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COAL HANDLING EQUIPMENT

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16. Abstracts

A detailed dynamic analysis, presented in a series of reports, was conducted on the seismic response and structural safety of key subsystems (steam generator, high pressure steam piping, coal handling equipment, cooling tower, chimney) of Unit #3 of TVA at Paradise, Kentucky in order to: (1) determine for the key components the natural frequencies below 50 Hz and the corresponding normal modes; (2) determine response of plant to seismic disturbances; (3) verify through full scale tests results obtained in (1) and determine estimates of damping needed in (2); (4) determine potential failure modes of major structural components; and (5) determine a spare parts policy for a power system so that outages due to damage from seismic disturbances are minimal. Analytical and experimental methods are used. Two elevated coal conveyors are modeled, using simple beams with appropriate static properties. The dynamic characteristics of the models, their natural frequencies, and mode shapes were found by using the finite element approach, and responses determined by modal analysis. Results are shown in linear and tabular form, based on application of stresses equal to those of the 1940 El Centro earthquake.

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Coal conveyors

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Summary Report

Prior to 1974 there has been no detailed dynamic analysis of the seismic structural response and safety of large fossil-fuel steam generating plants. In March, 1974, under NSF Grant GI41897, a detailed dynamical analysis was begun on the seismic response and structural safety of key subsystems

(steam generator,
high pressure steam piping,
coal handling equipment,
cooling tower,
chimney)

of Unit #3 of TVA at Paradise, Kentucky to accomplish the following objectives:

a) Determine for the key components the natural frequencies below 50 Hz and the corresponding normal modes.

b) Determine response of plant to seismic disturbances.

c) Verify through full scale tests, where possible, results obtained in a), and determine estimates of damping needed in b).

d) Determine potential failure modes of major structural components.

e) Determine a spare parts policy for a power system so that outage due to damage from seismic disturbances are minimal.

Analytical and experimental methods are used.

The attached Reports present what has been accomplished to date.

Before making a few summarizing remarks on the individual Reports, some comments must be made in order to provide perspective on the study.

Paradise, Unit #3 of TVA was selected for study because near-by mine operations provide excitation (due to blasting) for the plant, and TVA was willing to cooperate in the conduct of the study. It should be pointed out that this plant was not designed to resist earthquakes. However, it was felt that this disadvantage was outweighed by the experimental possibilities.

The key components selected for study are critical for operation of the plant and would cause significant outage if damaged. All components can be studied using similar types of analyses. These are the basic reasons for including in this study only the steam generator, high pressure piping, coal handling equipment, cooling tower, and chimney.

Basic data for the analyses were obtained from drawings provided by TVA and Babcock-Wilcox. In addition to these data, a number of assumptions had to be introduced into the analyses. These assumptions refer in the main to the nature of the connections among elements of known properties, the fixity of columns, the properties of hanger elements, etc. Choices were made based on physical as well as computational reasons.

The analyses were confined to the linear range. After such a study, it is possible to assess at what level of excitation parts of the structure become nonlinear.

Structure-foundation interaction was neglected. Unit #3 of Paradise rests on excavations in limestone. It is assumed that there is little interaction. However, experimental studies will be made on this point.

It was decided at the start that all computations would be carried out with an existing computer program. SAP IV was chosen. Some program modifications have proved necessary, but these have been relatively minor. To obtain familiarity with the program it was necessary to study a number of special cases of the actual structure to ensure that it was functioning properly. For example, substructures within the steam generator support were considered seperately; assumed values of viscous damping coefficients were used in generating time histories*; etc. We found the program execution

* It should be noted that the magnitude of the response with zero damping must be interpreted with some caution as systems with slightly different frequencies can exhibit significantly different magnitudes of response.

time slow in some respects which indicates that some of its internal subroutines, such as eigen value solution, could be improved. It is beyond the scope of this project, however, to improve existing programs.

The experimental part of the study has proved much more difficult to conduct than anticipated. TVA has been most cooperative. However, the sheer physical size of the units, the weather, etc. have caused a number of difficulties that were not easy to foresee. Progress is gradually being achieved.

Interest in simple models stems from their possible use in design studies. It was decided to develop a methodology for constructing simple models. At present, our simple models are in the embryonic stage. It is hoped that after the study of two more plants a useful methodology can be obtained. Simple models developed could have been used for one component under study; however, timing made this impossible.

No recommendations will be made or conclusions drawn at this time, except in special situations. The partial examination of one plant does not provide a sufficient basis for such actions. At the completion of the study conclusions and recommendations will be presented.

A number of factors of some importance have not been considered so far. For example, the steam generator's internal elements can move with respect to it, the steam piping exerts dynamic forces on its supports, dynamic stresses in steam piping are just part of its stress system, many different seismic excitations are available, plus many more. Also a spare parts policy was not considered. As additional progress is made, we shall consider some of these problems. However, it must be recognized that it is possible to consider in this study only those factors of major importance. A spare parts policy involves economic considerations; it may not be possible to acquire the information needed to address this point.

Contact with industry in this country and Japan clearly indicates that the current detailed study is of great interest.

An Advisory Committee consisting of

Carl L. Canon	- Babcock & Wilcox Product Design Supervisor for Structural Steel and Design
William A. English	- Tennessee Valley Authority Head Civil Engineer
Clinton H. Gilkey	- Combustion Engineering, Inc. Manager, Engineering Science
Richard F. Hill	- Federal Power Commission Acting Director, Office of Energy Systems

R. Bruce Linderman	- Bechtel Power Corporation Engineering Specialist
D. P. Money	- Foster-Wheeler Corporation Supervisor of Stress Analysis
R. D. Sands	- Burns & McDonnell Chief Mechanical Engineer
Erwin P. Wollak	- Pacific Gas & Electric Company Supervisor, Civil Engineering Division

has been formed to provide a forum for an interchange of practical and conceptual views on various aspects of the study. The aim is to ensure that what is developed (in simple models) will be of practical use to industry. The Advisory Committee has met twice and reviewed plans and the progress of the investigation.

Contact is also maintained with the following firms:

Mitsubishi Heavy Industries
Babcock-Hitachi
Ishikawajima Harima Heavy Industries
Kawasaki Heavy Industries
Taiwan Power Company

The initial visit provided considerable information on the methods they have used in seismic response studies conducted by the research groups in each organization and plant experience under seismic disturbances.

Comments from the Advisory Committee and reviewers have been most helpful and encouraging. Many of the comments have been considered. However, it is not possible to take account in our studies of all points that have been brought to our attention.

Five professors, 8-10 graduate students, 2 technicians, and a secretary devoted part time to the study. A great deal of effort was devoted to acquiring information and equipment. The cooperation of TVA and Babcock-Wilcox was most helpful and deeply appreciated. Progress was excellent when it is remembered that education of students is a major function of a University.

This research project was sponsored by NSF through Grant No. GI41897.

The Reports in this series are as follows:

Dynamic Behavior of the Steam Generator and Support Structures of the 1200 MW Fossil Fuel Plant, Unit #3, Paradise, Kentucky, by T.Y. Yang, M.I. Baig, J.L. Bogdanoff.

The High Pressure Steam Pipe, by C.T. Sun, A.S. Ledger, H. Lo.

Coal Handling Equipment, by K.W. Kayser and J.A. Euler.

Theoretical Study of the Earthquake Response of the Paradise Cooling Tower, by T.Y. Yang, C.S. Gran, J.L. Bogdanoff.

Theoretical Study on Earthquake Response of a Reinforced Concrete Chimney, by T.Y. Yang, L.C. Shiau, H. Lo.

A Simple Continuum Model for Dynamic Analysis of Complex Plane Frame Structures, by C.T. Sun, H. Lo, N.C. Cheng, and J. L. Bogdanoff.

A Timoshenko Beam Model for Vibration of Plane Frames, by C.T. Sun, C.C. Chen, J.L. Bogdanoff, and H. Lo.

COAL HANDLING EQUIPMENT

K. W. Kayser
J. A. Euler

Introduction

The coal handling system of the Paradise Steam Plant consists of underground and elevated conveyors, conditioning equipment building, and live piles. In this study, we are interested primarily in the supporting structures for the elevated conveyors. These conveyors transport coal into the yard, between conditioning buildings, to the live piles, and to the plant.

Two conveyor structures were selected for analysis. Paradise conveyors No. 13 and No. 14, which are supported by one structure, transport coal to the plant. This structure shown in Fig. 1 is also typical of conveyor structures which interconnect the conditioning buildings. The second structure shown in Fig. 2 houses conveyors No. 28 and No. 29 which feed live piles 3 and 4.

The general approach of the analysis was to model the complex structures with a few simple beams which were equivalent to the real structures in the sense of having the same static properties. The dynamic characteristics of the models, natural frequencies and mode shapes were found employing the finite element approach and responses calculated by modal analysis.

Description of the Structures

Coal handling structure No. 1 (CHS 1) which supports conveyors 13 and 14 consists of approximately 700 elements which were designed as and assumed to be truss elements in this analysis. It is 353 feet long

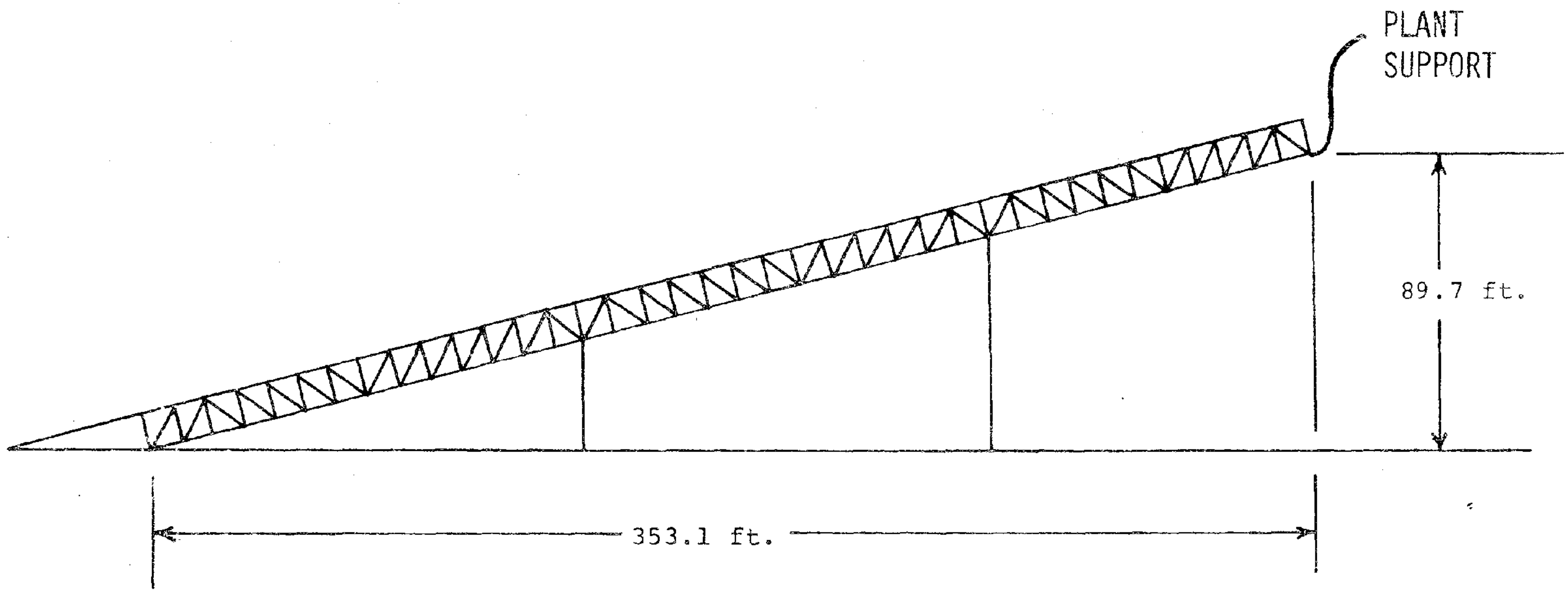


Fig. 1. CHS 1 Yard to Plant Conveyor.

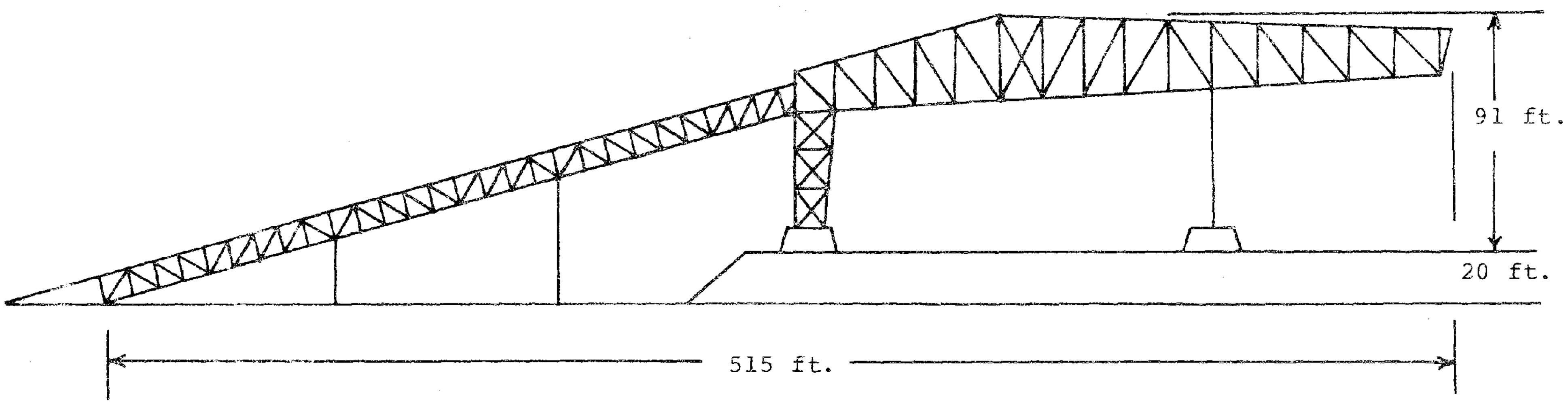


Fig 2. CHS 2 Conveyor for Live Pile 3 and 4.

and 90 feet high. At the lower end it is cantilevered from a concrete foundation and rests on rollers at the upper end which attaches to the plant. Intermediate support is furnished by two bents which are pinned at the top and fixed at the base to a concrete foundation.

Coal handling structure No. 2 (CHS 2), which is 515 feet long and 91 feet high, consists of two sections. The lower section is relatively uniform and has the same support and end conditions as CHS 1. The upper section has a nonuniform cross-section and is supported by a tower at one end and a bent in the center which is pinned at the top and fixed at the bottom. The upper end of CHS 2 is completely free. CHS 2 contains approximately 1000 truss elements.

Modeling of the Structures

Modeling a section of the structure as a simple beam requires the evaluation of three parameters: the bending stiffness about two axes (EI_x, EI_y) and the stiffness in extension (EA). As shown in Figure 3, CHS 1 was modeled by 3 beams (9 parameters) and CHS 2 by 6 beams (18 parameters). Each bent and the tower was modeled by a beam, and the entire conveyor by one beam in CHS 1 and two beams in CHS 2.

To find the stiffnesses for each bent, it was assumed that the base was fixed and the top free. Three sets of forces were applied as shown in Figure 4 for each bent and the corresponding static deflection $\delta_{,}$, δ_y, δ_z computed using the static analysis section of SAP IV. (This portion of SAP IV uses finite element analysis for each member, and all members of the bent were used.)

An simple beam with the same length "ℓ" as the bent would have the deflections for an applied force 2F:

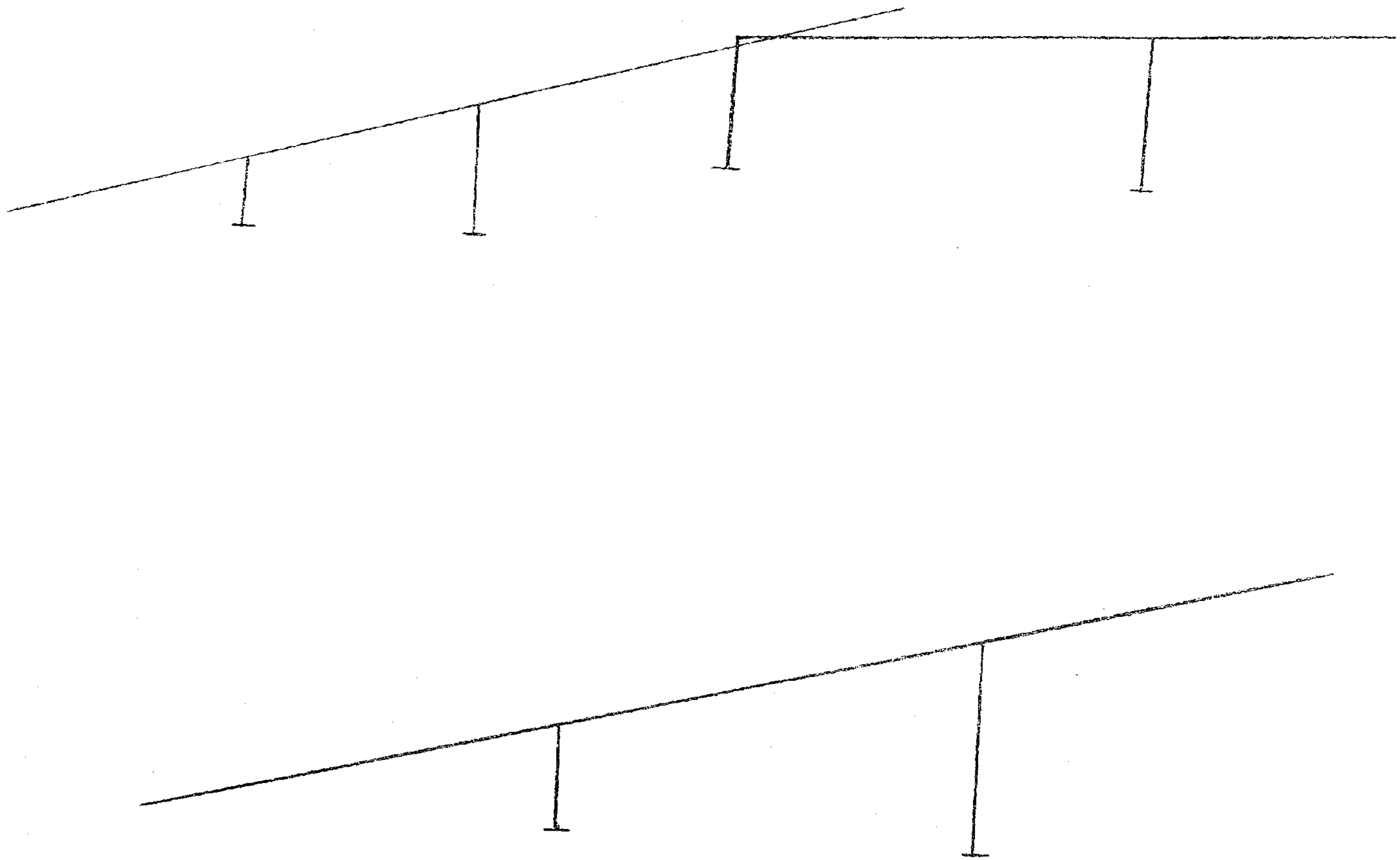


Figure 3. Simple Beam Models for Coal Structures

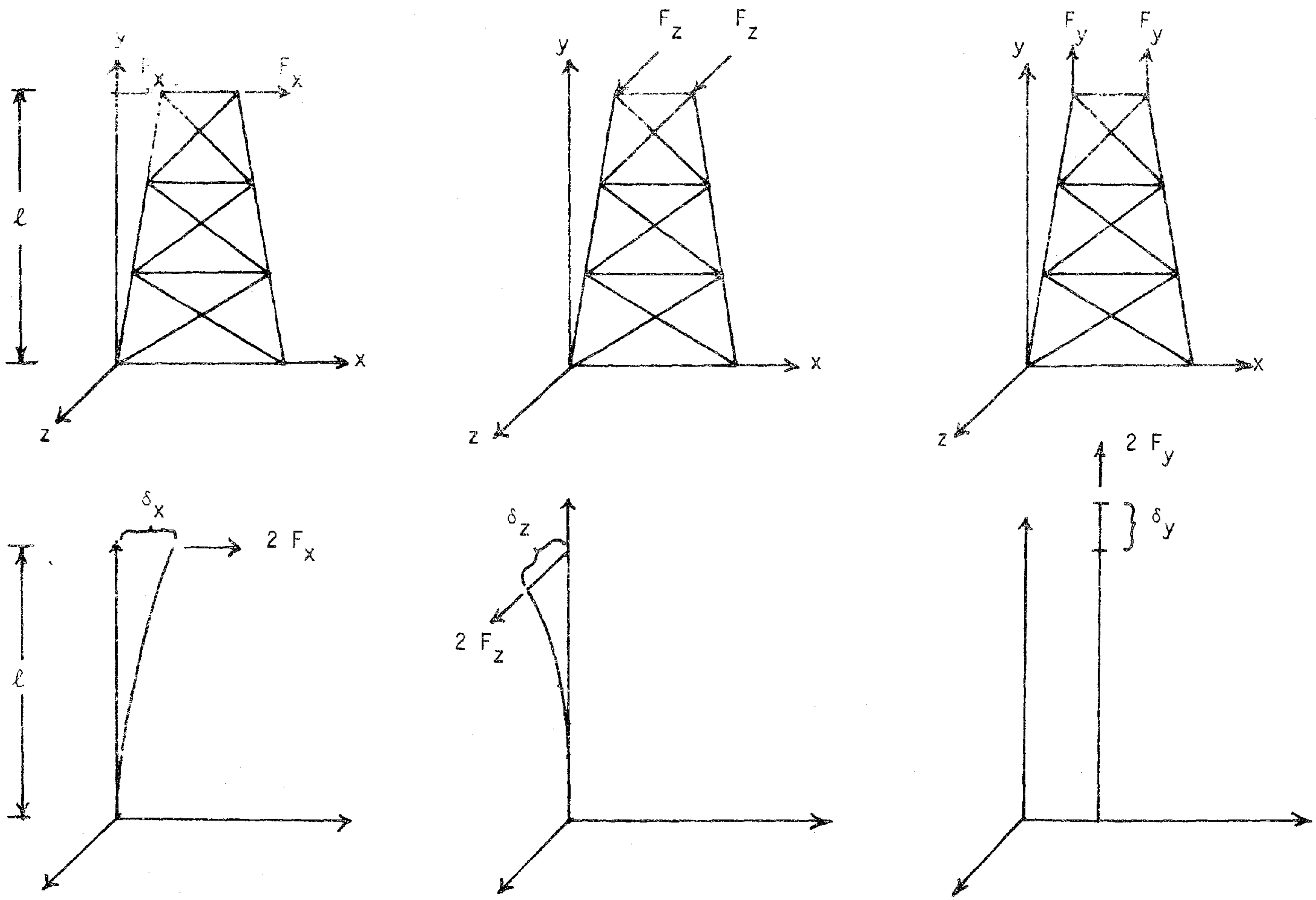


Figure 4. Beam Equivalency for Bents

$$\delta_x = \frac{2F_x\ell^3}{3EI_z} \qquad \delta_y = \frac{2F_y\ell}{EA} \qquad \delta_z = \frac{2F_z\ell^3}{3EI_x}$$

If the beam is to be equivalent in the sense of having the same static deflections, the beam stiffnesses are:

$$EI_z = \frac{2F_x\ell^3}{3\delta_x} \qquad EA = \frac{2F_y\ell}{\delta_y} \qquad EI_x = \frac{2F_z\ell^3}{3\delta_z}\ ,$$

where δ_x, δ_y, δ_z are the deflections from the SAP IV analysis of the bents. Table 1 gives the values of I_x, I_z and A for each bent when $E = 3.0x10^7$.

Table 1

Structure	Bent	I_x (in^4)	I_z (in^4)	A (in^2)
CHS 1	1	43,564	6,740	111.2
CHS 1	2	134,850	8,988	106.9
CHS 2	1	58,500	851	33.8
CHS 2	2	63,000	1,013	45.9
CHS 2	4	154,600	5,670	85.4

The tower for CHS 2 was analyzed in the same manner. Values obtained for I_x, I_z, and A were 1.07×10^6, 2.70×10^5, and 87.8 respectively.

The truss assumption was tested for the tower by computing I_x, I_z, and A for the case when all joints in the tower were rigid connections. The increase in stiffness for each parameter was less than ten percent, and the truss assumption was retained.

Modeling of conveyor sections was more difficult because as many as 600 members were represented by a single beam. The complexity made it infeasible to get the static deflections by analyzing the complete structure to be modeled. To surmount this problem, two approaches were tried.

The first approach relies on the fact that the conveyor structure is long and narrow, and is composed of a large number of similar sections. If we can find I_x, I_z, and A for a small section of the structure, we can assume the same properties for the rest of the structure.

Using the same technique as used on the bents, forces were applied as shown in Figure 5 to a few sections of the conveyor structure. The left end in Figure 5 was considered fixed. A simple beam under the action of the same forces would have static deflections

$$\delta_x = \frac{F_y b\ell^2}{EI_z} \qquad \delta_y = \frac{4F_y \ell}{EA} \qquad \delta_z = \frac{F_y a\ell^2}{EI_x} .$$

Then the stiffness parameters for an equivalent beam of equal length are given by:

$$EI_z = \frac{F_y b\ell^2}{\delta_x} \qquad EA = \frac{4F_y \ell}{\delta_y} \qquad EI_x = \frac{F_y a\ell^2}{\delta_z}$$

where δ_x, δ_y, δ_z are deflections found by applying forces to the sections and computed using SAP IV.

A question arises as to how large a portion of the structure must be used to estimate the stiffness parameters. I_x, I_z, and A were computed using different lengths of the structure to determine parameters. The results are given in Table II.

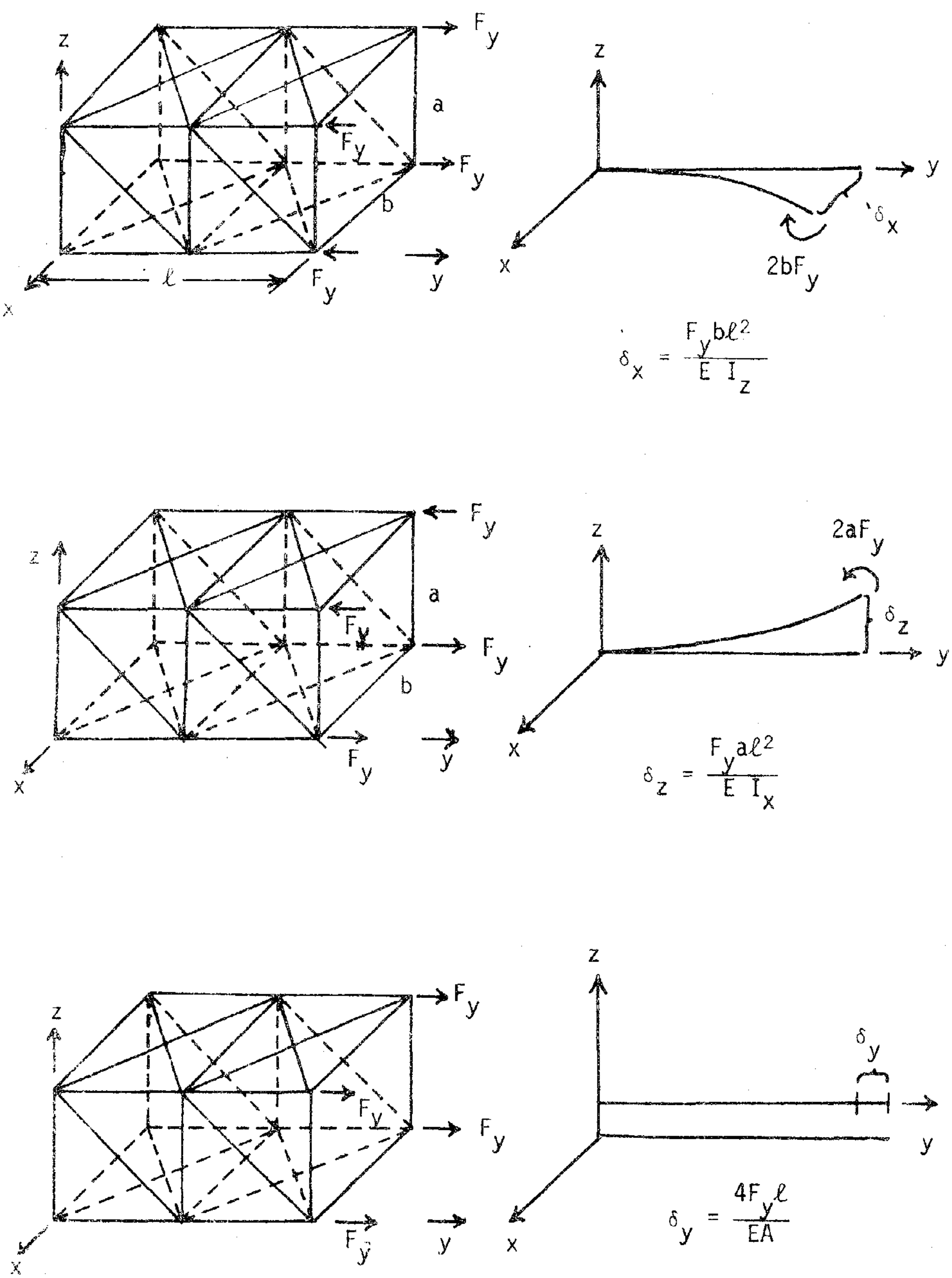


Figure 5. Beam Equivalency for Conveyor Section

Table II

Stiffness Parameters for Various Length Conveyor Structure.

Length (No. of Sections)	$I_z(in^4)$	$I_x(in^4)$	$A(in^2)$	$J(in^4)$
1	8,990	8,900	56.9	72,000
4	119,000	92,000	62.3	60,000
5	162,000	120,000	61.9	--
6	205,000	144,000	62.8	46,000
Est	603,990	292,980	67.3	100,000

J is the polar moment of inertia which will be discussed later.

In Table II we notice that while "A" is stable, the values for I_x and I_z are increasing with length. When six sections are used the length to width ratio is about 5 to 1, while a ratio of 10 to 1 is generally accepted as the minimum ratio where a simple beam provides a good model. This would require 12 sections for the computation of I_x and I_z; however, since there are only 12 sections between pinned supports, we must require that the cantilevered simple beam model parameters reflect the behavior of half that distance. The parameter values for 6 sections were used to construct the model.

The problem with nonconvergence could be solved by using a Timoshenko beam model which will give markedly better results for short sections but would result in a more complex model. Whether such a model is justified would have to be studied.

Simpler Model

A second, simpler, approach was also used for determining I_x and I_z for the simple beam model of the conveyor structure. The moments of inertia can be estimated by examining the physical character of the structure directly,and determining its load carrying capability. Figure 6 shows an "effective area" cross-section for the conveyor structure of CHS 1 previously shown in Figures 1 and 5. The average area of the chords is 14.22 sq. in and the equivalent area for the "x" bracing 2.69 sq. in., found as shown in Figure 7. The equivalent areas for the "x" bracing are evenly distributed along the top and bottom. I_x and I_z are then calculated by computing the moments of the areas about the appropriate axes, and A is simply the sum of all areas of the cross-section. The estimates obtained for CHS 1 are shown in Table II on page 10.

These estimates are correct only when the structure has pure moment loading and experiences no deflection in the x or z direction. In any other case the estimates are too high, and therefore, are an upper bound on the values for I_x and I_z.

It is also necessary to choose a value for the polar moment of inertia "J". Normally, we would expect J to be the sum of I_x and I_z; however, in Table II we see that this is not the case for the actual structure. Typically, J is much less than sum.

In order to develop a rationale for choosing J, the sensitivity of the natural frequencies to the J value was studied. In Table III, natural frequencies were computed for CHS 1 with different values of J, holding all other parameters constant. We see that the structure is relatively insensitive to the value of J. J was chosen to be approximately one-tenth the sum of I_x and I_z, a ratio close to that for the actual structure six section case.

The results of the simple approach are compared to the deflection approach in Table IV for both structures. The estimate values for the

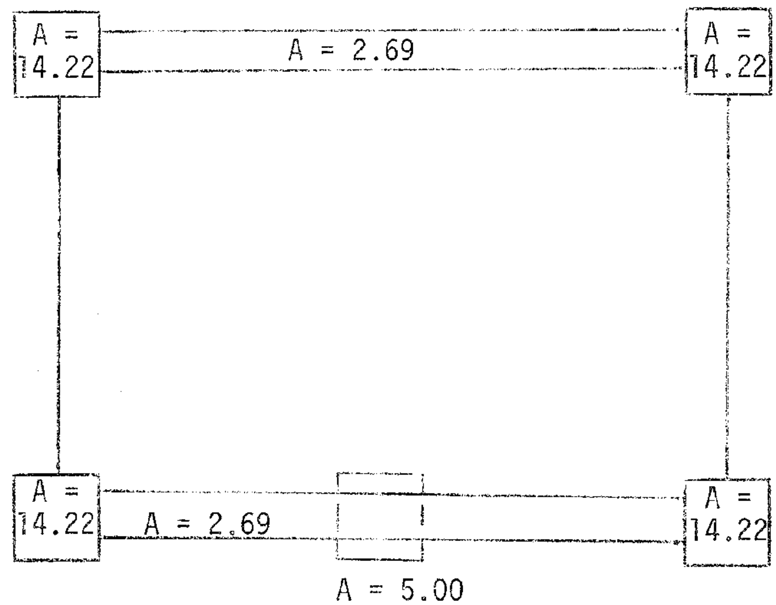


Figure 6. Cross Section Equivalent Areas.

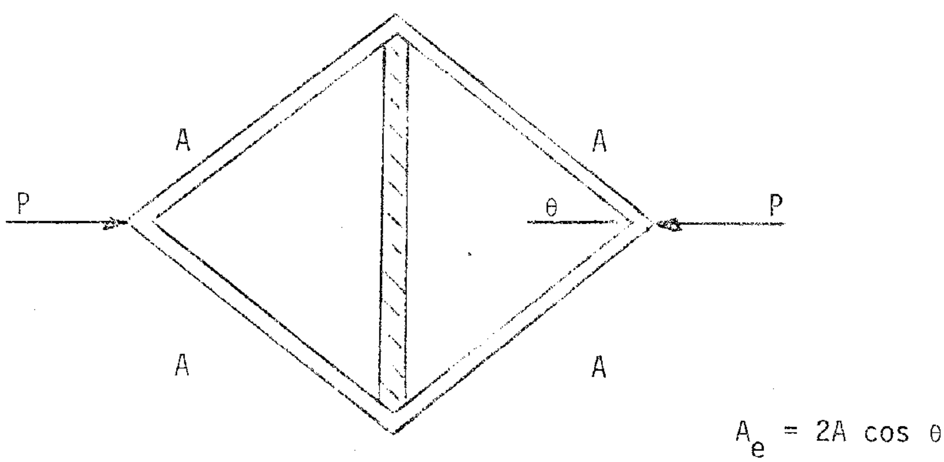


Figure 7. Equivalency for Bracing.

Table III

Mode	J = 100,000 in^4	J = 500,000	J = 800,000
1	.592	.654	.685
2	1.22	1.22	1.22
3	1.24	1.35	1.40
4	1.47	1.47	1.47
5	1.72	1.72	1.72
6	2.16	2.18	2.18
7	2.39	2.39	2.39
8	2.75	2.75	2.75
9	3.65	3.67	3.68
10	4.51	4.51	4.51

Table IV

Mode	CHS 1 Natural Frequencies (Hz)		CHS 2 Natural Frequencies (Hz)	
	Deflection	Estimates	Deflection	Estimates
1	.514	.592	.501	.480
2	.902	1.22	.882	.802
3	.916	1.24	.892	.829
4	1.26	1.47	1.08	.988
5	1.33	1.72	1.18	1.15
6	1.43	2.16	1.42	1.40
7	1.84	2.38	1.49	1.49
8	2.24	2.75	2.05	1.95
9	2.71	3.65	2.15	2.10
10	3.33	4.51	2.22	2.11

frequencies are close, especially considering the simplicity of the method. Even in CHS 2 where a very nonuniform section was modeled as a uniform section with average values, the agreement is excellent.

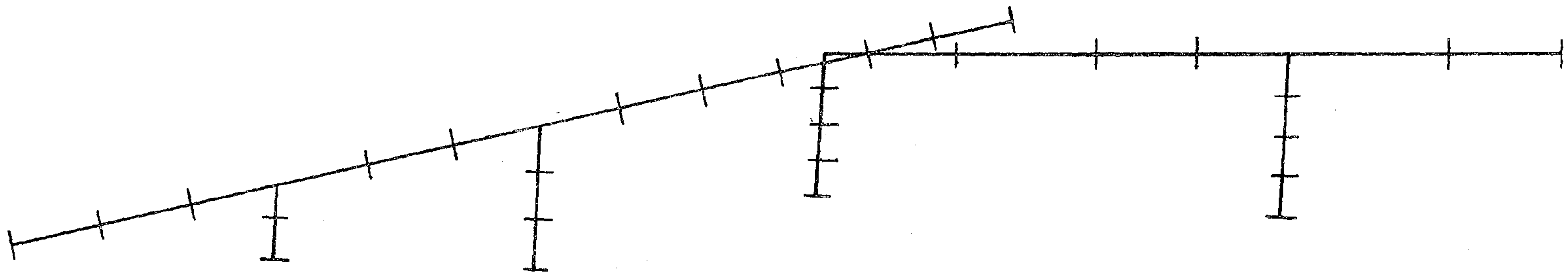
Computation of Natural Frequencies and Mode Shapes

The natural frequencies and mode shapes were calculated using the finite element approach which is incorporated in SAP IV. Figure 8 shows the finite element breakdown of the models for both structures. The resulting model for CHS 1 has 112 degrees-of-freedom and CHS 2 has 166 degrees-of-freedom. Computation of the lower twenty-five frequencies requires approximately 30 seconds of CPU time on a CDC 6500 computer.

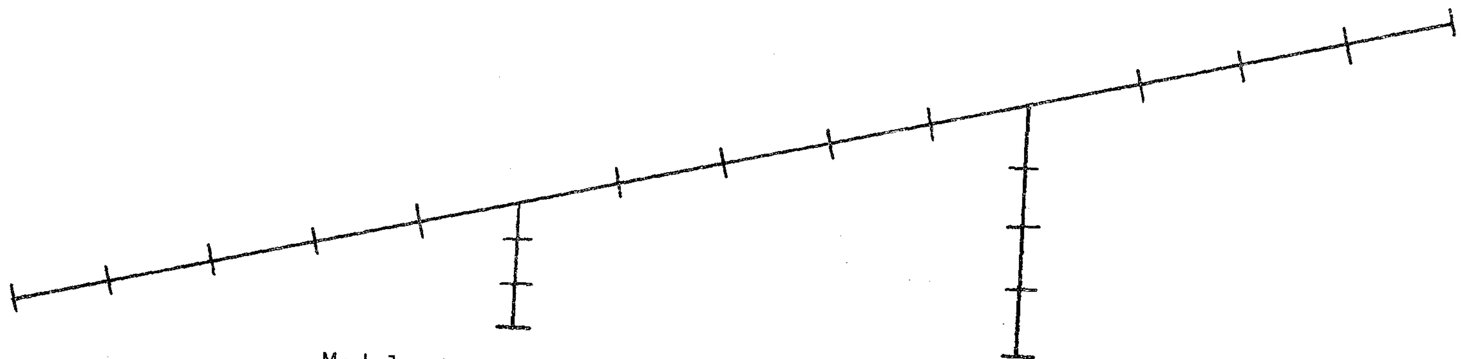
Table V gives the boundary conditions used for both structures. Boundary condition locations are given in Figure 8. Pinned connections

Table V. Boundary Conditions

B.C. Location	CHS 1	CHS 2
1	fixed	fixed
2	pinned	pinned
3	fixed	fixed
4	pinned	pinned
5	fixed	fixed
6	roller	fixed
7	--	fixed
8	--	roller
9	--	roller
10	--	pinned
11	--	fixed
12	--	free



Finite Element Model for CHS 2



Model of Coal Handling Equipment for Coal Yard

Figure 8. Finite Element Model for CHS 1

allow rotations only about "x" axis and roller connections allow rotation about the "x" and "z" axes and translation in the "y" direction.

Material properties for both structures were the same with Young's Modulus of 3.0×10^7 and Poisson's Ratio of .27.

The mechanical properties used for the following computations are given in Table VI.

Table VI. Mechanical Properties

Model	Section	$A(in^2)$	$J(in^4)$	$I_x(in^4)$	$I_z(in^4)$
CHS 1	-1	111.2	22.761	43,564	6,740
	-2	106.9	10,122	134,850	8,988
	-3	67.3	100,000	603,990	292,980
CHS 2	-1	33.8	59,350	58,500	851
	-2	45.9	64,010	63,000	1,013
	-3	87.8	1,339,000	1,069,000	270,100
	-4	85.4	160,300	154,600	5,670
	-5	27.3	135,000	59,687	79,665
	-6	59.5	1,780,000	650,190	1,133,900

The first 25 natural frequencies for CHS 1 and CHS 2 are given in Table VII and the first five modes for each structure are given in Figures 9 thru 18. Comparison of these values with experimental is given in a separate report.

Sample Response

The response of the structure to a time history input can be calculated using SAP IV. A sample input is shown in Figure 19. This is

Table VII. Natural Frequencies

Mode	CHS 1	CHS 2
1	.592 Hz	.480
2	1.22	.802
3	1.24	.829
4	1.47	.986
5	1.72	1.15
6	2.16	1.40
7	2.39	1.49
8	2.75	1.95
9	3.65	2.10
10	4.51	2.11
11	4.61	2.24
12	5.43	2.72
13	5.48	2.97
14	6.58	3.16
15	7.07	3.22
16	7.45	3.49
17	7.82	3.64
18	8.06	3.81
19	8.89	3.89
20	9.30	4.56
21	10.06	4.88
22	10.50	5.35
23	10.64	5.50
24	11.86	5.75
25	12.26	5.92

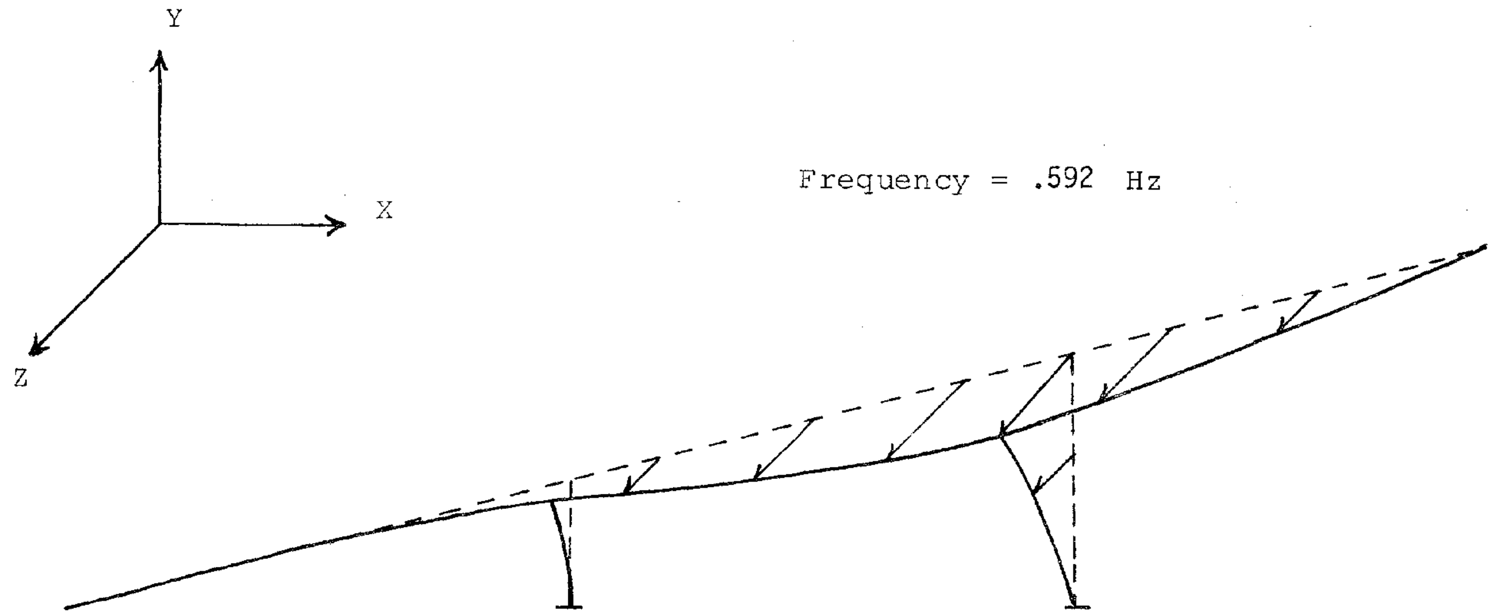


Figure 9. First Mode for CHS 1

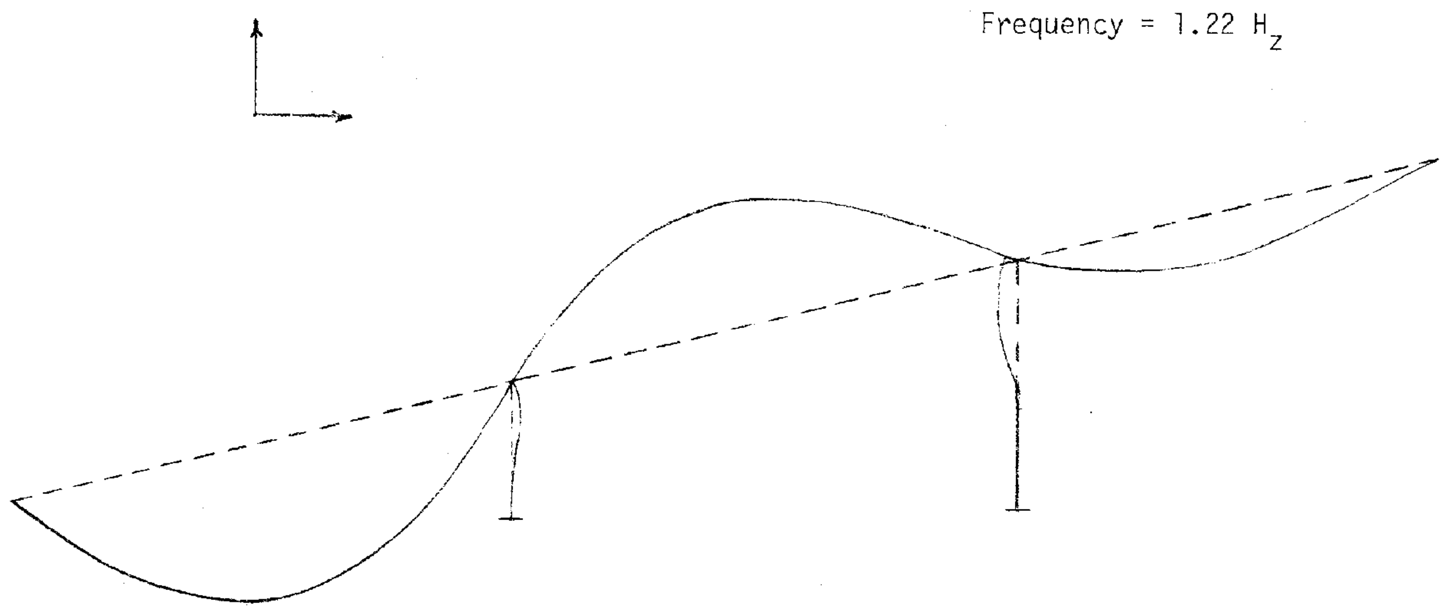


Figure 10. Second Mode for CHS 2.

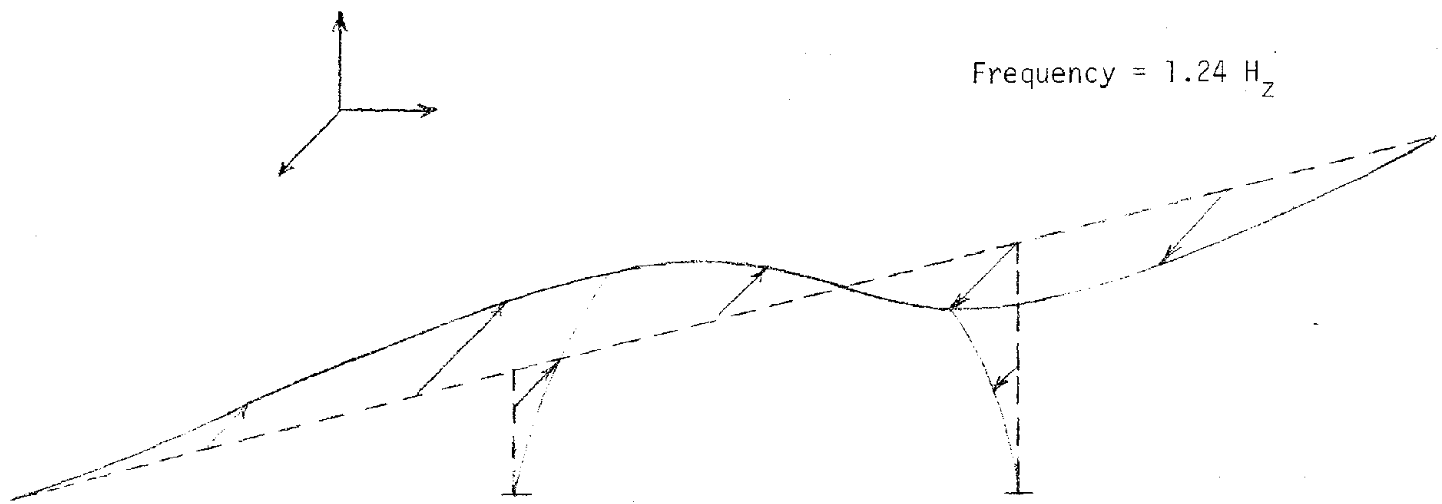


Figure 11. Third Mode for CHS 1.

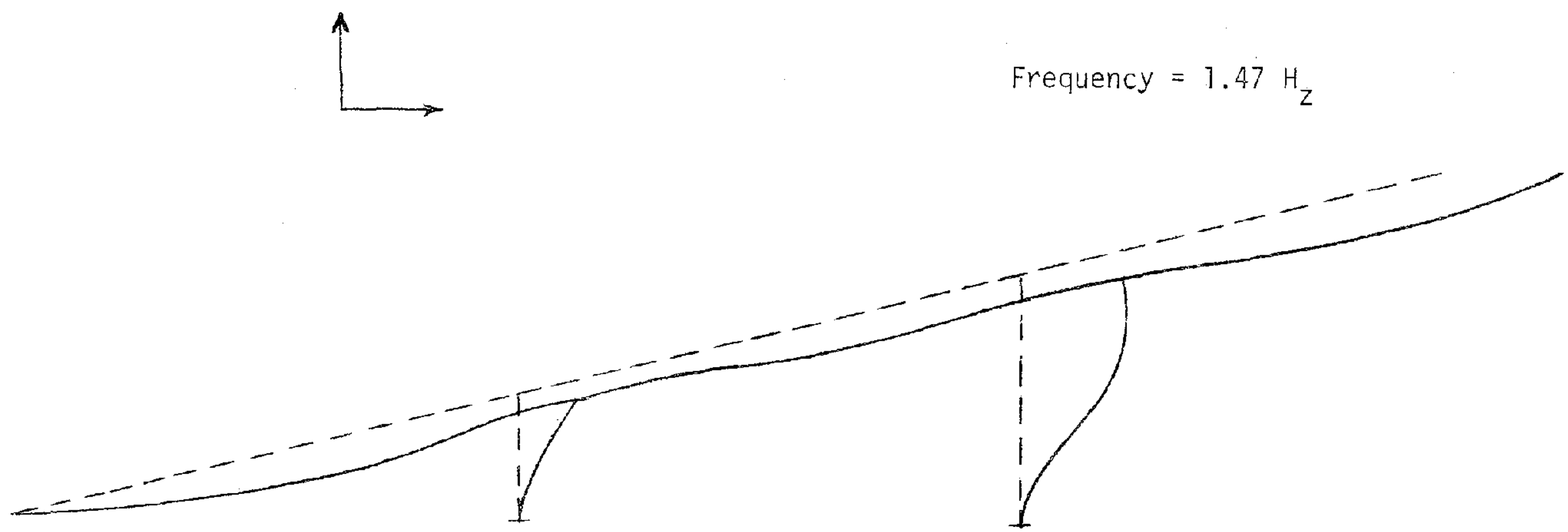


Figure 12. Fourth Mode for CHS 1.

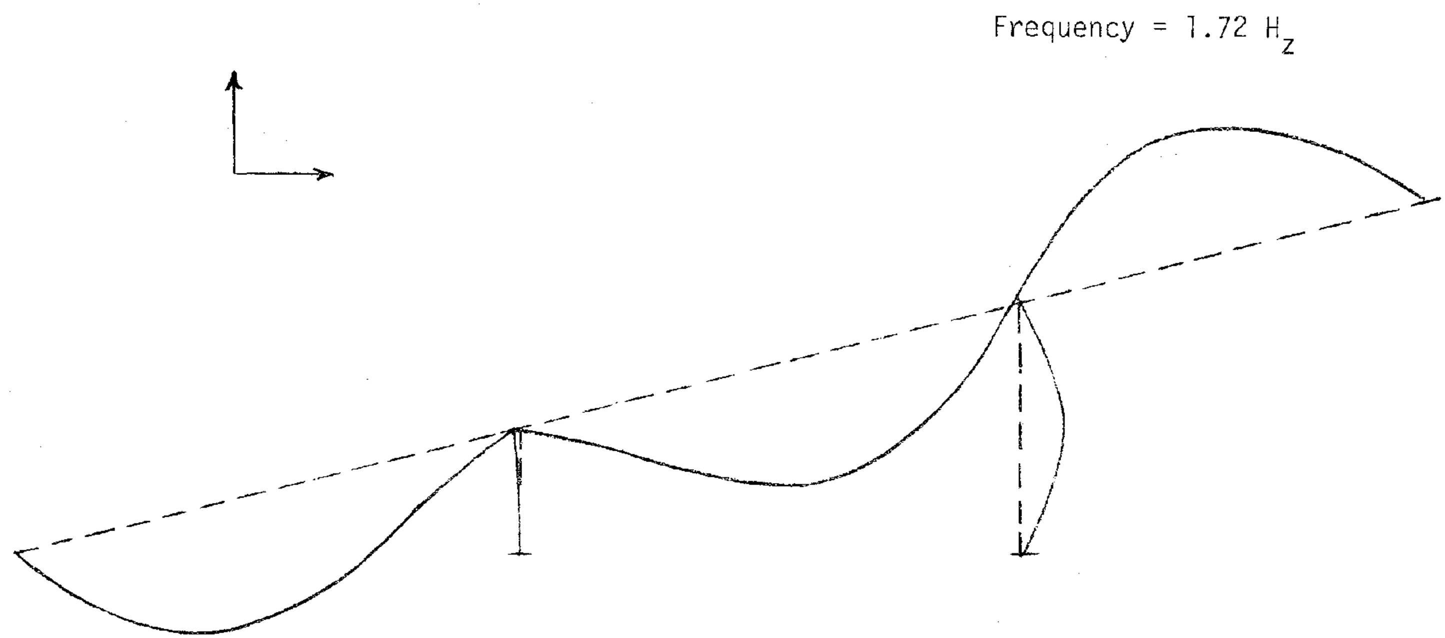


Figure 13. Fifth Mode for CHS 1.

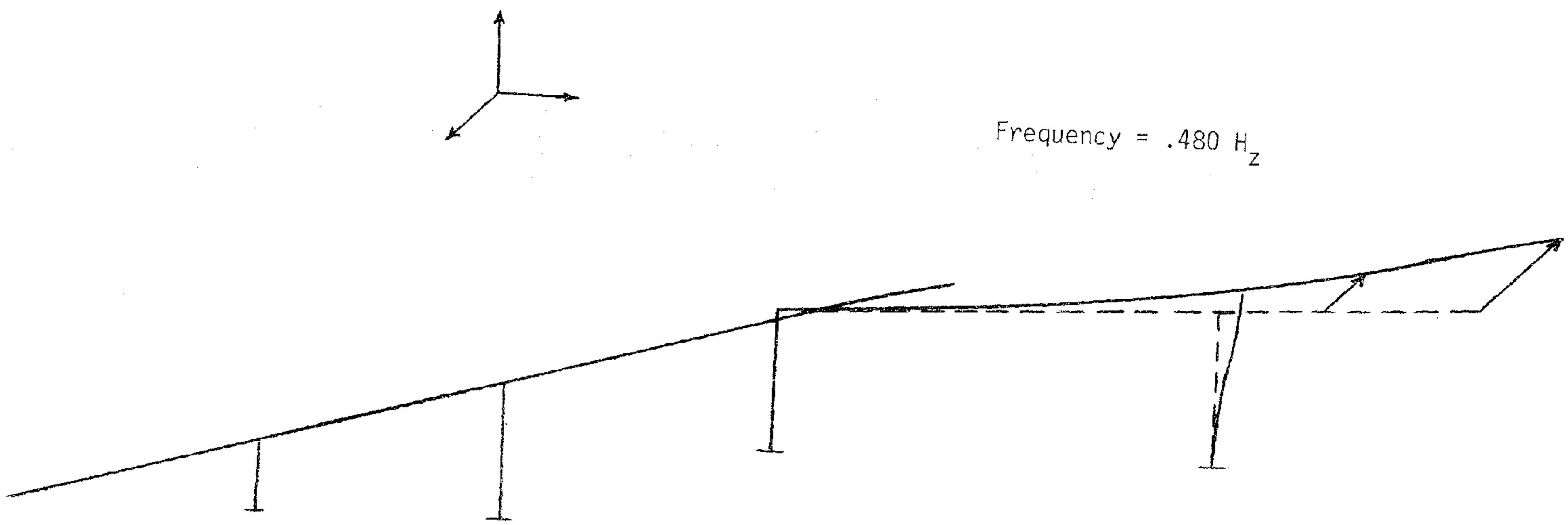


Figure 14. First Mode for CHS 2.

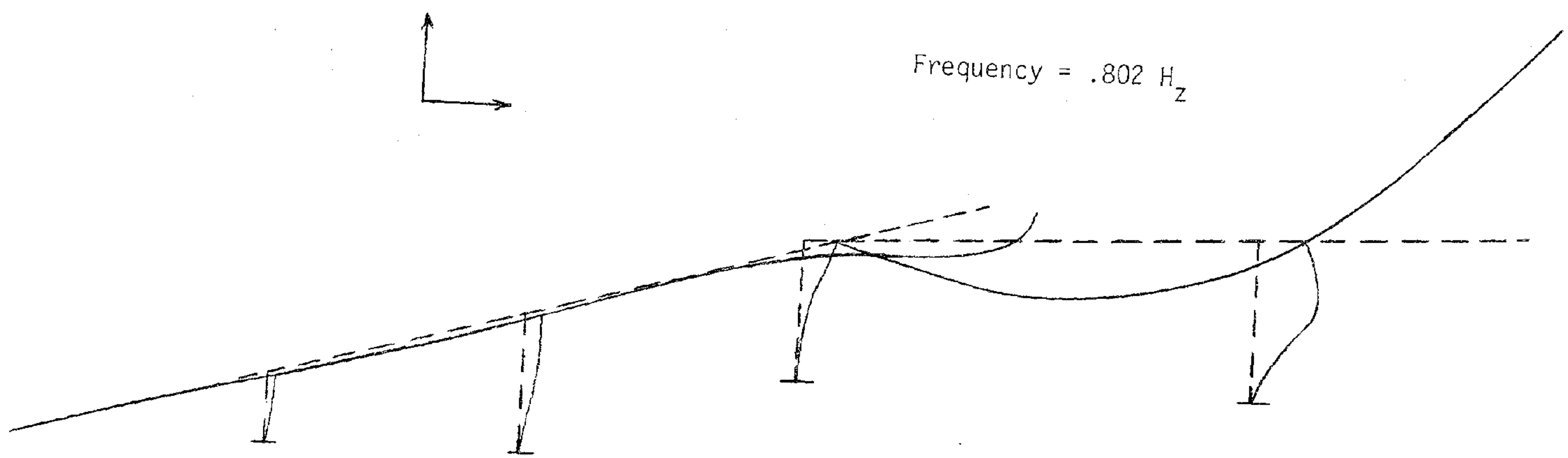


Figure 15. Second Mode for CHS 2.

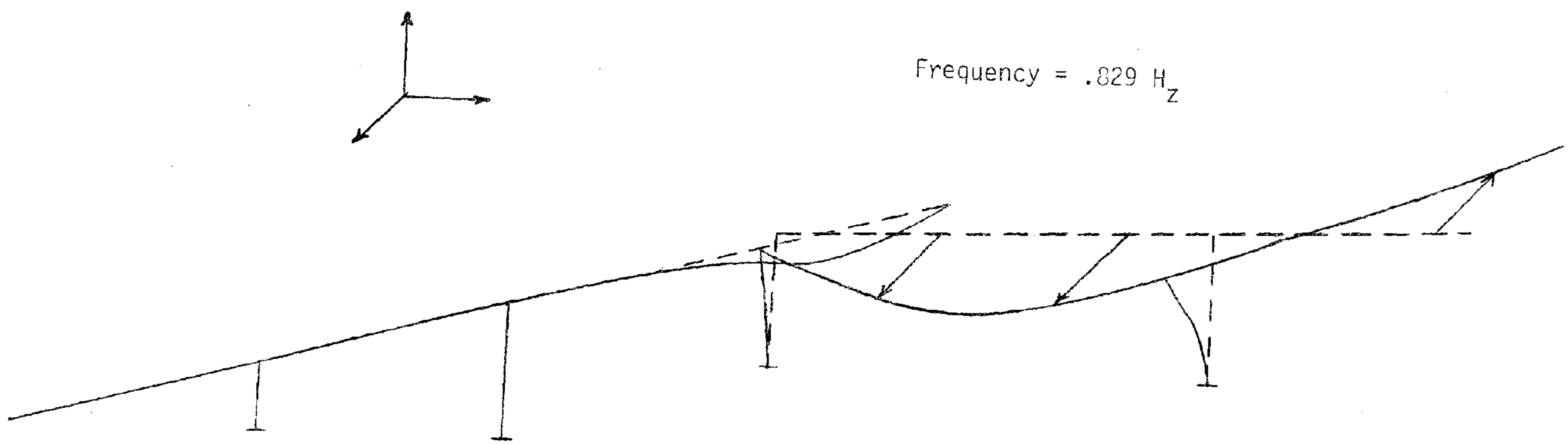


Figure 16. Third Mode for CHS 2.

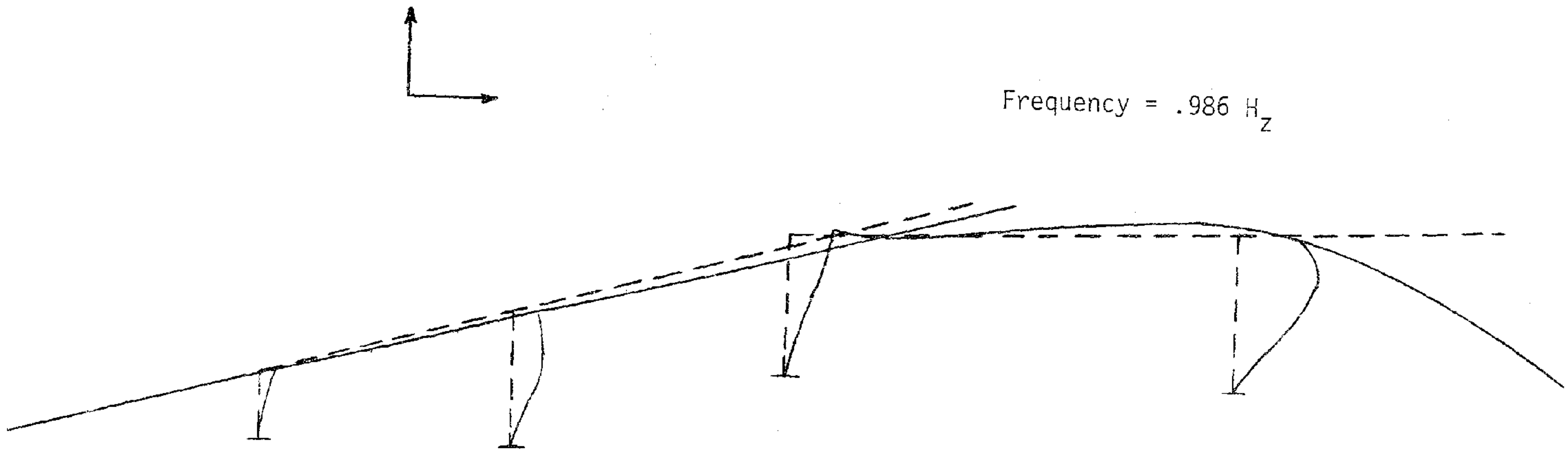


Figure 16. Fourth Mode for CHS 2.

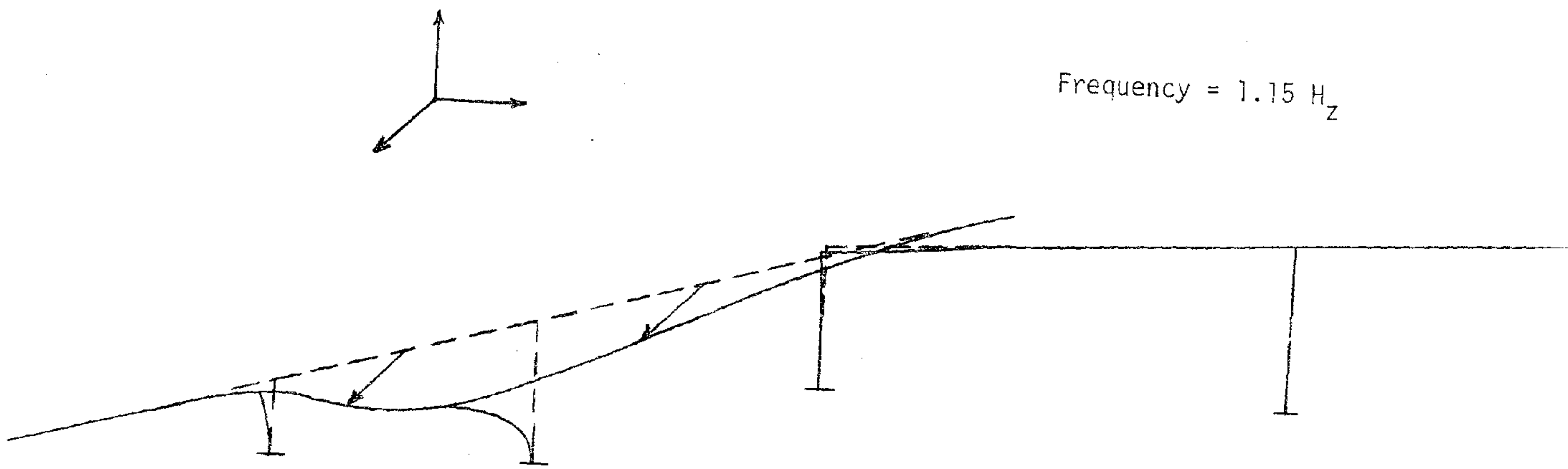


Figure 18. Fifth Mode for CHS 2.

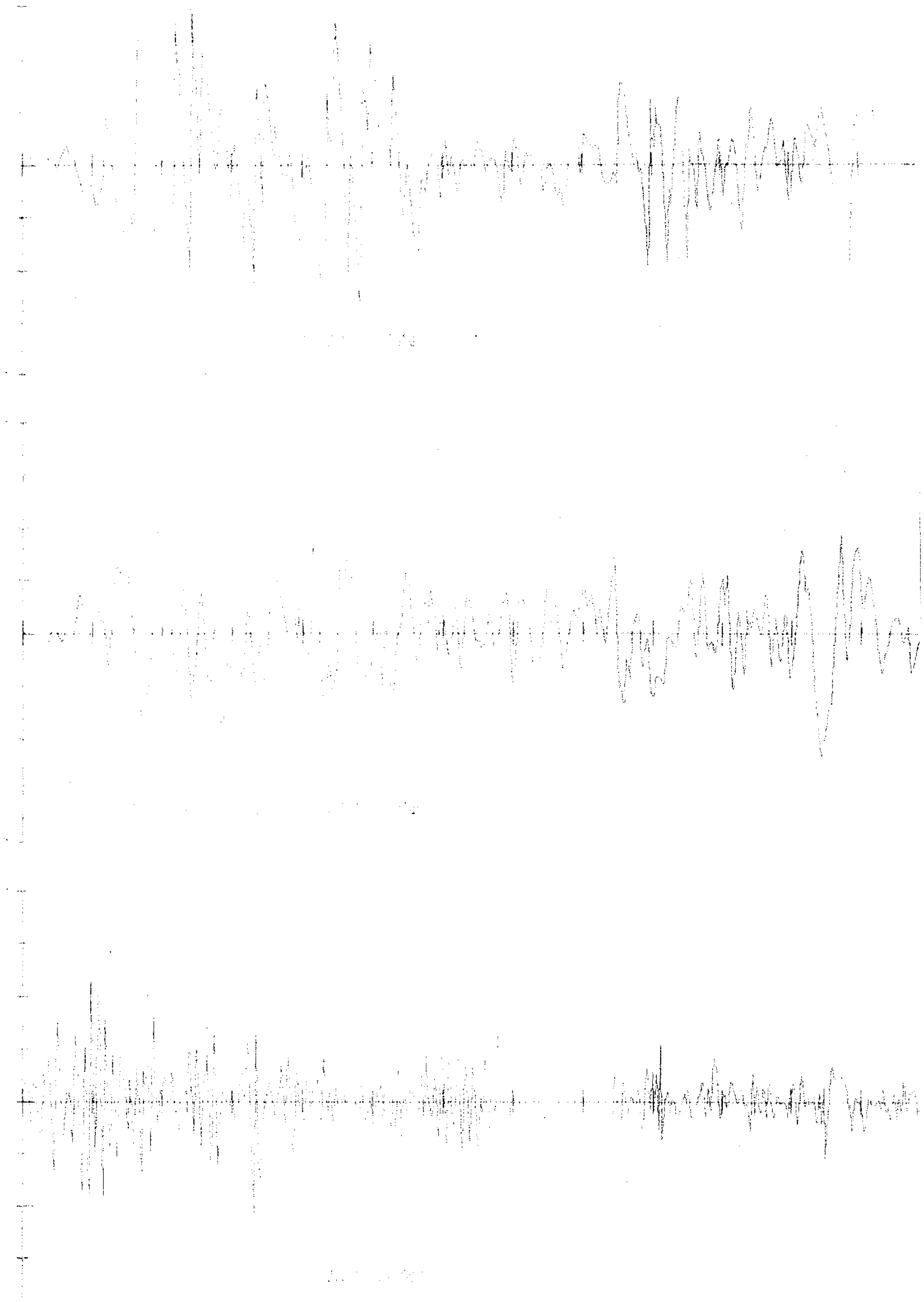


Figure 19

the first eight seconds of the "El Centro 1940" earthquake. The two orthogonal horizontal and the vertical components were applied simultaneously as input.

The structure response is computed by SAP IV using modal analysis for the first 25 modes. The damping for each mode was chosen to be three percent of critical. This value was determined experimentally as discussed in the experimental results report. The response is available for any point shown in Figure 9. The displacement perpendicular to the plane of the structure at a central point between the bents of CHS 1 is shown in Figure 20 and the bending moment in the model at that point in Figure 21.

The maximum stress in the actual structural members is not calculated directly by SAP IV; however, since the loading for each section of the structure are known, it is simple matter to calculate them by the following procedure. The response of the model for a time history is computed. The locations of maximum loads in the beam model are found by examination of the load time histories. These loads are then applied to the actual structure. This could be done using the static analysis section of SAP IV. The static stress in the actual members is calculated. These stresses are then estimates of the maximum dynamic stress developed in the structure for the applied time history.

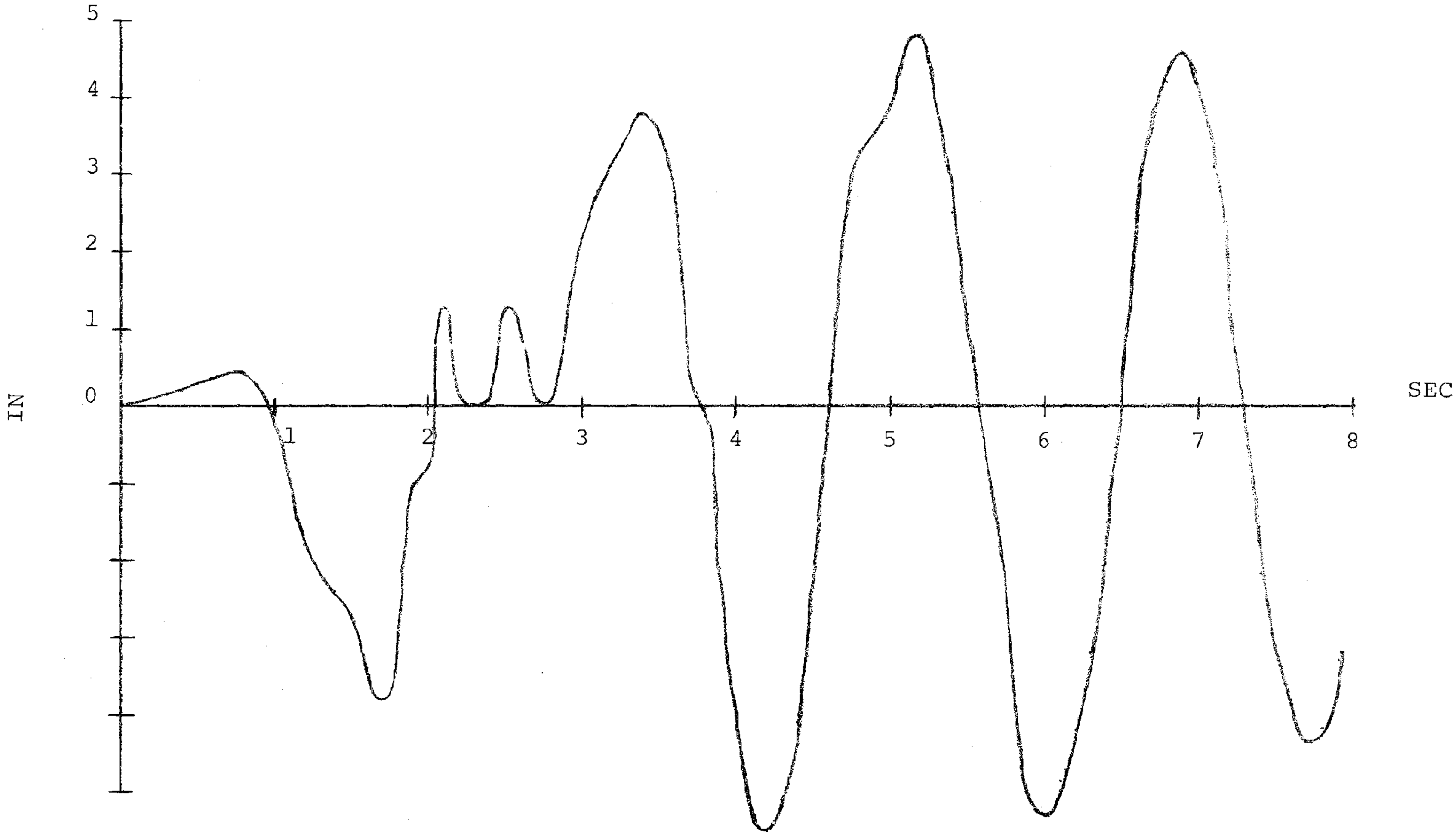


Figure 20. Lateral Displacement - Node 12 CHS 1.

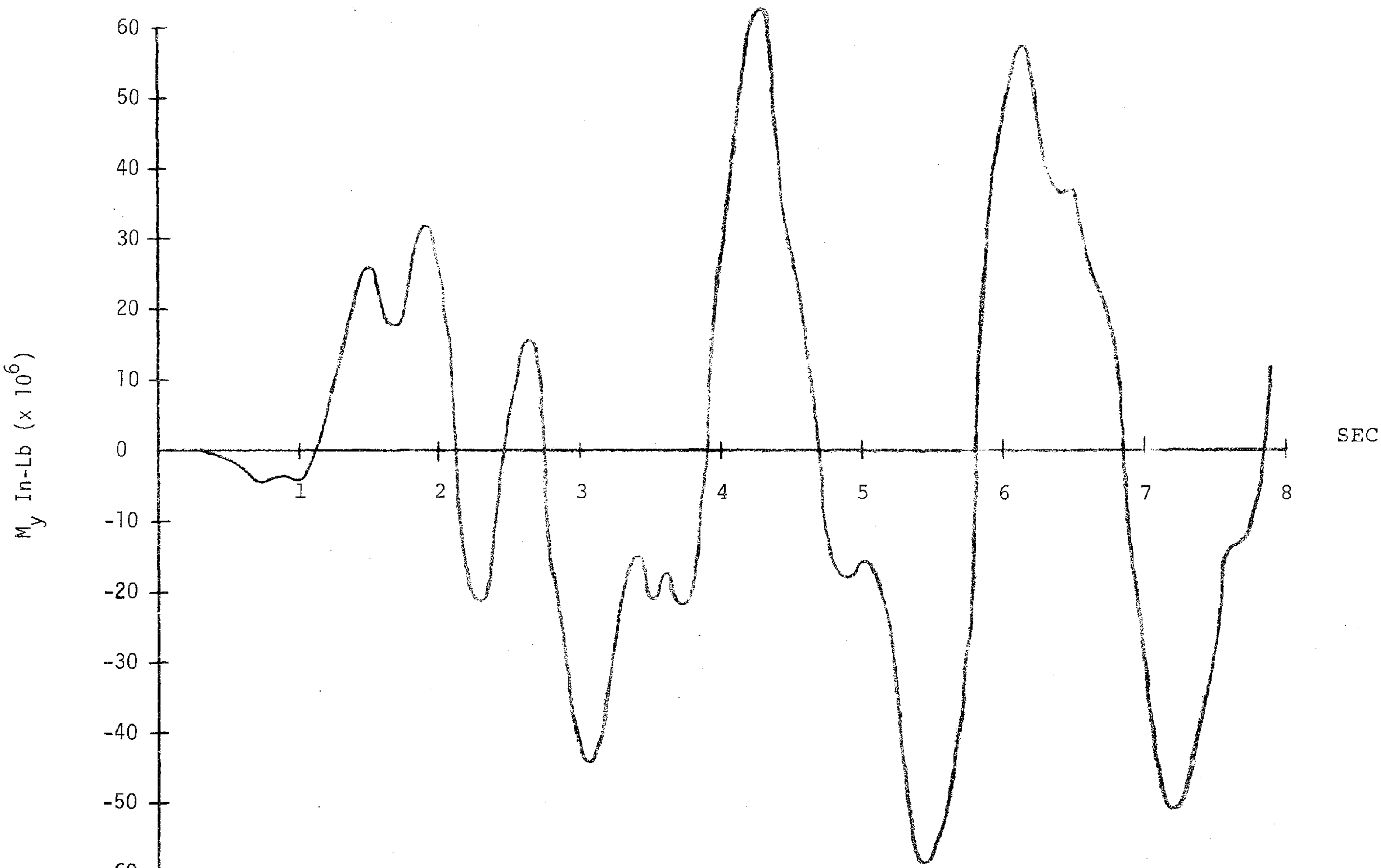


Figure 21. Moment Loading - Node 12 CHS 1.