77	30.61	7.26	
50	Ratio		6.32	1.00	4.50	4.22	3.27	391.09
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52	Pitch dia.(pinion)"		1.91	6.00	3.45	5.94	10.77	
53	Cir.P dia." Pinion		0.32	0.52	0.54	0.81	1.30	
54	Pitch dia.(gear)"		12.00	6.00	15.55	25.06	35.23	
55	Cir. Pitch dia."gear		0.31	0.52	0.54	0.81	1.30	
56	# of teeth (p)		19.00	36.00	20.00	23.00	26.00	
57	# of teeth (g)		120.00	36.00	90.00	97.00	85.00	
58	Hel./Spiral Angle		0.00	30.00	15.22	14.59	15.16	
59	PA angle		20.00	20.00	25.00	20.00	20.00	
60	Axial Thrust, lbs		0.00	878.68	1,438.62	3,601.00	8,712.50	
61	fpm		435.85	216.40	124.59	47.62	20.48	0.00
62	face width		5.50	1.25	3.50	5.25	7.00	
63	=============	========	========	========	========	========	========	========
64	Estimated Composite Windup - Holding Output Shaft							
65	Allow.Backlash	clearance	0.020	0.010	0.025	0.030	0.035	
66	Pitch dia.(pinion)	dia-p	1.91	6.00	3.45	5.94	10.77	
67	(gear)	dia-g	12.00	6.00	15.66	25.06	36.23	
68	Ratio "		7.4223	1.1803	0.1832	0.0375	0.0065	
69	Accum (degrees)		49.7268	10.3823	2.1475	0.3722	0.0000	
70								

FIGURE C - 2