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THE HIGH PRESSURE STEAM PIPE

Prepared by

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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.

THE HIGH PRESSURE STEAM PIPE

by

C.T. Sun, A.S. Ledger, and H. Lo

Introduction

The high pressure steam pipe connects the header at the top of the steam generator to the turbine at the ground level. It is a vital part of the electrical generating system in a fossil fuel power plant. A failure of piping system means a shutdown of the plant and, as a consequence, a great financial loss.

The current design for the piping system has been based upon static considerations. The supports are designed to take the dead weight and provide flexibility for thermal expansion. Lateral supports are either lacking or very weak. A lateral disturbance such as an earthquake can prove to be hazardous to the pipe.

The purpose of the present study is to describe how to determine the natural frequencies as well as the seismic response of a piping system in a power plant. It is hoped that the results of the present work will shed light on the seismic response problem that will prove useful in the development of the future design criteria for these piping systems.

<u>Geometry and Assumptions</u>

A sketch of the high pressure pipe is shown in Fig. 2.1. Except for the lower end portion, the pipe has 21.25" OD and 4" thickness. The central part runs vertically for about 185'. There are fifteen supports of which only one provides lateral constraints. A typical design of the support is shown in Fig. 2.2. Except the Support A as indicated in Fig. 2.1 which is a solid rod type of support. All the others contain the Counterpoise Hangers that allow additional displacement without increasing load. In view of this, only the support at A will be represented by an axial member while the others are taken to have no restoring force during vibrations.

For this analysis, the damping is taken to be 3% of the critical value. The effect of this amount of damping is obviously very small on the natural frequencies. Therefore, in the calculation of the natural frequencies, damping is neglected.

The internal pressure is high (3.600 psi) and thus is included in the free as well as the transient response analysis. Due to the presence of a high temperature (1005°F) the modulus of electricity is taken to be 20×10^6 psi.

Two basic types of finite elements are used in this study, namely, the pipe element and the truss element which are provided by the computer program SAP IV. The pipe element can be either straight or curved. Each element has two nodal points with six degrees of freedom at each node. Axial, bending as well as torsional deformations are all accounted for. Lumped mass procedure is used to obtain the mass matrix. The stiffness matrix is the same as given in Chapter 1 for beam finite elements.

The truss element (axial element) consists of two nodal points each having three translational degrees of freedom. The stiffness matrix is given by

$$[K] = \frac{AE}{L} \begin{array}{c} \begin{array}{cccccc} u_1 & v_1 & w_1 & u_2 & v_2 & w_2 \end{array} \\ \begin{bmatrix} \lambda^2 & & & & & \\ \lambda\mu & \mu^2 & & & \text{SYM.} & \\ \lambda^2 & \mu^2 & \nu^2 & & & \\ -\lambda^2 & -\lambda\mu & -\lambda\mu & \lambda^2 & & \\ -\lambda\mu & -\mu^2 & -\mu^2 & \lambda\mu & \mu^2 & \\ -\lambda^2 & -\mu\nu & -\nu^2 & \lambda^2 & \mu^2 & \nu^2 \end{bmatrix} \end{array} \qquad (2.1)$$

where A is the cross-sectional area, E the Young's modulus, L the length, and λ, μ, ν are the direction cosines between the local element coordinates and global coordinates.

The equations of motion for the discretized system can be written in matrix form as

$$[K]\ [\delta] + [M]\ [\ddot{\delta}] = [P] \tag{2.2}$$

in which [M] is the mass matrix, δ is the generalized nodal displacement, and the [P] represents the external loads.

<u>Free Vibration</u>

In the study of free vibrations of the pipe, we assume that the ends are clamped, i.e., all the degrees of freedom at the ends are suppressed. Since the external forces are absent, the equations of motion reduce to

$$[K]\ [\delta] + [M]\ [\ddot{\delta}] = [0] \tag{2.3}$$

The natural frequencies ω of the system are required to satisfy the frequency equation:

$$\left|\ [K] - \omega^2\ [M]\ \right| = 0 \tag{2.4}$$

In the numerical calculations, twenty-eight elements (in general, one element between two supports except at the bends) are used for the pipe. The hanger rod at Support A is represented by a truss element. The total number of degrees of freedom is 156. The solutions for the first ten modes are given in Table 2.1. The CP time for the computation is 26.6 seconds.

The mode shapes of the first three modes are shown in Figs. 2.3, 2.4, and 2.5, respectively. It is found that for the first two modes, the amplitudes in the x-direction are much greater than those in the y-direction, especially in the first mode. The y-direction displacement becomes more pronounced in the third mode. Going through the first ten modes, we find that the motion in the z-direction is negligible for the first eight modes. It becomes substantial only in the 9th mode. This clearly indicates that the vertical motion is of higher frequencies.

Seismic Response

The high pressure steam pipe is supported by the steel frame and connected to the steam generator and the turbine. During an earthquake, the piping system could pick up disturbances from the ground as well as the boiler frame. It seems reasonable to take into account only the interactions between the pipe and the header of the steam generator and the turbine as the supports can not transmit lateral motions. In this report we assume that the upper end is fixed while the lower ends are subjected to a ground acceleration. A more realistic consideration should take the motion of the frame under the same seismic disturbances as a forcing source at the upper end.

To reduce the computing time, we use 28 elements (156 dof) for the analysis of transient response. The El Centro 1940 earthquake record is used for the ground motion. One of the three components of the ground acceleration is shown in Fig. 2.6.

Under the ground acceleration $\ddot{\delta}_g$ the equations of motion are

$$[K]\ [\delta_r] + [M][\ddot{\delta}_r] = -[M][\ddot{\delta}_g] \qquad (2.5)$$

where δ_r is the relative displacement of the structure with respect to the ground. The solution to equation (2.5) can be carried out either by direct integration or mode superposition. The direct step-by-step integration is more effective for shock problems where many modes are included and fewer time steps are required. In the present study, by judging from the highly oscillatory nature and the long duration of the acceleration history, the method of mode superposition is employed. The ten lowest vibration modes are used in the analysis with the highest frequency being 3.756 Hz.

The ground acceleration history is discretized into 400 time steps for the first 8 seconds. The reasons for stopping at the 8th second are that the acceleration is much more intensive in the first 4 seconds and that use of less time steps would yield more accurate results.

In Fig. 2.7, the maximum displacements at the supports in the x-direction with and without damping are presented. The corresponding times of occurrence are also indicated. The similar results for the y-components of displacement are shown in Fig. 2.8. It is found that the amplitudes in the undamped case are much larger than those with damping, and that the undamped maximum displacements occur much later. The maximum displacement is 14.6" (17" undamped) at 5.1 seconds.

The maximum bending moments and the corresponding times of occurence are shown in Fig. 2.9. It is observed that the bending moment is more severe at the bend near the upper end. For the damped case, the maximum bending is 6.1×10^6 in-lb.

The torsional motion is noted to be quite pronounced, especially in the upper portion of the pipe where the maximum torque is found to be 2.4×10^6 in-lb. (2.9×10^6 in-lb. undamped) see Fig. 2.10. The maximum torque in the vertical portion of the pipe is obtained as 1.2×10^6 in-lb. (1.5×10^6 in-lb. undamped). The maximum torque in the lower branched sections is 0.62×10^6 in-lb. (0.78×10^6 in-lb. undamped).

Fig. 2.11 shows the configurations of the pipe at various times. It is important to note that the deformed configurations resemble that of the lower modes in free vibration. This indicates that the system could be undergoing a motion that is dominated by the first few modes. In order to find the approximate period at which the piping system vibrates under the seismic loading, the x- and y-components of displacement at point B (see Fig. 2.1) are plotted versus time in Figs. 2.12 and 2.13, respectively. The period for the motion in the x-direction is found to be approximately 3 seconds while that for the motion in the y-direction is about 2 seconds.

We recall that the period for the first natural mode was found to be 3.5 seconds and the period for the second mode was 2.07 seconds. From Figs.2.12 and 2.13, it is evident that damping can substantially reduce the amplitude of vibration, especially at larger times.

In Fig. 2.14, the bending moment about the y-axis at point B is shown for the first eight seconds. The effect of damping is even greater. This simply concludes that an appropriate amount of damping that is surely present in structures must be included for a more accurate account of the transient dynamic response.

Table 2.1 Natural Frequencies

MODE	NATURAL FREQUENCY (Hertz)	DIRECTION OF DOMINANT DISPLACEMENT
1	0.284	x-direction
2	0.482	x-direction
3	0.532	y-direction
4	0.922	x-direction
5	1.479	y-direction
6	1.696	x-direction
7	2.895	y-direction
8	3.154	x-direction
9	3.541	z-direction
10	3.756	x-direction

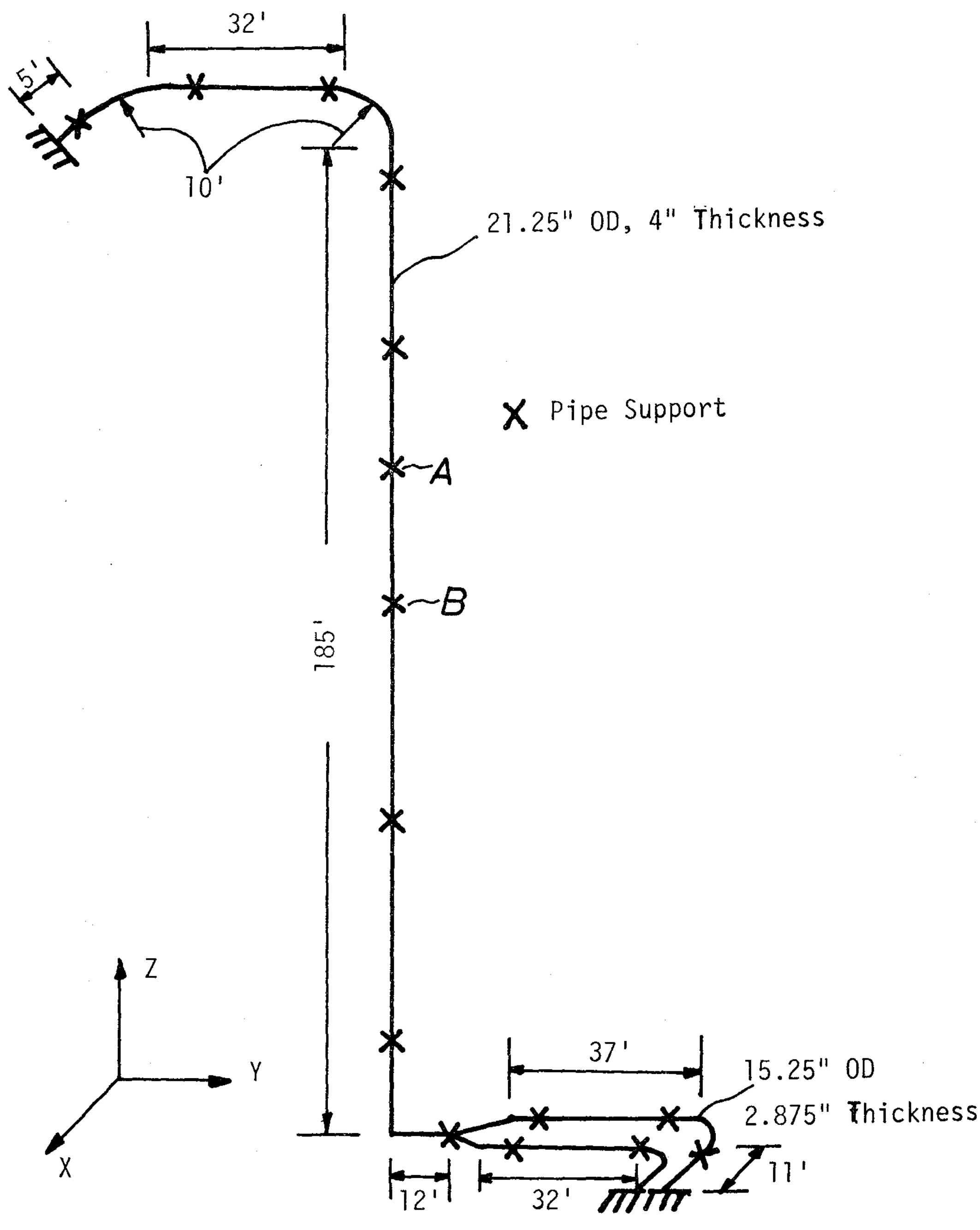

Fig. 2.1 Geometry of the high pressure steam pipe

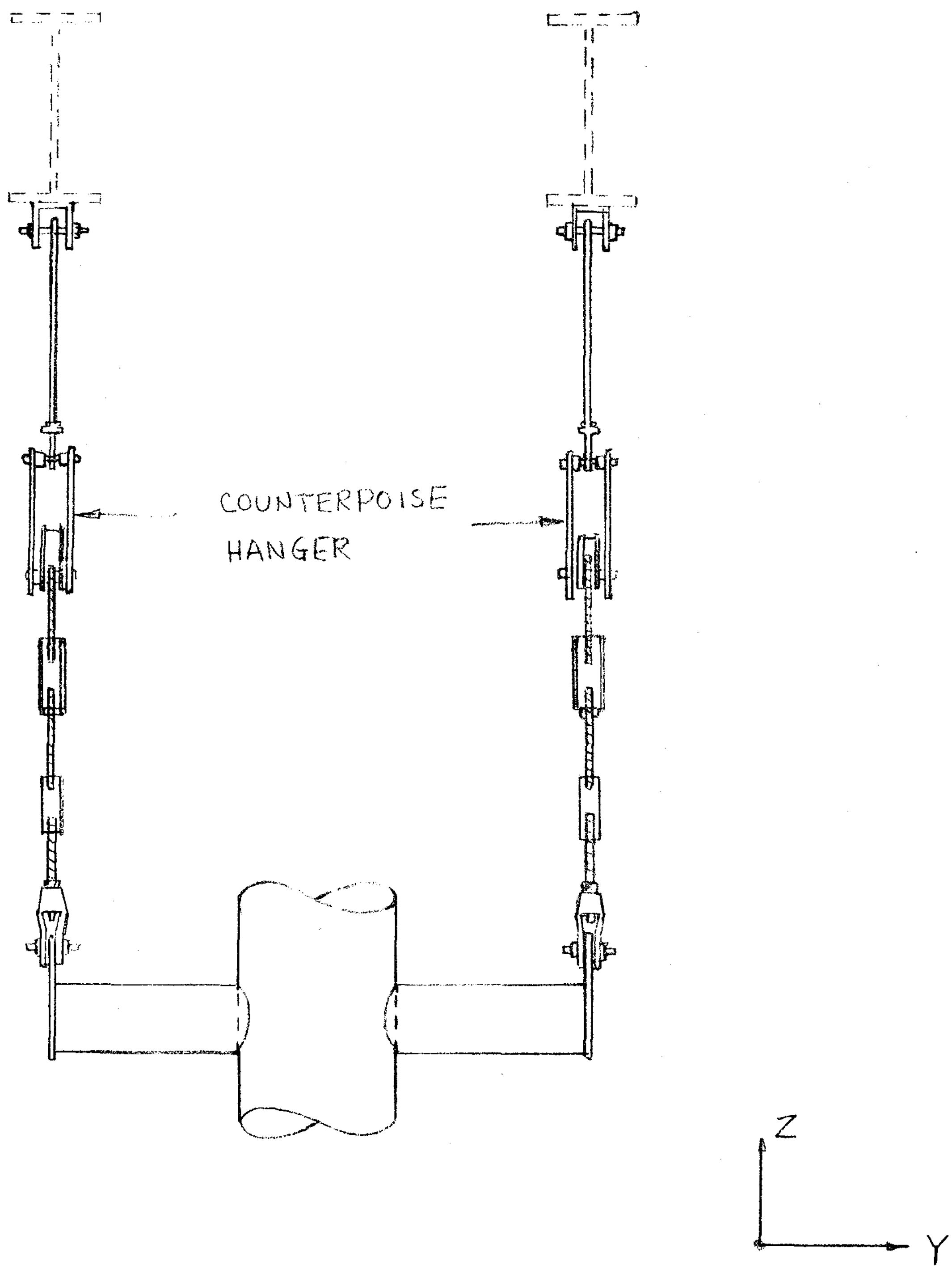

Fig. 2.2 The pipe support

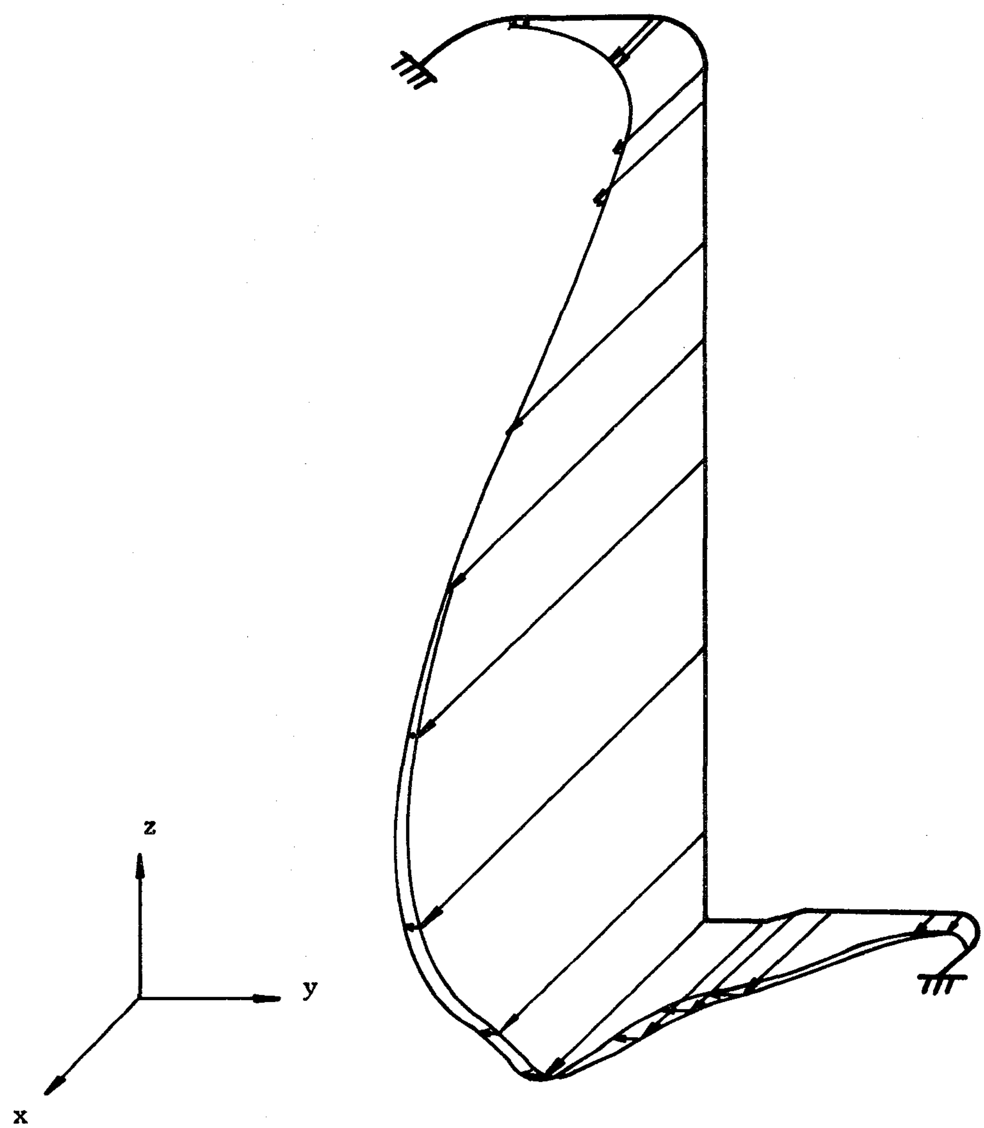

Fig. 2.3 First natural mode.

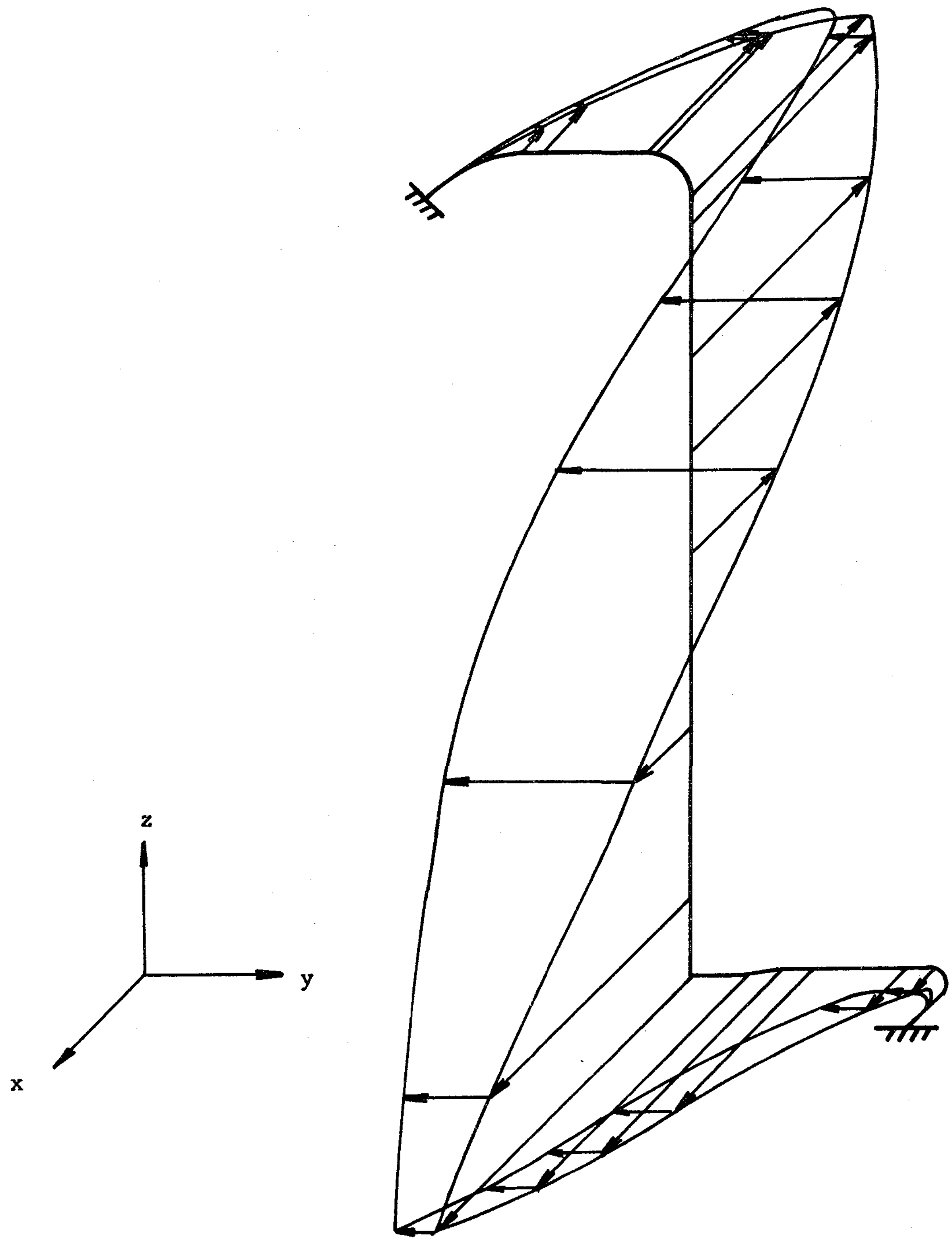

Fig. 2.4 Second natural mode.

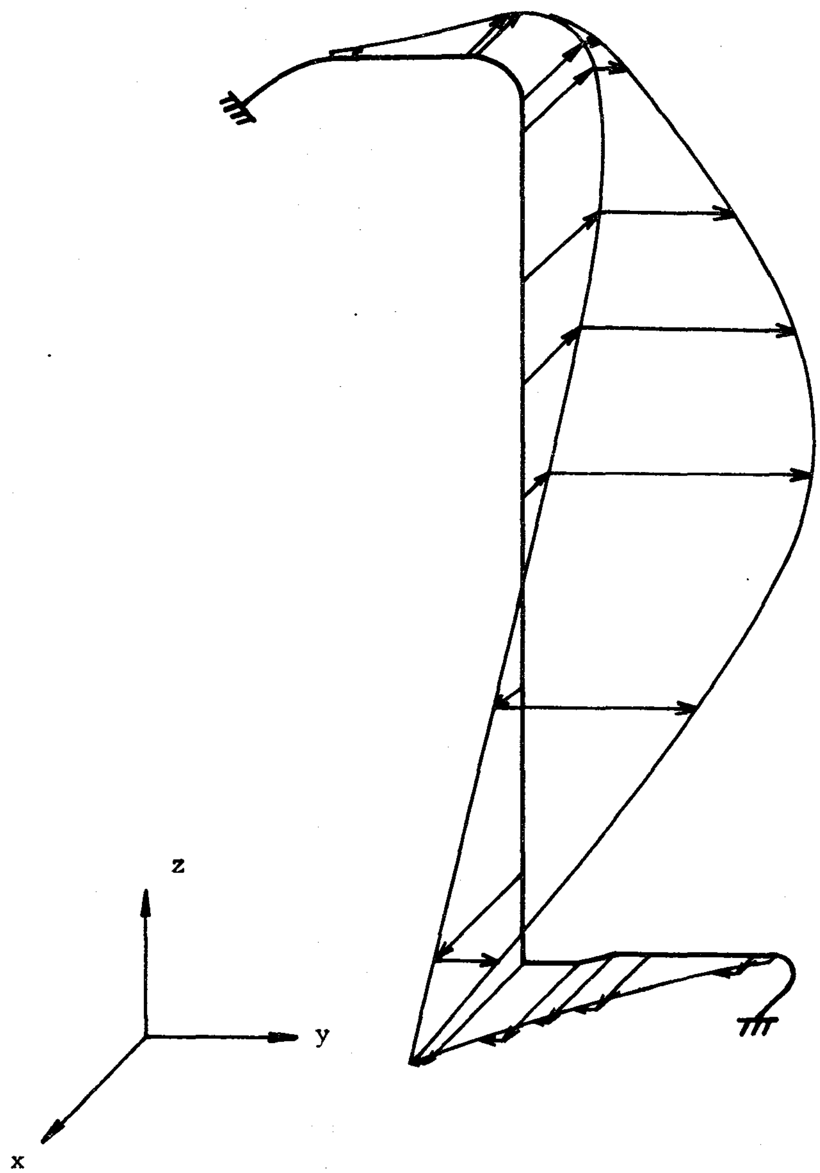

Fig. 2.5 Third natural mode

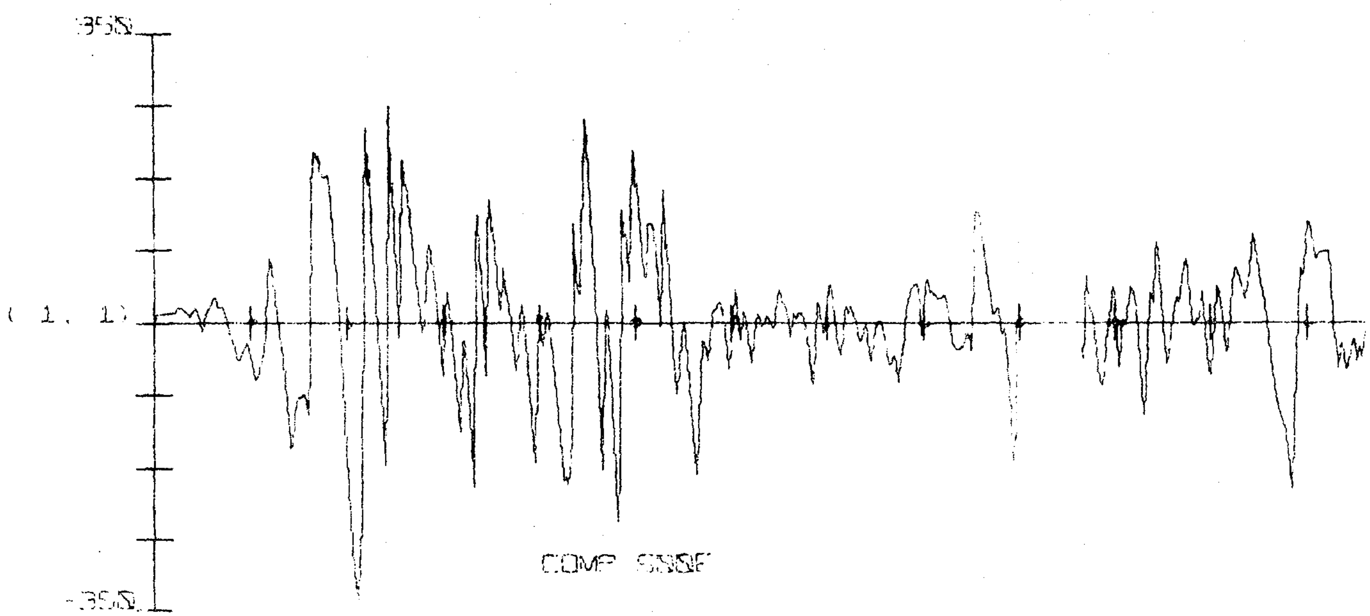

Fig. 2.6 The El Centro earthquake (North-South acceleration)

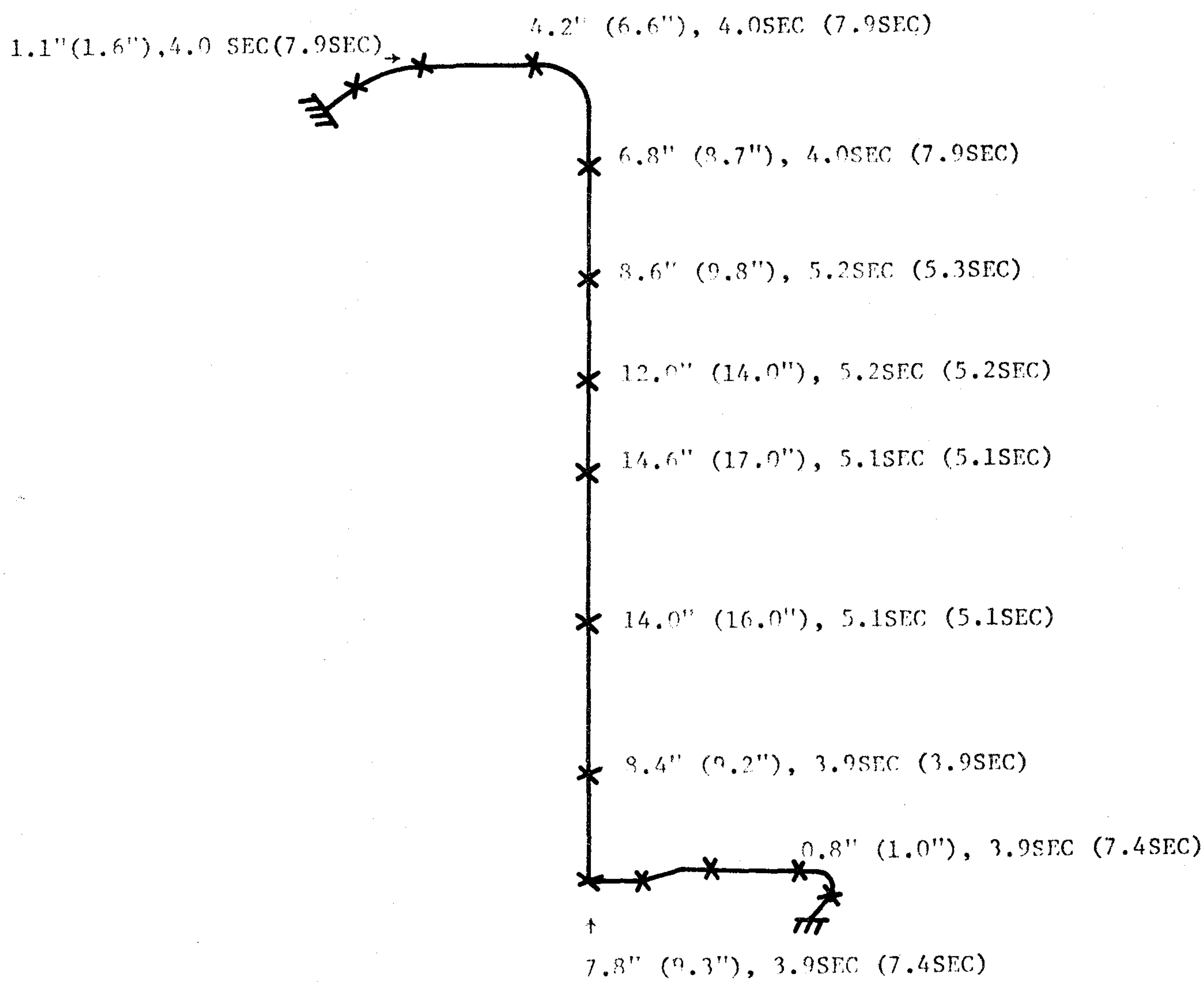

Fig. 2.7 Maximum damped (undamped) displacements in x-direction and times of occurance

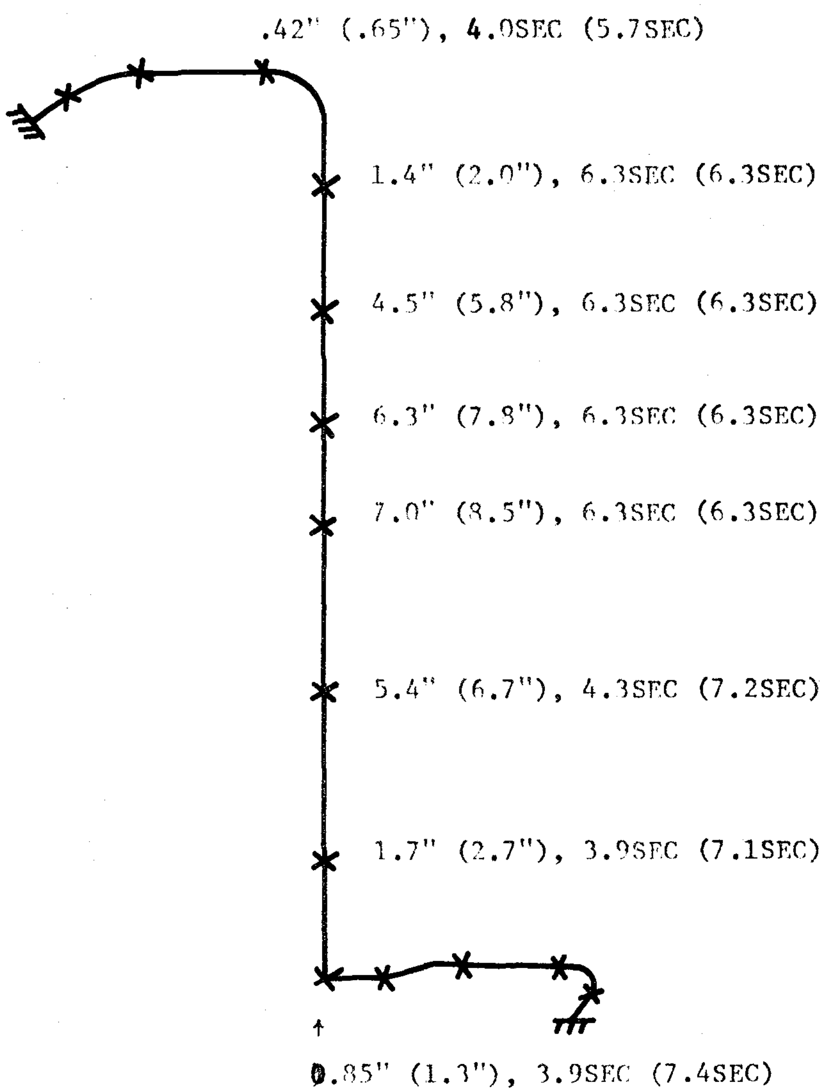

Fig. 2.8 Maximum damped (undamped) displacements in y-direction and the times of occurance.

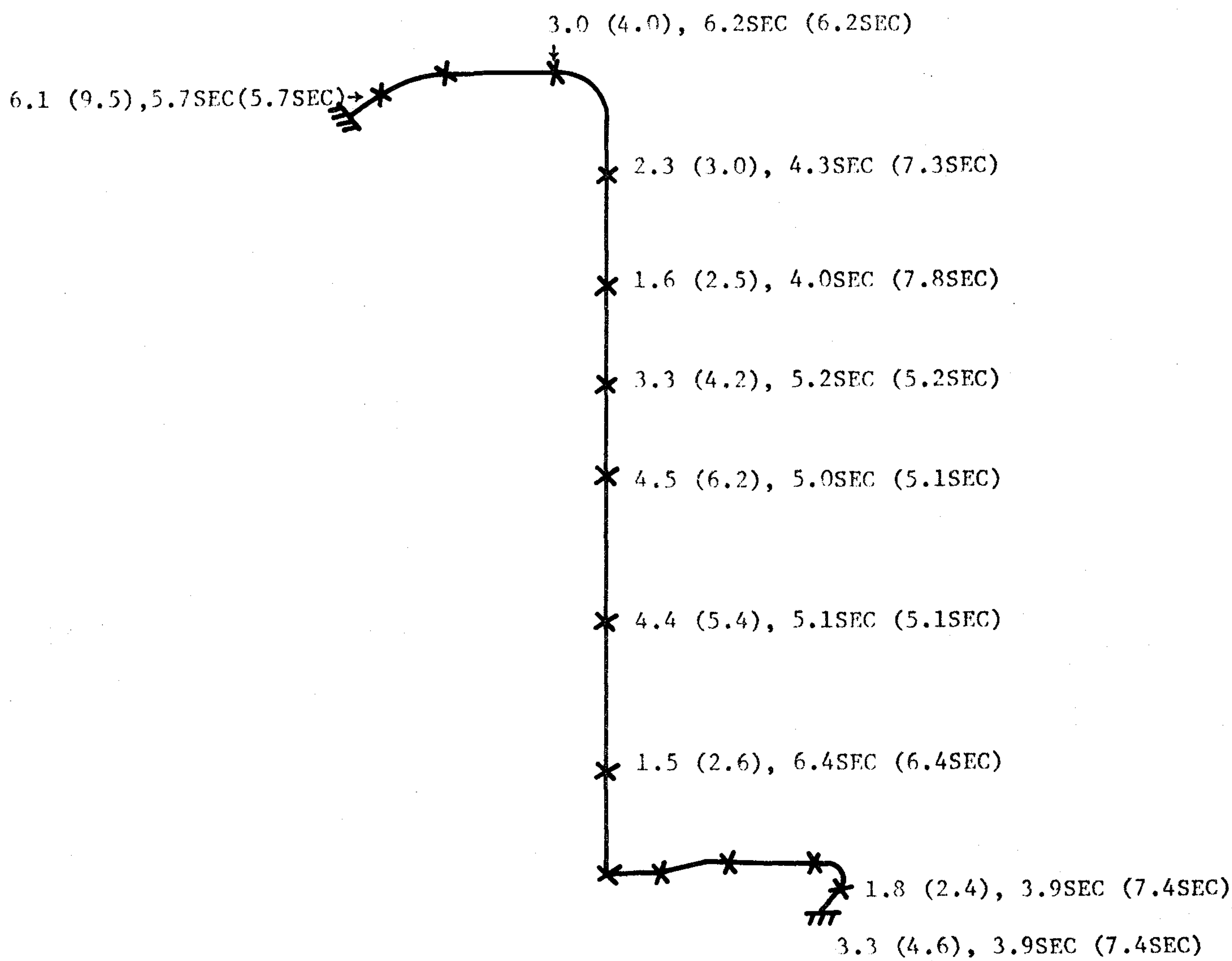

Fig. 2.9 Maximum damped (undamped) bending moments in million in-lb and the corresponding times of occurance.

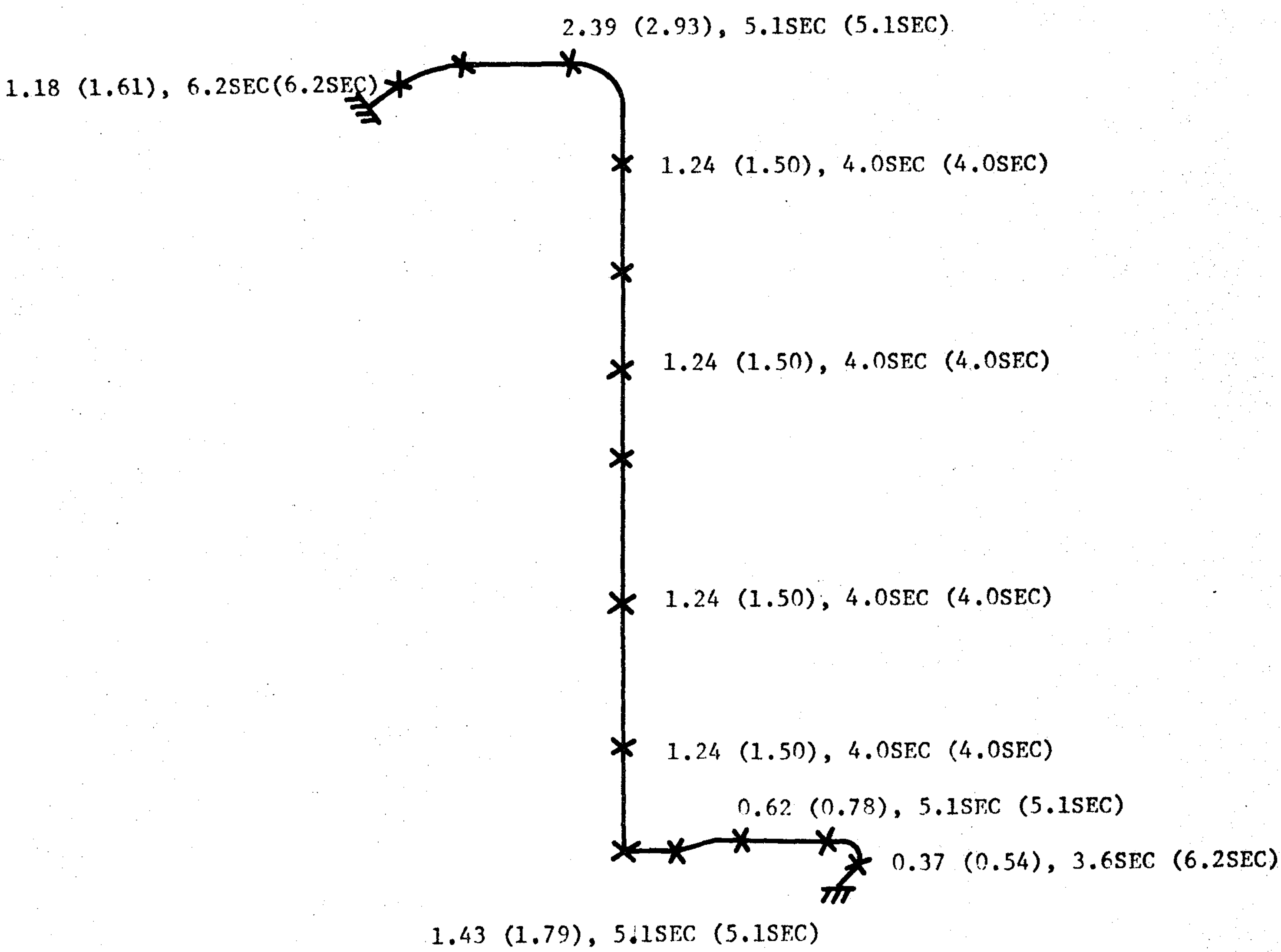

Fig. 2.10 Maximum damped (undamped) torques in million in-lb and times of occurance.

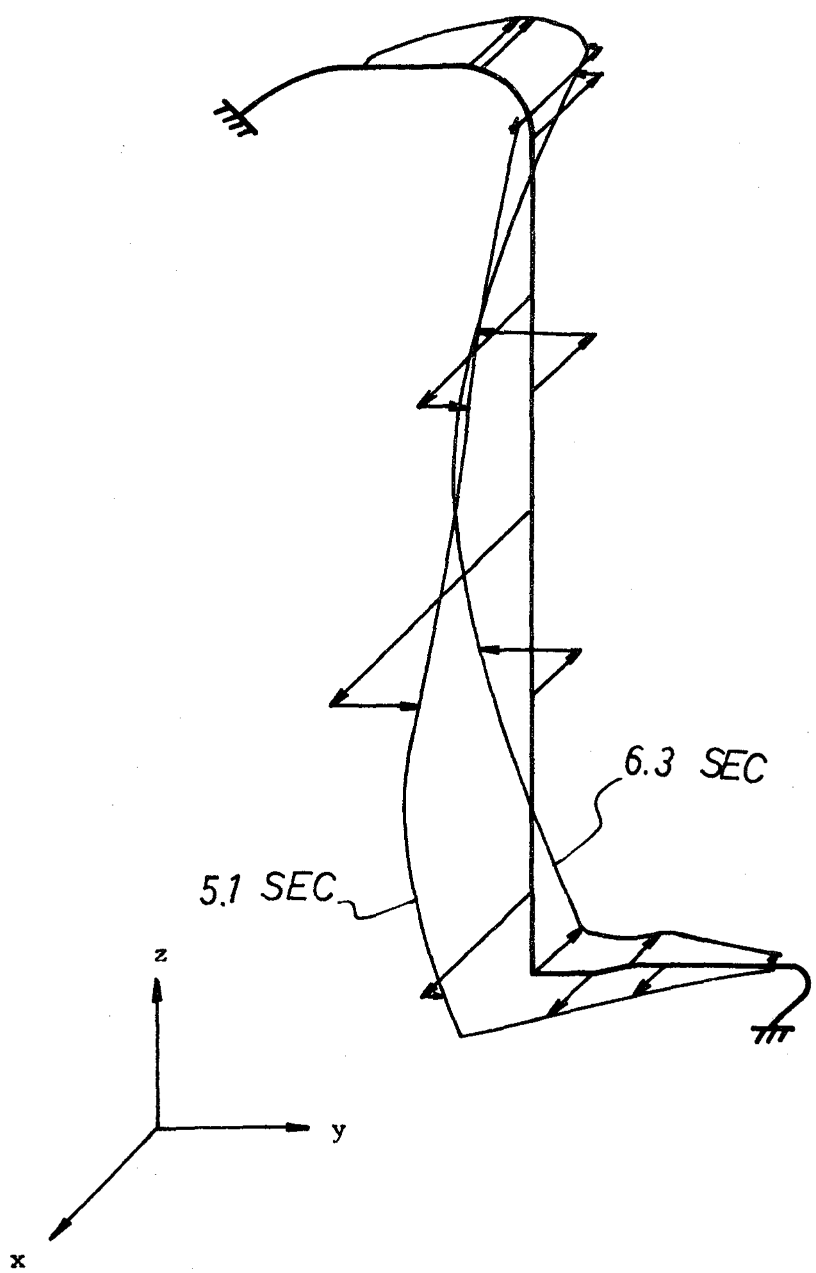

Fig. 2.11 Deformed configurations at t=5.1 and 6.3 seconds (with damping).

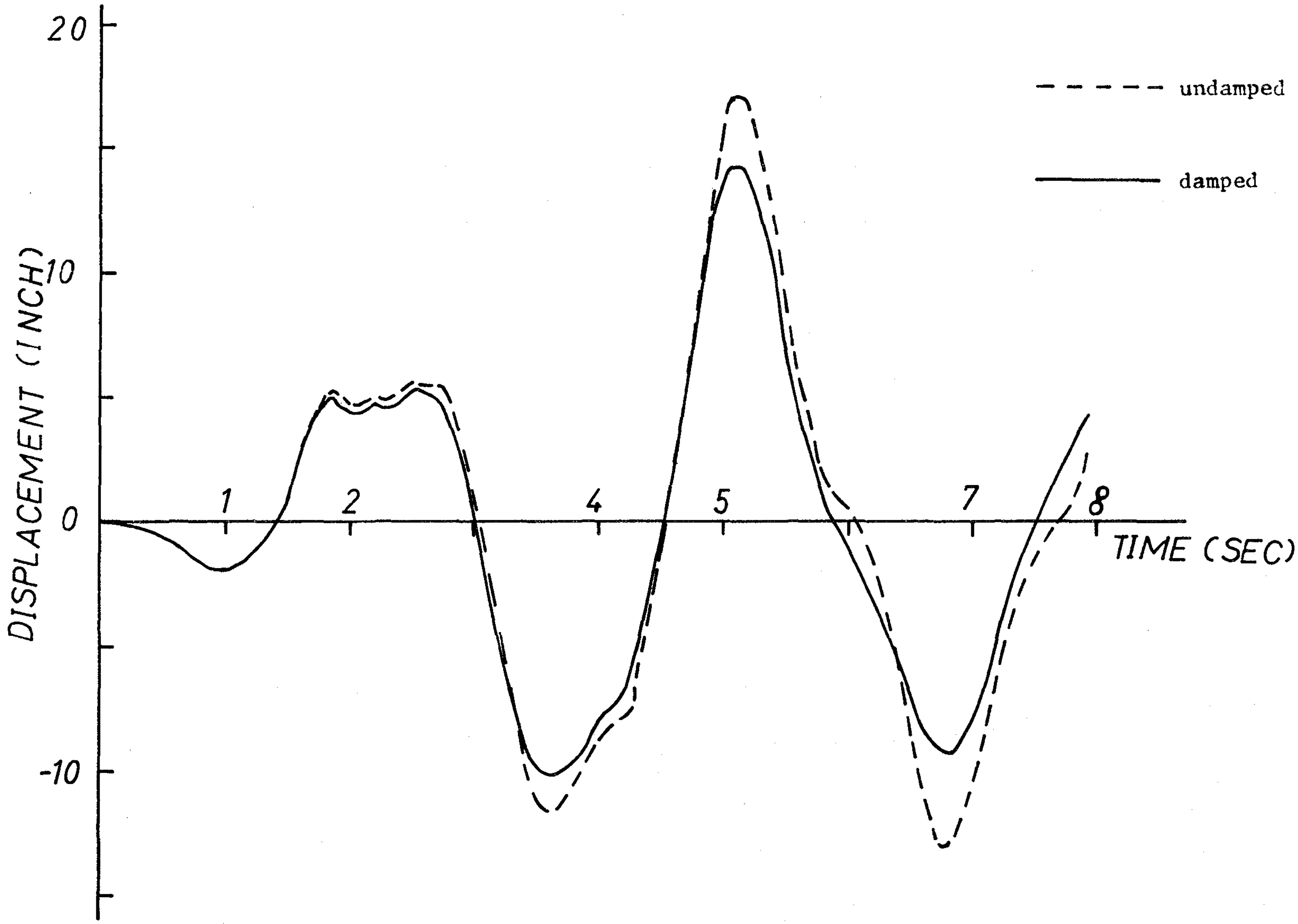

Fig. 2.12 Displacement in the x-direction at Point B (Fig. 2.1) as a function of time.

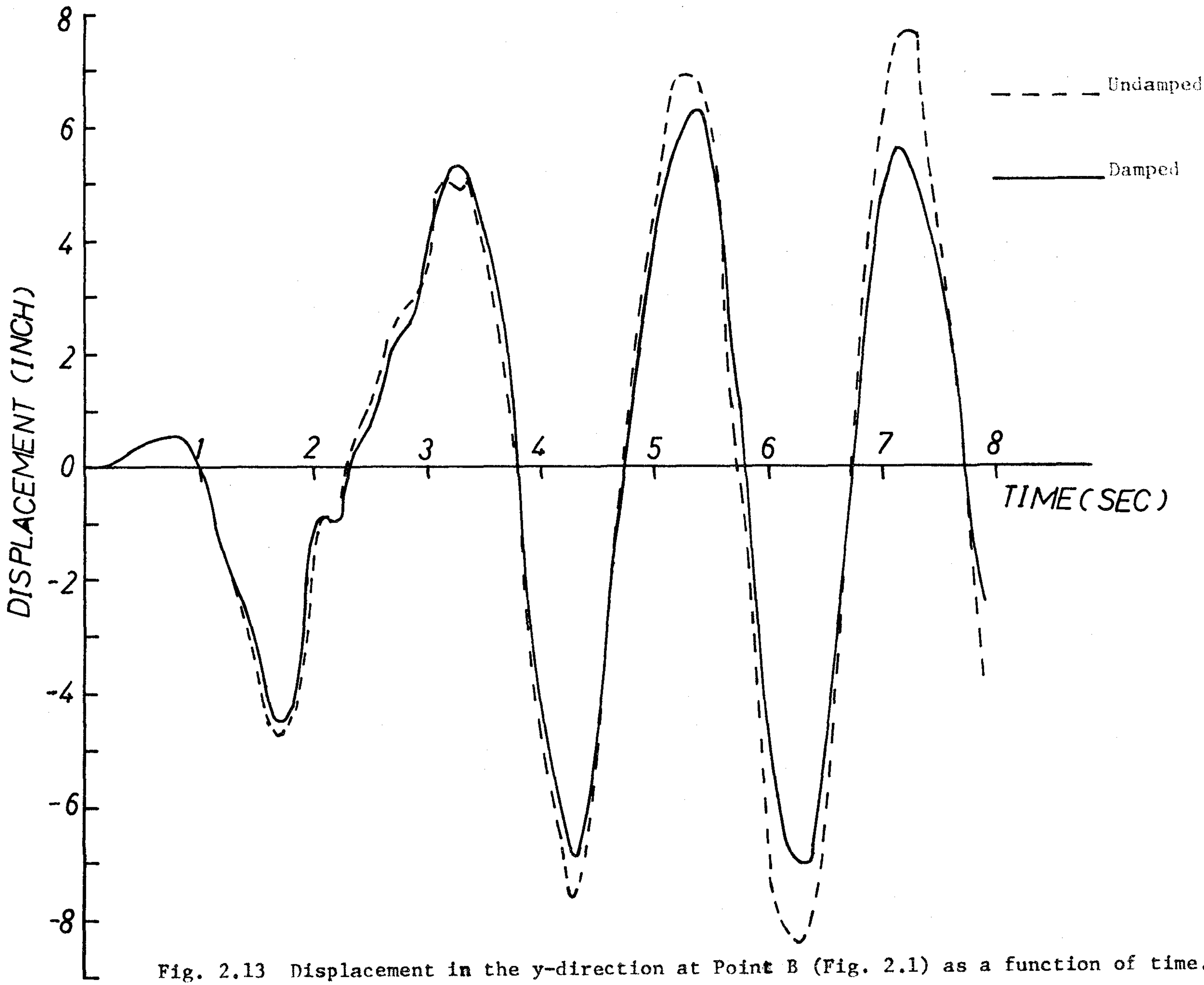

Fig. 2.13 Displacement in the y-direction at Point B (Fig. 2.1) as a function of time.

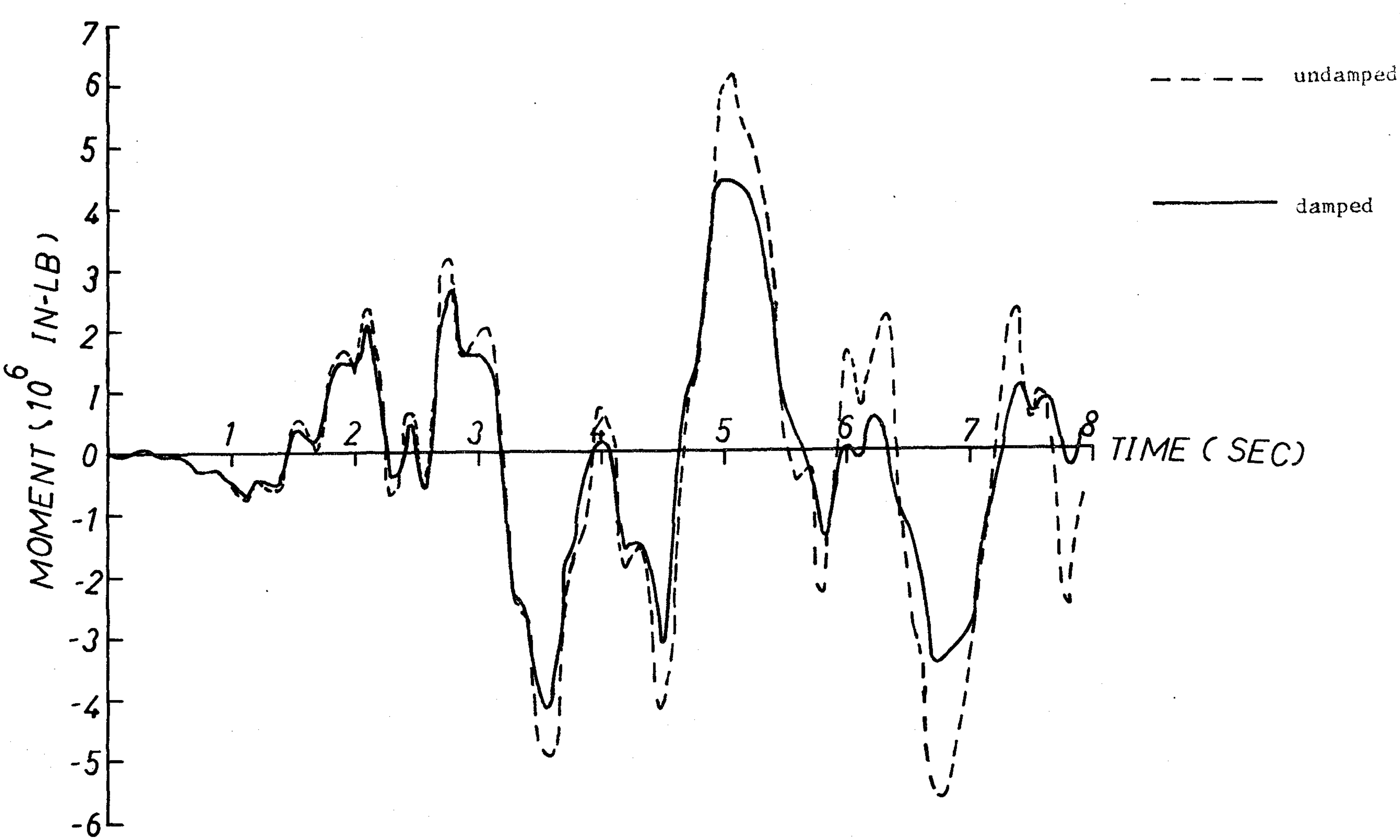

Fig. 2.14 Bending moment about the y-axis at Point B (Fig. 2.1) as a function of time.