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PART

Report on the

Structural Response of the BART Concrete Ties

for

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by

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September, 1990

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STRUCTURAL RESPONSE OF THE BART CONCRETE TIES

Scope of Project

The primary objective of this project is to obtain an indication of the structural response of five concrete ties instrumented with electrical resistance strain gages, when subjected to moving loads from BART trains.

In preparation for the collection of field data from strain gage readings of the ties in track, five concrete ties were removed from track in the Oakland area and delivered to the Structures Laboratory at San Jose State University. Twelve strain gages were attached to each of the five ties. The ties were then subjected to static loadings to produce positive and negative bending moments at both the rail seat and the centerline. Calibration curves relating strain to bending moment were produced. These calibration curves served as the basis for determining bending moments in the ties when placed in track and subjected to the structural effects of moving trains.

The five ties were installed in a section of outbound track west of the Lafayette Station. The exact location of the ties is at Milepost 10.8 on the C-1 track. The track at this location is on a horizontal curve with a radius of 3,115 feet. Also at this point, the track has a vertical curve with the ties being located on the uphill side with a slope of approximately 2%. The track has a superelevation of 7 inches. Figure 1 shows the test site, looking west. Figure 2 shows the five instrumented concrete ties in the foreground with the track leading toward the Lafayette Station.

Figure 1 Test Site - Looking West

Figure 2 Test Site - Looking East

Details of the laboratory testing program of the five concrete ties are described in the report, "Strain Gage Instrumentation and Calibration of BART Concrete Ties." (1)

Installation of Ties in Track

The five concrete ties and strain gaged rail clips were installed during the week of March 16, 1987. In addition, strain gages were attached to the running rails at the site. Each of the 72 strain gage lead wires were identified with weather resistant plastic tags. The lead wires were water resistant and had a banana plug connector attached to each end. Plastic bags were used to waterproof the wire ends and connectors.

The five ties were installed adjacent to each other at a center to center spacing of 30 inches, as shown in Figure 3. The "A" end of each tie is on the outside of the horizontal curve.

In order for the concrete ties to respond in a structural manner similarly to ties which have not been removed from track, adequate track tamping is essential. This is necessary to obtain ballast pressure reactions, rail seat loadings, and tie bending moments which are comparable to an undisturbed track. It was agreed that manual tamping would be adequate. Subsequent to the initial tamping, the track was allowed to settle, after which strain gage readings were taken on July 15, 1987. It was obvious from the visual observation of the tie loading and the inconsistent gage readings that the ballast beneath the ties was not adequately tamped. Strain gage readings were also taken on April 4, 1989 and September 19, 1989, but these readings were also inconsistent owing to inadequate tamping. However, after adequate tamping and some time afterwards, consistent readings were taken on February 14, 1990. It is the readings of

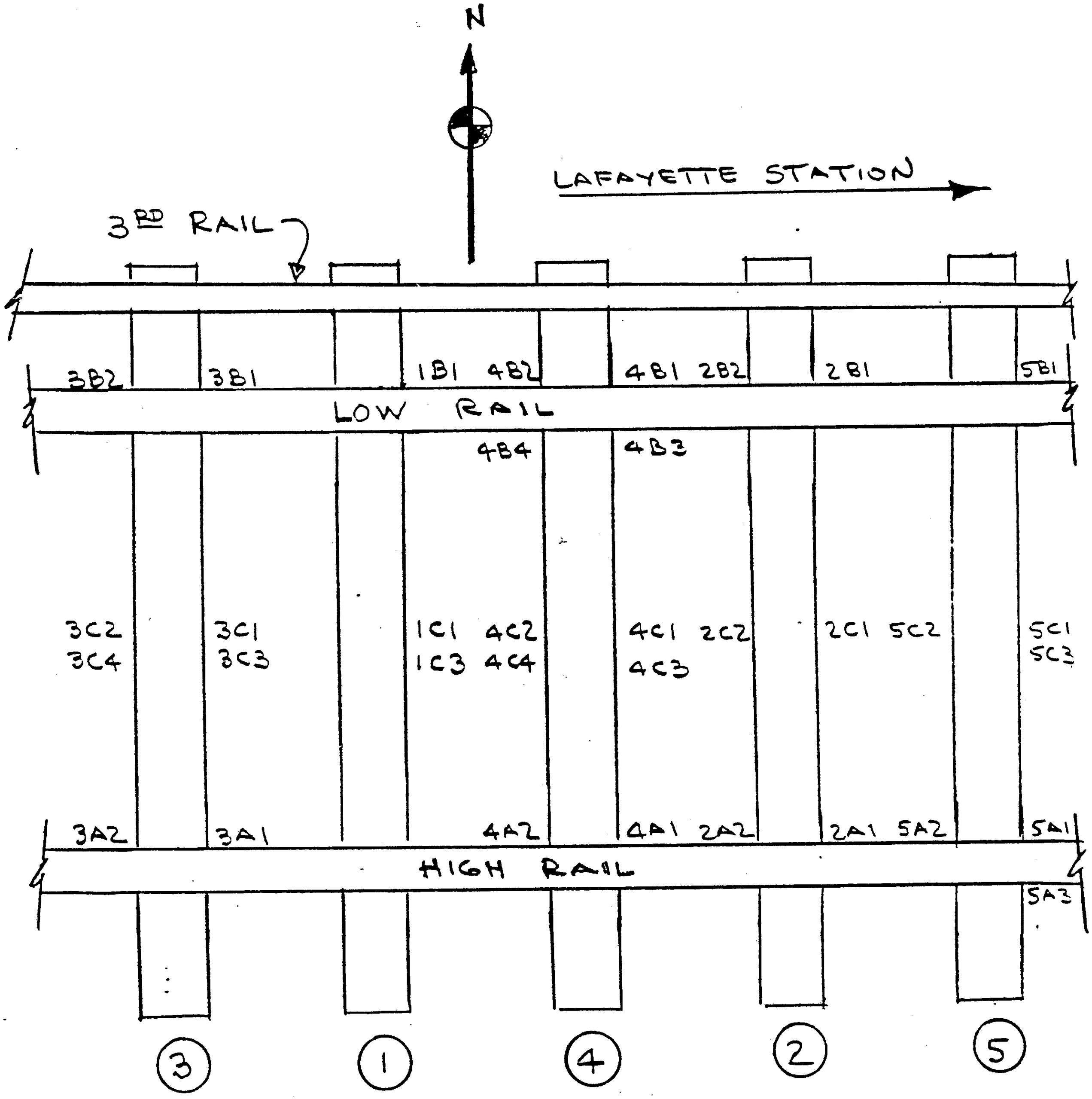


Figure 3 Tie Position in Track

strain gages taken at this time that form the basis for this report. Unfortunately, since a long period of time elapsed from the time of installation to the time of the data collection, some of the gages on the ties, rails, and rail clips were damaged which precluded collecting data from all gages.

Instrumentation and Data Processing

Figures 4 and 5 show the instrumentation set-up at the test site. Figures 6 and 7 are additional photographs showing a BART train during one of the 14 data runs and the lead wires from the instrumented ties, respectively.

Strain Gages. The strain gages attached to the ties were manufactured and purchased from Micro Measurements. The gages used on the concrete ties were catalog number EA-06-20CBW-120 indicating a 2 inch 120 ohm gage. The 2 inch gage length reduces the errors due to the irregularities of the concrete. These gages are temperature compensating, although the compensation is not correct for concrete. Temperature compensation is not important since all gages were zeroed for all test runs. All gages are encapsulated and were protected from the environment by multiple layers of foam, tape and silicone caulking.

Field Tests. Obtaining data from the strain gages in the field required an instrumentation system to be assembled that was portable (the test site was accessed by a stairway). Also, the system should have a large data capacity and dynamic capability.

Signal Conditioning. A sixteen channel rack of DC strain gage conditioners and amplifiers was utilized to provide a signal (+ or - 10 volts) that could be monitored accurately by the data acquisition

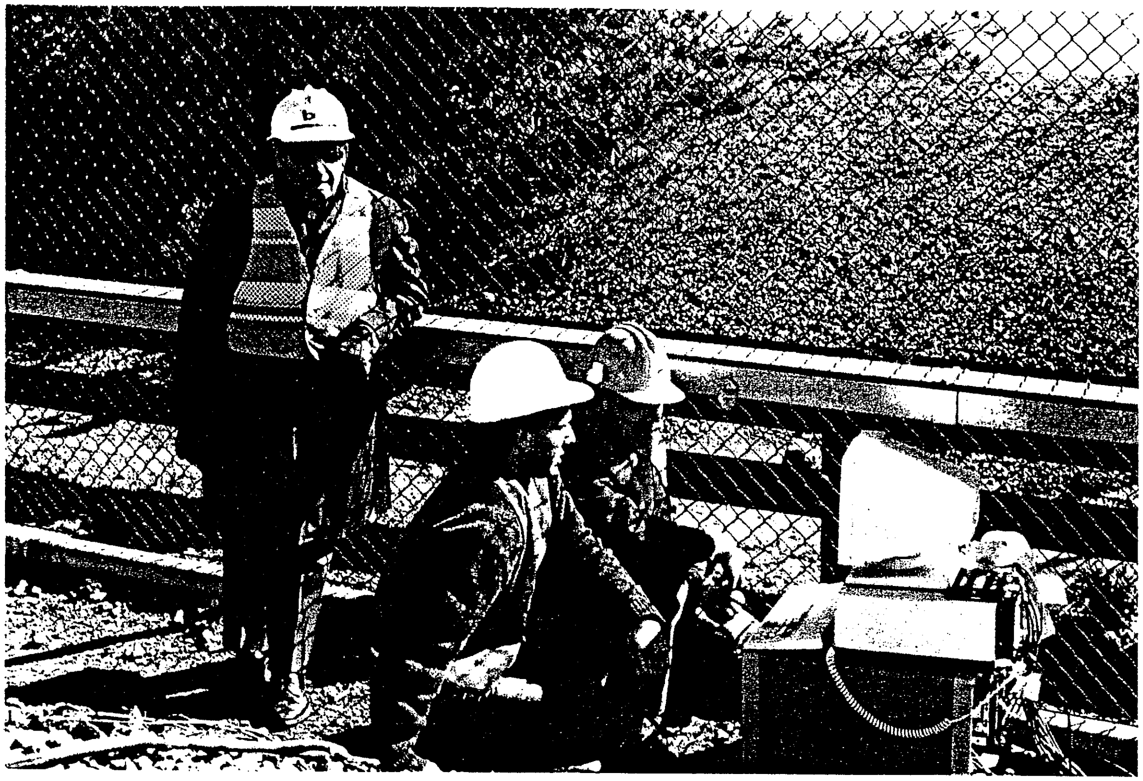


Figure 4 Data Acquisition Instrumentation

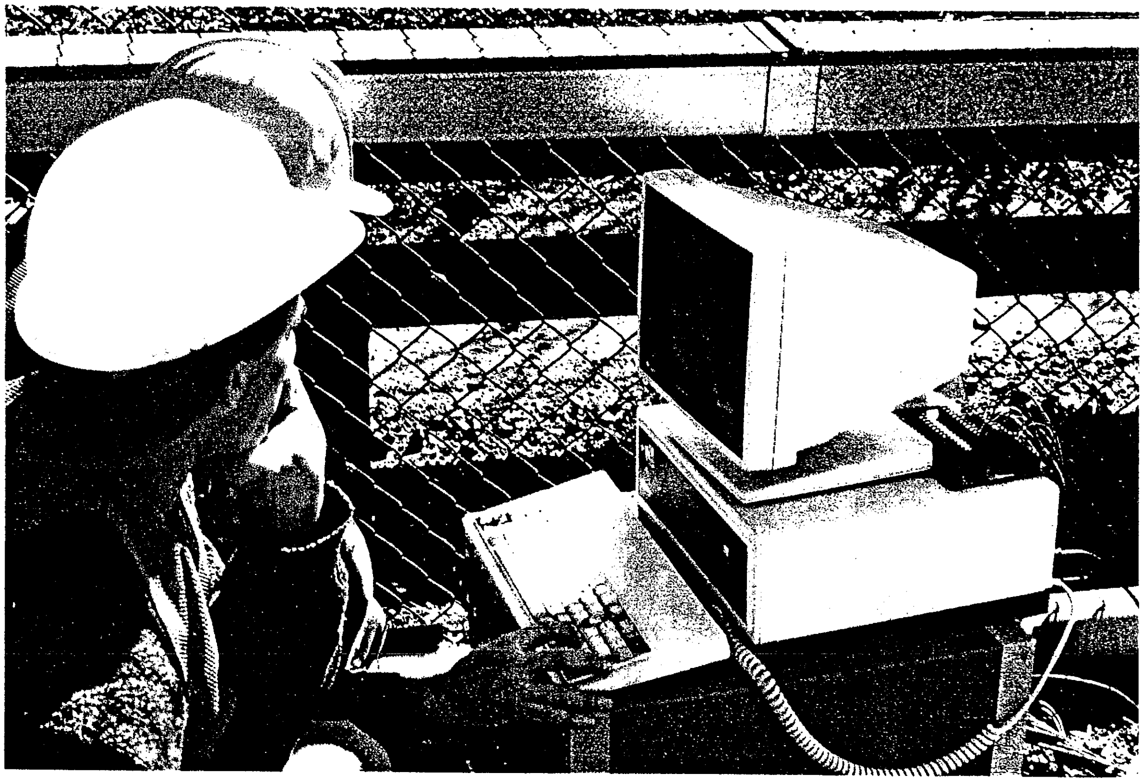


Figure 5 Data Acquisition Instrumentation

Figure 6 Test Ties With BART Train

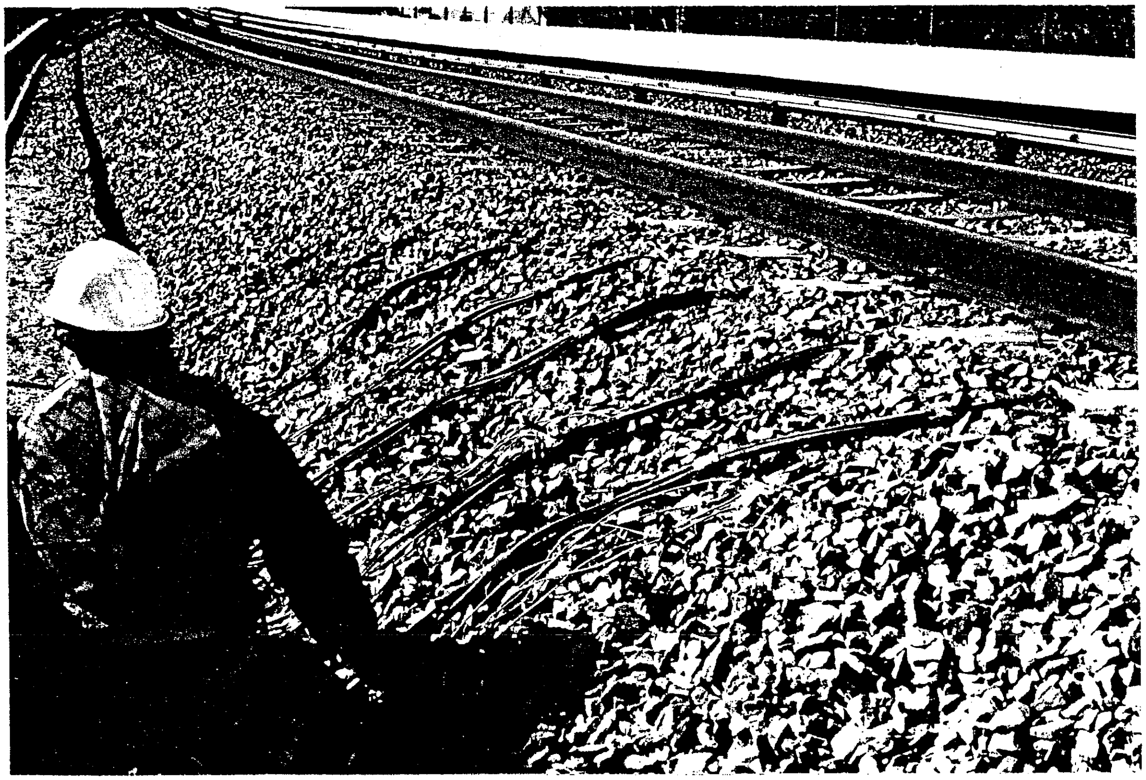


Figure 7 Test Ties and Strain Gage Wires

system. The Vishay model 2100 strain gage conditioners were configured for a 1/4 Wheatstone bridge input with an internal 120 ohm compensation and shunt calibration. The internal shunt utilizes a switch to simulate + or - 1000 micro-inches per inch. Bridge excitation was set at 8 volts and the amplifiers adjusted to provide a 5 volt signal at 1000 micro-inches per inch. No filters were used to modify the signal from the amplifiers which are rated at + or - 0.5 dB from 0 to 5 kHz.

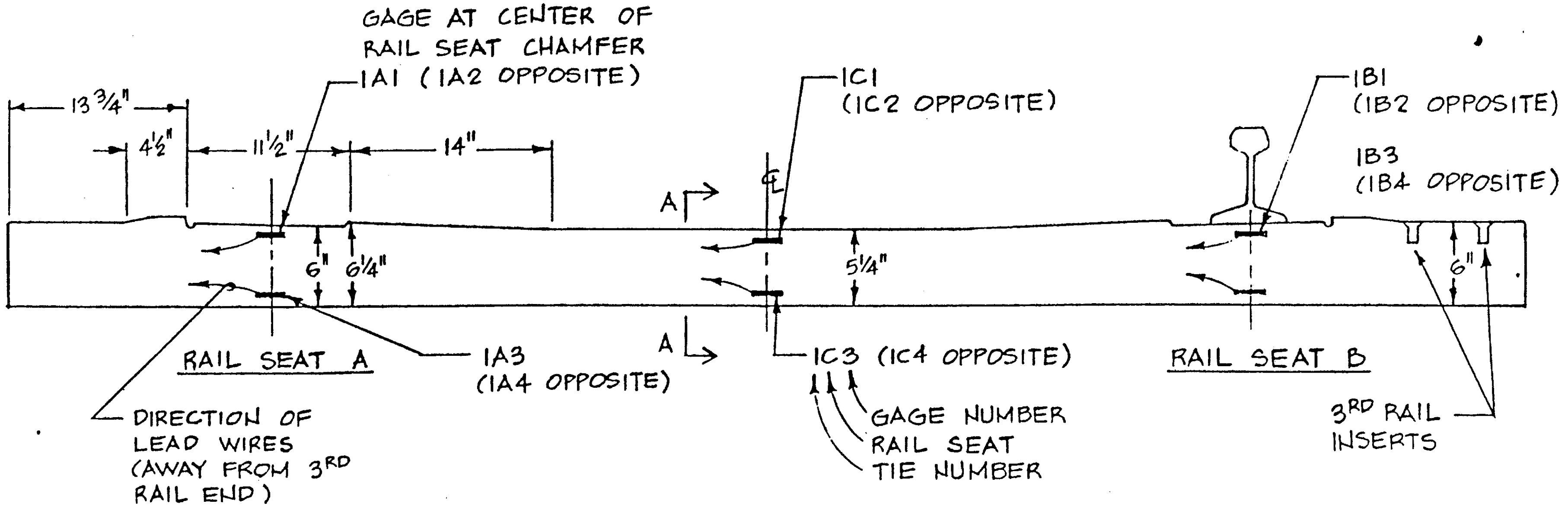
Analog to Digital Conversion. The analog signal from the strain gage conditioners was monitored and converted to digital data by a Data Translation model DT2801 AD/DA system. The DT2801 was configured to monitor 16 channels with a + or - 10 volt range. The 12 bit processor provided 0.00488 volt resolution. Linearity is rated at + or - 0.00244 volts. The board is capable of sampling at 13.7 kHz. An IBM AT compatible computer with a 40 Mb hard disk drive was used to support the DT2801 board. Channels were sampled at the rate of 800 Hz for 1 second for Runs 1 through 12 and at a rate of 2,000 Hz for 6 seconds for Runs 13 and 14. Data from Run No. 13 was lost due to a software memory overload during testing. With this sampling rate, it is believed that frequencies of the fundamental mode of vibration were captured even though the actual value of the fundamental frequency is not known.

Software. Data Translations Labtech Notebook software provided control for real time data acquisition and display. Labtech Notebook controls the sample rate, calibration factors, zero offsets, data file set-up and displays data graphically during acquisition. All data for this test was stored as volts and converted to strain at a later time.

Table 1 - Gage Readings for Data Acquisiton Runs

Channel	Run													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Gage No. *													
0	4B2		4B2		2B1		4B1		4B1		4C1		--	4B1
1	4B4		4B3		2B2		4B2		4B2		4C2		--	--
2	4C2		4C1		--		3B1		4B3		4C3		--	--
3	4C4		4B1		--		3B2		4B4		4C4		--	--
4	4A2		4B4		2C1		1B1		3B1		3C1		--	--
5	1B1		4C2		2C2		2B1		3B2		3C2		--	--
6	1C1		4C3		2A1		2B2		1B1		3C3		--	--
7	1C3		4C4		2A2		5B1		2B1		3C4		--	--
8	3B1		4A1		5B1		3A1		2B2		1C1		--	--
9	3B2		4A2		5C1		3A2		5C1		1C3		--	--
10	3C1		2B1		5C2		4A1		5C2		2C1		--	--
11	3C2		2B2		5C3		4A2		5B1		2C2		--	--
12	3C3		2C1		5A1		2A1		3C1		5C1		--	--
13	3C4		2C2		5A2		2A2		1C1		5C2		--	--
14	3A1		2A1		5A3		5A1		4C2		5C3		--	--
15	3A2		2A2		--		5A2		2C2		--		--	--
Time of Day (P.M.)	2:08	2:23	2:38	2:53	3:08	3:23	3:38	3:53	4:11	4:24	4:40	4:53	5:06	5:21
Time to Pass (seconds)	8.47	9.29	9.67	4.85	4.59	5.22	6.17	7.09	7.64	9.09	7.31	9.13	9.20	9.15
No. of Cars	9	10	10	5	6	6	7	8	10	9	10	10	10	10
Approx. Speed (mph)	51	51	49	49	62	55	54	54	56	47	65	52	52	52

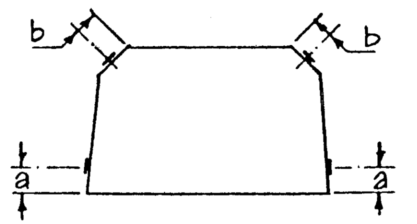
* The first number indicates the tie number. The letter indicates the location along the tie. The second number indicates the position of the strain gage.



ELEVATION
1" = 1'-0"

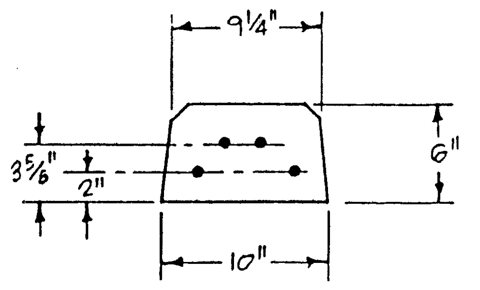
6 GAGES EACH SIDE
12 GAGES PER TIE
4 @ EACH ℄ OF RAIL SEATS
4 @ ℄ OF TIE

TIE	DISTANCE ABOVE BOTTOM (a)		
	A	C (℄)	B
1	3/4"	3/4"	1/2"
2	1/2"	1/2"	1/2" & 1 1/2" ONE SIDE
3	1/2"	1 1/4"	3/4"
4	1/2"	1/2"	1"
5	1/2"	1/2"	1/2"



a = (SEE TABLE)
b = 1/2" @ RAIL SEATS
b = 3/4" @ CENTER LINE

SECTION A-A
NO SCALE



END VIEW
1" = 1'-0"

FIGURE 8 BART TIE STRAIN GAGE DESIGNATIONS

TABLE 2

Gauge	Moment Coefficient	Gauge	Moment Coefficient
1A1	.275	3C3	.543
1B1	.345	3C4	.480
1B3	.415	4A1	.321
1C1	.250	4A2	.340
1C3	.275	4B1	.304
2A1	.340	4B2	.384
2A2	.365	4B3	.538
2B1	.325	4B4	.545
2B2	.360	4C1	.293
2C1	.255	4C2	.282
2C2	.275	4C3	.309
2C3	.295	4C4	.320
2C4	.235	5A1	.354
3A1	.330	5A2	.300
3A2	.365	5A3	.377
3B1	.325	5B1	.402
3B2	.355	5B3	.400
3B3	.385	5C1	.303
3C1	.300	5C2	.274
3C2	.300	5C3	.330

Super Cal 4, a spreadsheet program by Computer Associates, was used for data reduction and generation of plots.

Data Acquisition. Strain gage data was collected for 14 separate runs. The list of active gages for each run is shown in Table 1. (The output from Run No. 14 is not included in this report since the 6 second run was made primarily to identify the electrical disturbances in the BART system.) Other pertinent data is also included in the table. Figure 8 shows the identification and location of each gage and Figure 3 shows the position of the 34 operable gages.

Data Analysis and Time Histories of Bending Moment

In my previous report (1), the correlation of elastic strain with bending moment for the five ties is described. With the relationship between elastic strain and moment (positive and negative) for each strain gage known, bending moment resulting from track loading was determined with the field instrumentation previously described.

The response plots of moment vs. time for the various runs are shown in the Appendix, A1 to A184. Rather than place them in the sequential orders of the run, they are presented in the numerical order of the tie number, starting with the A gages, followed by the B gages, and then the C gages. For each gage of a particular tie, for which multiple runs were made, the data is presented in the numerical order of the runs. Positive bending moment (compression on the top surface) is plotted above the origin.

For plotting purposes, the field data was converted to moments in inch-kips by multiplying by a factor of ten and a moment coefficient. The moment coefficient was obtained by taking the average slope of the negative and positive moment vs. micro-strain plots for each gage as provided in the report, "Strain Gage Instrumentation and Calibration of BART Concrete Ties," (Ref. 1). The coefficients used are listed in Table 2.

Sample plots as generated using the above method show a high degree of noise. This noise consists of three parts. First strong flux fields generated in the middle of each passing car created large voltage fluctuations in the circuit. Second is a 60 Hz voltage fluctuation created presumably by the portable generator. Third is background noise from various sources. In order to filter these signals for easier plot interpretation the data was further modified using a straight 25 point average, 12 points before and after plus the point of interest divided by 25. This technique yields the plots as generated.

For tests 1-12, the data translation and plot preparation was done using the spreadsheet software "SuperCalc 4." For test 14, "SuperCalc 5" was used in order to handle the large amount of memory required.

Due to the short time span of each test, no reference is provided for the true 0 voltage reading of each channel during testing. Due to drift, the zero voltage or balance point for each channel was occasionally observed to change, however without a reference, no constant can be included to establish the true zero moment reading for each plot. Consequently, the moment scale as representated on the plots may deviate from the true moment by some small constant.

With the 25 point averaging method, some plots resulted in smooth curves (A17, as an example), while some plots exhibited the disturbances (A1, as an example). It might be observed that of the plots of moment at the rail seats (Gages A and B), there appears to be more external noise from the B gages, which were closer to the third rail (see Figure 3).

Most of the plots show the peak moments due to the wheel loads of the passing cars quite well. For instance, in A19, the four peak moments due to the four axle loads of a single car are shown. At 0.25 seconds, the loading of the forward truck of a car is shown and at 0.80 seconds, the loading of the rear truck is shown. Referring to A22, at 0.30 seconds, the loading of the rear truck is shown, and at 0.55 seconds, the loading of the forward truck of the following car is shown.

Table 3 gives the maximum bending moments derived from each strain gage reading for each run. In some cases, both positive and negative moments were recorded. For these cases, only the maximum value (positive or negative) moment is given. The actual variation of moment over the time period of data acquisition of one second can be observed from the individual plots which are presented in the Appendix.

Evaluation of Experimental Data

With reference to Table 3, it is observed that for different ties and runs there is a range of recorded maximum moments. The difference in moment values is due to variations in car loading, ballast reaction pressures, and the normal variations experienced in the collection of field data. This variation is shown in Table 4 which lists the maximum positive and negative moment for each tie.

Table 3 - Maximum Bending Moments (inch-kips)

Tie	Gage	Run											
		1	2	3	4	5	6	7	8	9	10	11	12
1	B1	12	12	12	--	--	--	15	15	14	15	--	--
	C1	6	7	--	--	--	--	--	--	-6	-4	-5	-8
	C3	8	8	--	--	--	--	--	--	--	--	-6	-6
2	A1	--	--	13	14	14	13	14	13	--	--	--	--
	A2	--	--	8	13	12	12	11	11	--	--	--	--
	B1	--	--	10	11	9	9	9	11	9	10	--	--
	B2	--	--	10	12	12	10	10	11	10	13	--	--
	C1	--	--	4	5	5	3	--	--	--	--	-2	-4
	C2	--	--	4	4	5	-2	--	--	-3	-1	-4	-6
3	A1	15	14	--	--	--	--	15	14	--	--	--	--
	A2	14	13	--	--	--	--	15	15	--	--	--	--
	B1	19	17	--	--	--	--	17	21	17	22	--	--
	B2	24	20	--	--	--	--	20	21	20	24	--	--
	C1	10	8	--	--	--	--	--	--	6	7	5	4
	C2	10	8	--	--	--	--	--	--	--	--	6	5
	C3	16	16	--	--	--	--	--	--	--	--	10	-7
	C4	14	14	--	--	--	--	--	--	--	--	5	-6
4	A1	--	--	21	21	--	--	21	19	--	--	--	--
	A2	14	15	13	16	--	--	16	15	--	--	--	--
	B1	--	--	4	5	--	--	5	6	4	6	--	--
	B2	16	11	7	8	--	--	8	-11	7	8	--	--
	B3	--	--	8	-8	--	--	--	--	-6	-10	--	--
	B4	16	17	6	-11	--	--	--	--	-7	-10	--	--
	C1	--	--	4	5	--	--	--	--	--	--	-1	-6
	C2	8	8	-3	3	--	--	--	--	-4	4	-4	-8
	C3	--	--	3	2	--	--	--	--	--	--	-4	-5
	C4	9	9	4	3	--	--	--	--	--	--	4	-3
5	A1	--	--	--	--	17	16	15	15	--	--	--	--
	A2	--	--	--	--	12	12	12	12	--	--	--	--
	A3	--	--	--	--	10	11	--	--	--	--	--	--
	B1	--	--	--	--	16	11	12	14	11	14	--	--
	C1	--	--	--	--	6	4	--	--	2	2	2	7
	C2	--	--	--	--	5	4	--	--	3	2	-3	4
	C3	--	--	--	--	-4	4	--	--	--	--	-4	-5

Table 4 - Maximum and Minimum Moments (in-k)

Tie	Maximum Positive Moment at the Rail Seat	Maximum Negative Moment at the Tie Center
1	15	-8
2	14	-6
3	24	-7
4	21	-8
5	17	-5

It is commonly accepted that under normal loading conditions, a concrete tie will experience positive moment at the rail seat and negative moment at the center. However, due to particular ballast pressure distributions, dynamic excitation of the tie, or unbalanced rail seat reactions, negative moment could occur at the rail seat and positive moment at the tie center. Therefore, only the maximum positive moment at the rail seat and maximum negative moment at the tie center are shown in Table 4.

Although shearing forces in a prestressed concrete member could be critical, they are not considered to be of importance for the loading conditions imposed on the BART tie and are, therefore, not considered in this analysis.

The original BART specifications for concrete ties (2) specifies a required positive bending moment at the rail seat of 82 inch-kips, without cracking, and a required negative bending moment at the tie center of 113 inch-kips without cracking. The maximum moments recorded in track were substantially lower than these requirements (Table 4).

In order to evaluate the theoretical moments in the BART tie, a computer analysis was made. The objective was to determine the maximum rail seat reaction under normal loading conditions, considering the rail as a continuous beam or an elastic foundation. The conditions assumed were:

-- 10,000 lb. wheel loads (a fully loaded BART car with a total weight of 80,000 lbs.)

-- A track modulus of 8,000 lb./in/in.

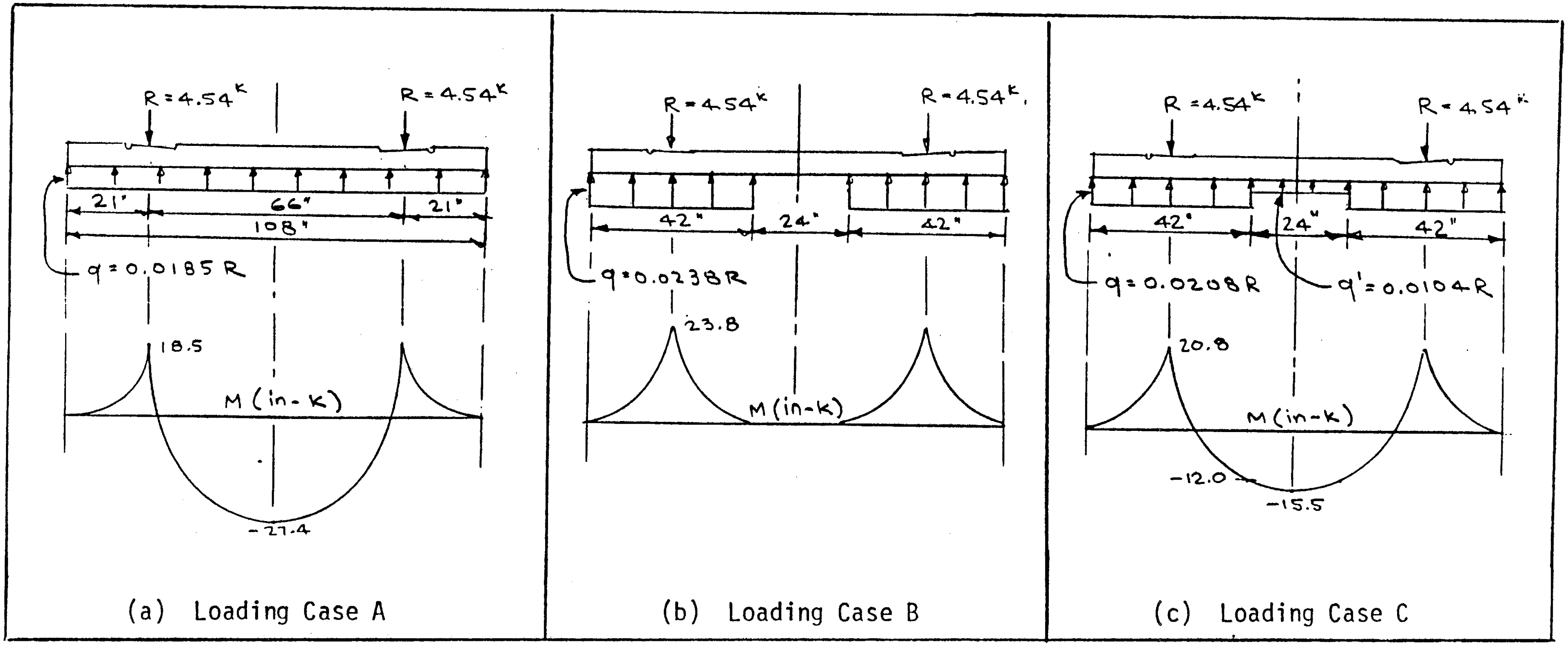
-- 119 lb. rails.

-- 30 inch tie spacing.

In the computer static analysis, loading was considered from the two rear axles of a car and the two forward axles of the following car. Axle loads beyond these points have very little effect on track load and were not considered. A total track length of 60 ft. was used in the analysis. Accounting for all the parameters listed above, the maximum rail seat reaction calculated was 4.54 kips.

With the rail seat reactions known, the moment diagram along the length of the tie can be constructed. However, the bending moments are a function of the assumed ballast pressure distribution. Figure 9 shows three commonly assumed ballast pressure distributions. In Figure 9(a), a uniform pressure is assumed along the entire tie length where R is expressed in kips and q expressed in kips/inch. In Figure 9(b), a uniform pressure is assumed only along the 42 inch length centered at the rail seats. In Figure 9(c), a uniform pressure of q is assumed along the 42 inch length under the rail seats in addition to a reduced pressure distribution of q'=1/2q under the central 24 inch length of the tie.

In the analysis, the effects of the weight of the third rail and track dynamics were not considered.



(a) Loading Case A

(b) Loading Case B

(c) Loading Case C

Figure 9 Assumed Ballast Pressure Distributions

Considering the loading case of Figure 9(a), for a concentrated rail seat load of R = 4.54 kips, the maximum positive moment at the rail seat is 18.5 inch-kips and at the tie center, the maximum negative moment is 27.4 inch-kips. However, if track tamping and subsequent track loading results in no ballast pressure in the central portion of the tie, as assumed in Figure 9(b), no bending moment will be produced at the tie center. A compromise assumed pressure distribution is shown in Figure 9(c) where both positive and negative moments of somewhat equal magnitudes will be produced at the rail seat and tie center, respectively.

It is accepted that the actual ballast pressure distribution in the BART track is none of those assumed, but perhaps some composite with non-linear pressure distributions. In comparing the maximum values of record track moments shown in Table 4 with the theoretical moment values of Figure 9, it seems that they are somewhat similar and of the same order of magnitude. Giving due consideration to both the experimental and theoretical values of bending moment, it seems that the structural loading on the BART concrete ties is far below that for which the ties were designed.

Summary

Five concrete ties were removed from the BART track and instrumented with electrical resistance strain gages. In the laboratory, they were loaded to produce positive and negative bending moments at the rail seat and tie center, to produce a relationship between elastic strain and bending moment.

The five ties were installed in the BART track near the Lafayette Station. After several tampings and consolidation of the ballast, strains were recorded for a number of passing trains during peak traffic hours in the afternoon.

Plots of moment vs. time which were generated for each passing train are shown in the Appendix. Maximum positive bending moments varied between 14 and 24 inch-kips at the rail seat. Maximum negative bending moments varied between 5 and 8 inch-kips at the tie center (Table 4). These experimental values compare favorably with theoretical values of maximum positive moment at the rail seat and maximum negative moment at the tie center for different ballast pressure distributions (Figure 9). BART specifications require a positive bending moment of 82 inch-kips at the rail seat without cracking and a negative bending moment of 113 inch-kips at the tie center without cracking. Based on the results included in this report, the BART specifications are on the conservative side.

REFERENCES

1. Venuti, William J., "Strain Gage Instrumentation and Calibration of BART Concrete Ties," San Jose, California. April, 1986.
2. BART Specifications, "Prestressed Concrete Ties," Contract No. 2Z 4487, Addendum No. 3., 1967.