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DYNAMIC BEHAVIOR OF THE STEAM GENERATOR AND SUPPORT STRUCTURES OF THE 1200 MW FOSSIL FUEL PLANT, Unit #3, PARADISE, KENTUCKY

Prepared by

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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 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. In this volume, the steam generator and the supporting structures of a 1200 mw fossil plant are studied by using a 2715 degree-of-freedom finite element model. Fundamental frequencies and modes are found first for various versions of the subsystem. Three frequencies and modes are then found for the total system. The mode shapes are presented in 3-D view.

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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.

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Abstract

The steam generator and the supporting structures of a 1200 MW fossil plant are studied by using a 2715 degree-of-freedom finite element model. The steam generator is modeled by 60 lumped masses connected by rigid bars. The hanger rods and the horizontal ties that support the steam generator are modeled by elastic truss bar finite elements. The two concrete floors are modeled by plate finite elements. The framing and bracing members are modeled by 3-D beam finite elements.

Fundamental frequencies and modes are first found for various versions of the subsystem to develop confidence in the computer program and to check the validity of the results in terms of consistency. Three frequencies and modes are then found for the total system. The mode shapes are presented in 3-D view, elevation view as well as plan view for both the steam generator and its supporting structure. The motions of side-sway and torsion are found to be coupled even in the first mode. This finding indicates that in dynamic analysis the 3-D model is needed.

Introduction

Literature on the study of natural frequencies and corresponding normal modes for large fossil fuel steam generator and its supporting structures is sparse. Because of the complexity involved in the system, computations have only been made for extremely simplified models. Typical of what is available is referenced in [1-3]. In reference 1, three different kinds of plane models were used to analyze two steam generator systems. The three plane models include a Rahmen structure model, a truss model, and a shear type frame model. In reference 2, a 600 MW steam generator and the supporting frame was studied by using a simple plane model. The model consisted of a plane portal frame and a 10-lumped mass steam generator. The portal frame included 22 lumped masses, 22 vertical shear members, and 3 horizontal flexural members. The steam generator was connected to the portal frame by 3 horizontal ties and 2 hanger rods. In reference 3, a three-dimensional simple model analysis was attempted for a 1000 MW steam generator and its supporting structure. The system was modeled by a simple 3-D rectangular box frame model supporting a 32-lumped mass steam generator model. The box frame model consisted only four vertical plane frames at the four sides. Thus far, no dynamic analysis has been made for the steam generator and its supporting structures by using a realistic three-dimensional complex modeling.

In this report, the free vibration behavior of the 1200 MW steam generator and its supporting structure of the TVA power plant Unit #3 at Paradise, Kentucky is studied by a realistic and complex three-dimensional modeling. The steam generator is modeled by 48 lumped masses interconnected by rigid bars. The supporting structures are modeled by 1782 3-D beam finite elements for the beams, columns, and bracing members and by 72 plate finite elements for the two concrete floors. The total modeling results in 2715 degrees-of-freedom. The steam generator model is connected to the frame model by 4 equivalent vertical hanger rods and 11 horizontal ties. To date, no one has made a study of the natural frequencies and corresponding normal modes for a steam generator system with such complex and realistic modeling.

Because of the complexity of the structure and because no prior computations have been made, a number of modelings for various subsystems have been developed and analyzed prior to the analysis of the total system. The purpose of doing this has been to develop confidence in the computer program's capability and the techniques used to achieve complex modelings. The various models of sybsystem are constructed by adding or neglecting the stiffnesses and masses of certain portions of the total system. The fundamental natural frequencies and normal modes have been computed for these subsystems. The results show that the effects due to adding or neglecting certain portions of the stiffnesses and masses are consistent among the various models of subsystem.

After the computation and evaluation of results for the subsystems have been performed, the total system is considered. Due to the enormous computing time required in the extraction of eigenvalues by subspace iteration, only three natural frequencies and corresponding normal mode shapes have been obtained. The present results have, however, not been fully converged in iteration simply because each cycle requires approximately two hours of CDC 6500 central processing time. It is conservatively estimated that the values for the first two frequencies should not vary by more than 20% if full convergence is achieved.

The mode shapes are presented for the steam generator and the supporting frames in three-dimensional view, elevation view, and plan view. It is found that noticeable torsional motions are present even in the first mode. The previous simple plane models could not account for such motions.

Description of the System

The steam generator is described by a vertical plane view in Fig. 1. It is also described by a rough three-dimensional sketch (without the air heater) in Fig. 2. The walls are composed of closely spaced tubes for carrying the circulating water. The walls are held in place horizontally by steel beams called buckstays. The steam generator is hung at the top by 220 steel rods which are connected to the deep plate girders on top of the supporting structure. Such hanging system allows the steam generator to expand downward when subjected to the operating temperature. The steam generator is also supported horizontally by ties at the corners as shown in Fig. 2. Each tie is made of a pair of bars which connect the buckstay to the supporting column with pinned conditions at both ends. In the event of earthquake or other disturbances, the ties transmit the lateral inertia force from the steam generator to the supporting structure.

The steam generator weighs approximately 24,000 kips. The distribution of weight for various components is listed in Table 1.

The air heater as shown in Fig. 1 is connected to the steam generator by an expansion joint which provides little bending or torsional rigidity. The air heater weighs approximately 15% of the steam generator. The supporting columns for the air heater rest on the concrete foundation with no rotational or torsional restraint. The air heater is stabilized from rocking motion by horizontal tie rods connected to the steel columns.

The steel framing structure is described in Fig. 3 by a three-dimensional sketch marked with overall dimensions. It is an all steel structure except at the planes at 42 feet and 169 feet above ground. At the two levels there are 5 and 4 concrete slabs, respectively, with 8 inches thickness. The structure has a total of 1412 major beam and column members and 370 cross bracing members. All the cross bracing members are in the vertical frames. The stiffening of the horizontal frames is accomplished by closely spaced beams parallel to the major

Table 1 Weight distribution of the structural components in the steam generator

No.	Structural Component	Weight (Kips)
1	Furnace Front Wall	1,400
2	Furnace Rear Wall	1,130
3	Furnace Side Walls (2)	820
4	Front Wind Box	1,400
5	Rear Wind Box	1,370
6	Pendant Side Walls (2)	164
7	Furnace Floor	1,400
8	Horizontal Convection Pass Side Walls (2)	330
9	Convection Pass Rear Wall	380
10	Convection Pass Front Wall	295
11	Risers	270
12	Economiser Enclosure	470
13	Pendant Floor	376
14	Secondary Super Heater	2,920
15	Furnace Roof	710
16	Pent-House	650
17	Pendant Reheat	1,154
18	Horizontal Reheater	1,400
19	Primary Super Heater	1,430
20	Economiser	3,400
21	Roof Outlet	250
22	Economiser Stringers	515
23	Supply Tubes	12
24	Secondary Super Heater Outlet	258
25	Primary Outlet	380
26	Secondary Super Heater Inlet	880
27	Economiser Inlet	340

ΣWeight 24,104 (Kips)

girders with quite rigid end connections. There are 611 joints among which 66 are at the base. The largest girders are at the top of the frame hanging the steam generator. Such plate girders have flanges of 30 x 4 $in.^2$ and are 20 feet deep. The heaviest columns are at the lower level built with 14 WF 730 wide flanges with two cover plates of 32 x 4 $\frac{3}{4}$ $in.^2$ The total weight of the whole steel framing structure is over 13,000 kips which is approximately 50% of the combined weight of the steam generator and the air heater.

There are 23 coal silos extended from the levels of 101 to 175 feet. When the silos are filled with coal, the weight could be 6000 tons.

Finite Elements

Two types of finite element are used. One type is the three-dimensional beam finite element with three displacement and three rotational degrees of freedom at each nodal point. The truss bar finite element, without the rotational degrees of freedom at the nodes, is a special case of the beam element. The other type is a three-dimensional quadrilateral plate finite element.

i The three-dimensional beam finite element

The three-dimensional beam finite element is described in Fig. 4. The element is assumed to have six degrees of freedom at each nodal point: three displacements $\bar{u}$, $\bar{v}$, and $\bar{w}$ in the local $\bar{x}$, $\bar{y}$, and $\bar{z}$ directions, respectively; and three rotations $\theta_{\bar{x}}$, $\theta_{\bar{y}}$, and $\theta_{\bar{z}}$ about $\bar{x}$, $\bar{y}$, and $\bar{z}$, respectively. Corresponding to the six nodal degrees of freedom, there are three forces $F_{\bar{x}}$, $F_{\bar{y}}$, $F_{\bar{z}}$, one twisting moment $M_{\bar{x}}$, and two bending moments $M_{\bar{y}}$, $M_{\bar{z}}$, respectively.

The element formulation is derived in the form that the 12 nodal forces are related to the 12 nodal displacements (in local coordinates) by the stiffness and mass matrices.

$$\underset{12x1}{\{\bar{F}\}} = \underset{12x12}{[\bar{k}]} \underset{12x1}{\{\bar{q}\}} - \omega^2 \underset{12x12}{[\bar{m}]} \underset{12x1}{\{\bar{q}\}} \tag{1}$$

where the stiffness matrix is shown in Table 2. In Table 2, the terms EA, EI, and GJ are defined as the axial, bending, and torsional rigidities, respectively and L is the length of the element. The stiffness matrix can be derived either by the stress-strain equilibrium method or by the minimum strain energy method. The mass matrix $[\bar{m}]$ is formulated on the basis of lumped masses. The rotatory inertia is neglected. There are only six nonzero terms on the diagonal of the mass matrix, which correspond to the $\bar{u}$, $\bar{v}$, $\bar{w}$ displacements at both nodal points. These terms are all in the same form of $\rho AL/2$ which is half of the mass of the finite element.

Before the assemblage of each individual element, the equations of motion (1) for each element must be transformed from the local coordinates ($\bar{x}$, $\bar{y}$, $\bar{z}$) to the global coordinates (x, y, z) by using the nine direction cosines defined as follows.

$$\begin{cases} \lambda_i = \cos\theta_{xi} \\ \mu_i = \cos\theta_{yi} \\ \nu_i = \cos\theta_{zi} \end{cases} \qquad i = \bar{x}, \bar{y}, \text{ and } \bar{z} \tag{2}$$

The equations of motion with reference to the global coordinates are in the form

Table 2 The stiffness matrix $[\bar{k}]$ for a local 3-D beam finite element

$\frac{AE}{L}$											
0	$\frac{12EI_{\bar{y}}}{L^3}$										
0	0	$\frac{12EI_{\bar{z}}}{L^3}$									
0	0	0	$\frac{GJ}{L}$								
0	$-\frac{6EI_{\bar{y}}}{L^2}$	0	0	$\frac{4EI_{\bar{y}}}{L}$							
0	0	$\frac{6EI_{\bar{z}}}{L^2}$	0	0	$\frac{4EI_{\bar{z}}}{L}$						
$-\frac{AE}{L}$	0	0	0	0	0	$\frac{AE}{L}$					
0	$-\frac{12EI_{\bar{y}}}{L^3}$	0	0	$\frac{6EI_{\bar{y}}}{L^2}$	0	0	$\frac{12EI_{\bar{y}}}{L^3}$				
0	0	$-\frac{12EI_{\bar{z}}}{L^3}$	0	0	$-\frac{6EI_{\bar{z}}}{L^2}$	0	0	$\frac{12EI_{\bar{z}}}{L^3}$			
0	0	0	$-\frac{GJ}{L}$	0	0	0	0	0	$\frac{GJ}{L}$		
0	$-\frac{6EI_{\bar{y}}}{L^2}$	0	0	$\frac{2EI_{\bar{y}}}{L}$	0	0	$\frac{6EI_{\bar{y}}}{L^2}$	0	0	$\frac{4EI_{\bar{y}}}{L}$	
0	0	$\frac{6EI_{\bar{z}}}{L^2}$	0	0	$\frac{2EI_{\bar{z}}}{L}$	0	0	$-\frac{6EI_{\bar{z}}}{L^2}$	0	0	$\frac{4EI_{\bar{z}}}{L}$

$$\underset{12\times1}{\{F\}} = \underset{12\times12}{[T]^T} \left[\underset{12\times12}{[\bar{k}]} - \omega^2 \underset{12\times12}{[\bar{m}]} \right] \underset{12\times12}{[T]} \underset{12\times1}{\{q\}} \tag{3}$$

where the coordinate transformation matrix is defined as

$$[T] = \begin{bmatrix} \Lambda & & & \\ & \Lambda & & \\ & & \Lambda & \\ & & & \Lambda \end{bmatrix} \tag{4}$$

with

$$[\Lambda] = \begin{bmatrix} \lambda_{\bar{x}} & \mu_{\bar{x}} & \nu_{\bar{x}} \\ \lambda_{\bar{y}} & \mu_{\bar{y}} & \nu_{\bar{y}} \\ \lambda_{\bar{z}} & \mu_{\bar{z}} & \nu_{\bar{z}} \end{bmatrix} \tag{5}$$

In the assemblage of such finite elements, the hinged joint conditions can be achieved by neglecting the compatibility requirement for the three rotational degrees of freedom. This is done by eliminating such unwanted degrees of freedom at the element level.

Since the stiffness and mass matrices are in the form of band matrix, only the bands are stored in the computer for the calculation of frequencies and mode shapes. The bands are stored in blocks and are solved by a subspace iterative procedure. A careful numbering of the joints of the structural model can minimize the bandwidth and result in saving computing time. For the 12 degree of freedom element, the bandwidth is calculated by the formula

$$\text{Bandwidth} = 2(6n + 5) + 1 \tag{6}$$

where n is the maximum numerical difference between any pair of connected nodal point numbers.

ii Quadrilateral plate finite element

The quadrilateral plate finite elements are used to model the two concrete floors. The element has five degrees of freedom at each of the four corner nodal points: three displacement degrees of freedom in the three Cartesian local coordinate directions, respectively; and two slope degrees of freedom about the two orthogonal axes in the plane of the plate. For reasons of computational efficiency, the quadrilateral element is composed of four triangular plate elements. The four triangles share a common central nodal point with the averaged coordinates of the four corner nodal points. The five degrees of freedom at this central nodal point are eliminated at the element level prior to the assemblage. Thus the quadrilateral element effectively has a total of 20 degrees of freedom, five per nodal point.

The membrane stiffness of each sub-triangular element is based on the constant strain assumption with linear inplane displacement functions [4]. The bending stiffness of each sub-triangular element is represented by the fully compatible HCT element based on the lateral deflection function that varies cubically with the inplane coordinates [5]. The mass matrix for the element is formulated on the basis of lumped masses.

iii Treatment of boundary conditions by springs

Springs are used to treat the joints that are elastically restrained from displacement or rotation. Such springs can be either extensional or rotational and can be oriented in any specified direction. By assigning infinite values to the springs, the conditions with zero displacements and rotations can be achieved.

The Modeling

(1) The modeling of the steam generator

Based on the distribution of weight given in Table 1, the steam generator is modeled by 60 lumped masses. This model is described graphically in Fig. 5 and numerically in Table 3. The magnitude and location of each mass are decided on the basis of the distribution of the weight and the consideration of the bandwidth in the resulting matrices for the entire system of both the steam generator and the supporting structure.

Although the steam generator is not a rigid body, its stiffness may have little or no effect on the gross dynamic behavior of the total system of both the steam generator and the supporting structure. This assumption is especially true in the present case where the ties that connect the steam generator to the frames are less stiff than the steam generator itself. Based on this reasoning, the lumped masses in the present model are connected by rigid bars. The dynamic behavior of the steam generator itself can, however, be predicted if its stiffnesses are accounted for. Such behavior is not of primary interest in this study.

(2) The modeling of the supporting structures

The detail designs of the supporting structures involve enormous amount of engineering drawings. It is difficult to visualize the total structure based on so many separate drawings. It is also difficult to prepare input data for the finite element modeling based on these drawings. To circumvent such difficulties, a small model is built with balsa wood

Table 1 Lumped mass modeling for the steam generator.

Mass No.	x-ordinate Measured from 23 line	y-ordinate Measured from gv line	z-ordinate Measured from EL0.0	Weight kips
1	106.00'	0.00	422.0	806.0
2	10.34'	0.00	422.0	806.0
3	106.00'	54.00	422.0	806.0
4	10.34'	54.00	422.0	806.0
5	106.00'	0.00	461.5	529.0
6	10.34'	0.00	461.5	529.0
7	106.00'	54.00	461.5	529.0
8	10.34'	54.00	461.5	529.0
9	106.00'	10.45	494.0	106.0
10	10.34'	10.45	494.0	106.0
11	106.00'	43.55	494.0	106.0
12	10.34'	43.55	494.0	106.0
13	106.00'	10.45	512.0	134.0
14	10.34'	10.45	512.0	134.0
15	106.00'	43.55	512.0	134.0
16	10.34'	43.55	512.0	134.0
17	106.00'	10.45	535.0	198.0
18	10.34'	10.45	535.0	198.0
19	106.00'	43.55	535.0	374.8
20	10.34'	43.55	535.0	374.8
21	106.00'	10.45	568.5	122.5
22	10.34'	10.45	568.5	122.5
23	106.00'	43.55	568.5	522.5
24	10.34'	43.55	568.5	522.5
25	106.00'	10.45	582.0	319.3
26	10.34'	10.45	582.0	319.3
27	106.00'	43.55	582.0	1178.1
28	10.34'	43.55	582.0	1178.1
29	106.00'	79.65	582.0	1209.6
30	10.34'	79.65	582.0	1209.6
31	106.00'	79.65	553.0	1127.8
32	10.34'	79.65	553.0	1127.8
33	106.00'	79.65	535.0	413.1
34	10.34'	79.65	535.0	413.1
35	106.00'	79.65	505.0	1042.1
36	10.34'	79.65	505.0	1042.1
37	106.00'	91.96	481.6	46.4
38	10.34'	91.96	481.6	46.4
39	106.00'	121.67	481.6	46.4
40	10.34'	121.67	481.6	46.4
41	106.00'	121.67	505.0	1042.1
42	10.34'	121.67	505.0	1042.1
43	106.00'	111.15	535.0	964.1
44	10.34'	111.15	535.0	964.1
45	106.00'	111.15	568.5	33.55
46	10.34'	111.15	568.5	33.55
47	106.00'	111.15	582.0	315.3
48	10.34'	111.15	582.0	315.3

Total Weights = 24,211.30 Kips

members with a scaling factor of 1/64. The overall dimensions of the model is of 5 x 3.27 square feet in base area and 3.72 feet high. A photograph of the model is shown in Fig. 6. Each member in the model is labeled with its dimensions and weight per unit longitudinal length.

The finite element model is completely based on the balsa wood model. The nodal points are numbered from the base area upward. By doing so, the total number of resulting equations is 2715 and the bandwidth is 945. The balsa wood model not only helps for the preparation and check of input data, it also helps for interpreting the output data.

(3) <u>The connections between the steam generator model and the supporting structure model</u>

The steam generator model is hung at the top by 12 elastic hanger rods whose stiffnesses and masses are equivalent to those for the 220 actual hanger rods. These hanger rods are connected with hinged conditions to the girders at the top of the frame model.

The vertical corner edges of the steam generator model are connected to the columns of the frame model by 11 elastic ties. The locations of these ties are shown in Fig. 2. All ties have hinged end conditions.

Basic Assumptions

(1) The bases of the outside columns (far from the steam generator) were designed by using heavy anchor bolts to produce full capacity to resist bending moment. The bases of the inside columns were not designed to resist bending moment. The inside columns are under high initial compressive forces resulted from the dead weights of the steam generator and the steel frames. When the system is subjected to the overturning

moment due to earthquake disturbances, the inside columns are subjected to lesser axial forces than the outside ones. Thus the initial compressions in inside columns are likely to be higher than the tensions produced by the overturning moment. It is felt that for these columns, the base conditions are closer to the fixed case than the hinged case. For this reasoning, all the column bases are assumed to be fixed. It is noted that the concrete footings and the base floor-slabs are buried in the excavated limestone rock foundation.

(2) When a frame structure is full of cross bracing members such as the one shown in Ref. 1, the results of frequencies appear to be almost independent of joint conditions, either rigid or hinged. However, the present frame has 1412 beam and column members, 370 vertical cross bracing members, and 2 concrete floors. Examination of designs for connections found that all joints do generally provide sufficiently long resisting moment arms among bolts. All the joints are thus assumed as rigid in this study. This assumption provides a stiffer structure than the hinged assumption. It also results in twice the number of d.o.f.'s.

(3) The steam generator can vibrate in two possible modes: a pendulum type swaying mode and a breathing type mode. The latter mode is not of primary interest in this study. Thus all the masses in the steam generator model are assumed to be connected by rigid bars.

Results

The present system is notoriously complex and no previous computations on the natural frequencies have been made for the similar system without severe simplifications. It appears that some analyses of the subsystems are needed before the total system is considered. Such preliminary subsystem analyses are important for the following reasons. By carefully selecting and neglecting certain portions of the total system, the effects of those portions on the dynamic behaviors can be studied and the consistency among various sets of results can be checked. Such analyses not only provide with the insights to the problem but also the confidence on the computer program used.

Four subsystems, all related to the central portions of the system, had been analyzed before the total system was studied.

(1) <u>The central structure without both the steam generator and the bracing members</u>

The central portion of the supporting frame structure as shown in Fig. 7 was first analyzed. The steam generator and the cross bracing members were neglected. This structure has 434 joints and 865 beam and column members. Among the 434 joints, 36 are at the base. This results in a total of 1968 equations. The way that the joints are numbered results in a matrix bandwidth of 426.

The first mode frequency was found to be 0.4299 Hz. The corresponding normal mode shape plotted in a three-dimensional view for the outside members is shown in Fig. 8. Because of the unsymmetrical arrangement of the members within the structure, the mode shape is seen to be a combination of strong side-swaying motion and slight torsional motion. The eigenvector output shows that the vertical displacements of all the joints are two-order of magnitude smaller than the horizontal displacements. Such degrees of freedom could have been suppressed in the analysis of the first few modes.

The central processing time for the CDC 6500 computer was 50 minutes.

However, the transference of the enormous amount of input and output units between core and tapes required about eight hours.

(2) The central structure without the steam generator but with the bracing members

There are a total of 147 cross bracing members in the central portion of the structure. They are all in the vertical planes. The bracing members have been known to have stiffening effect on the frame structure. They were included in the free vibration analyses of the central structure.

The fundamental natural frequency for this subsystem was found to be 0.5517 Hz. The bracing members are seen to stiffen the structure and increase the fundamental frequency by 28%. The corresponding normal mode shape in a three dimensional view is shown in Fig. 9. Because the arrangement of the cross bracing members is quite irregular and non-symmetrical, the torsional motion is more pronounced than that seen in the previous case. The computation for this case took virtually the same amount of time as the previous case.

(3) The central structure with the steam generator but without the bracing members

The steam generator, without including the air heater, has a total weight of 24,000 kips. The central structure without bracing members has a total weight of 7400 kips. When the two subsystems are combined, the natural frequencies should be considerably less than those for the central structure alone.

The fundamental natural frequency was found to be 0.1556 Hz as compared with the 0.4299 Hz found for the central structure without the steam generator. A 64% drop in fundamental frequency is seen. The corresponding normal mode shape is shown in Fig. 10. The mode is seen to be predominantly in side-swaying motion with unnoticeable torsional motion. The swaying motion of the steam generator, which is symmetrical about one vertical plane, apparently overrides the slight torsional motion of the central structure.

Since the fundamental mode for this case contains only side-swaying motion with no torsional motion, the second mode was also found and shown in Fig. 11. The second mode shows a side-swaying motion in the direction perpendicular to that of the first mode. Again no torsional motion is seen. The second mode frequency was found as 0.1987 Hz which is 28% higher than the first mode frequency.

It is noted that this subsystem is quite similar to (but with considerably more complexity in modeling) the simple three-dimensional box model used by Suehiro [3] for the analysis of a 1000 MW steam generator structure. The first two normal modes found here agree well with the first two mode shapes found by Suehiro.

The system has a total of 2328 equations with a bandwidth of 474. The CDC 6500 central processing time was 96 minutes for the first mode and 104 minutes for both the first and the second modes.

(4) <u>The central structure with both the steam generator and the bracing member</u>

With the inclusion of the 147 cross bracing members, the central frame structure is expected to be stiffer. The fundamental mode natural frequency is found to be 0.2060 Hz which is 32% higher than the structure without the bracings. The corresponding normal mode shape for the frame structure in a three dimensional view is shown in Fig. 12. A predominant side-swaying motion is seen. The corresponding normal mode shape for the steam generator is shown in Fig. 13. It is noted that the rigid-body translational motion in the direction of the frame motion is not shown. Only the pendulum type swining motion, which is in the same direction as the frame motion, is shown.

The CDC 6500 central processing time used was 101 minutes.

A summary of the results for the first natural frequencies for the four subsystems is given in Table 4. The results are seen to be consistent among the four cases.

After confidence had been gained through computation and evaluation of the results for the four sybsystems, the total system was analyzed.

(5) The total system

The total system contains the steam generator model and the supporting structure model, as described in the section of modeling, plus the air heater which has 15% of the mass as the steam generator. The supporting structure contains 1412 beam and column elements, 370 cross bracing members, two concrete floors, and 611 joints. In the computation of the first few frequencies, the vertical displacement degrees of freedom were considered as small in comparison with the horizontal degrees of freedom and were thus neglected. Such assumption is customary and has been confirmed by the above computation of the first two frequencies for the central structure. Excluding the zero degrees of freedom of the 66 joints at the base and all the vertical degrees of freedom, the total system results in a set of 2715 equations. The present numbering sequence results in a bandwidth of 945.

Table 4 THE FIRST MODE FREQUENCIES FOR THE ANALYSES OF CENTRAL STRUCTURE

Subsystem Number	Steam Generator	147 Bracing Members	Number of Degrees of Freedom	Band Width	CDC 6500 CP Time (Minutes)	Frequency
1	No	No	1968	426	50	0.4299 Hz
2	No	Yes	1968	426	52	0.5517 Hz
3	Yes	No	2328	474	96	0.1556 Hz
4	Yes	Yes	2328	474	101	0.2060 Hz

So far, only three natural frequencies have been obtained. The coal silos were assumed as empty in the computation. The results are given in Table 5.

Table 5. The first three natural frequencies for the total system

Mode Number	Frequency (Hertz)	Frequency (rad./sec.)	Periods (seconds)
1	1.3127	8.2480	0.7618
2	2.1178	13.3065	0.4722
3	3.5964	22.5969	0.2781

Because of the enormous time involved in computing the eigenvalues by subspace iteration, the present eigenvalues were obtained without satisfying the convergence tolerance. Six iterative cycles were performed for computing the first natural frequency, two cycles for the second frequency, and only one cycle for the third. Each cycle of iteration took approximately 2 hours of central processing time by the CDC 6500 computer. Transference of the input and output units during one cycle of iteration took 26 hours of clock time. From the experience gained in computing the eigenvalues for the above-mentioned subsystems, it is believed that the values obtained for the present first two frequencies should not alter by 20% if full convergence is obtained.

The normal mode shapes for the supporting structure corresponding to the first natural frequency is shown in a three-dimensional view in Fig. 14. It is seen that the mode includes not only the side-swaying motions in both the south-north and the east-west directions, but also torsional motion. A top view of a horizontal cross-section at the elevation of 169 feet above ground vibrating in the first mode is shown in Fig. 15. This figure clearly describes the mixing of the two orthogonal side-swaying motions plus the torsional motion. Three lines Nz, 20, and 28 are marked in Fig. 15. The first mode motions for the vertical plane frames at the three sides Nz, 20, and 28 are shown in Figs. 16, 17, and 18, respectively. The three figures show that none of them is stationary and each vibrates in the "conventional" first mode.

The normal mode shapes for the steam generator corresponding to the first mode is shown in a three-dimensional view in Fig. 19. The horizontal rigid-body motion, parallel to the motion of the top girders of the supporting structure are not shown in Fig. 19. Only the pendulum type of swinging motions are shown. The torsional motion is seen to be quite pronounced. A top view of the motion of the horizontal cross-section at the top of the steam generator is shown in Fig. 20. Fig. 20 clearly describes the mixing of the translational and torsional modes. To give more description, a front view of the motion of the vertical wall of the steam generator along line AB is shown in Fig. 21 and a side view of the motion of the wall along line BC is shown in Fig. 22.

The normal mode shapes for the supporting structure corresponding to the second natural frequency is shown in a three-dimensional view in Fig. 23. The mode shape appears to be composed of the side-swaying motion in both the south-north and the east-west directions plus torsional motion. The difference between the first and the second modes is seen when comparing the motions of the two front vertical plane frames for the two modes as shown in Figs. 16 and 24, respectively. In Fig. 16, the plane frame vibrates in the first mode while in Fig. 24 the plane frame vibrates in the second mode. The motion of the vertical plane along line 20 on the side is shown in Fig. 25. The motion is virtually the same as that of the first mode in Fig. 17.

As regard to the steam generator, it vibrates in the second mode the similar way as that in the first mode. A top view of the second mode motion of the horizontal cross-section at the top of the steam generator is shown in Fig. 26. The mode is composed of translation motions in the two orthogonal directions plus the torsional motion. A side view of the second mode motion of the front vertical wall along line AB is shown in Fig. 27.

The normal mode shapes for the supporting structure corresponding to the third natural frequency is shown in a three-dimensional view in Fig. 28. Again, the mode is composed of the two orthogonal side-swaying motion plus the torsional motion. The motions of the vertical plane frames along the front line Nz and the side line 20 are shown in Figs. 29 and 30, respectively. It is seen that the inplane motion of the plane frame along the front line Nz as shown in Fig. 29 is in the first mode, the same as that shown in Fig. 16. However, the inplane motion of the plane frame along the side line 20 as shown in Fig. 30 is in the second mode, which is different from the ones shown in Figs. 17 and 25, respectively. The third mode motion of the steam generator is not obviously different from those in the first and second modes. It is not presented.

Concluding Remarks

The free vibrations of a 1200 MW steam generator and its supporting structures have been studied by the use of a three-dimensional complex model with 2715 degrees of freedom. It appears in the literature that no modeling in such degree of complexity has been attempted previously.

Fundamental frequencies and modes have first been found for four different versions of subsystems which include or exclude certain portions of the system. The consistency among results for various subsystems have been checked.

For the total system, three natural frequencies and corresponding normal mode shapes have been found. The three frequency values obtained have not been completely converged due to the enormous computing time required. The computation by a CDC 6500 computer took approximately a total of 12 hours for central processing.

It is customarily understood that for a symmetrical three-dimensional frame structure, the vibration modes are such that the structure sways in one direction in the first mode and sways in the orthogonal direction in the second mode, and so on. But this is not the case for the present complex structure. The present results show that the system sways in both orthogonal directions in the first mode. Furthermore, the torsional motion which cannot be accounted for by the plane model is present in the first mode. In the first mode, the steam generator moves with the top hanging girders and with some additional pendulum type swinging motion. Torsional motion is also observed.

The second and third modes are also composed of the two orthogonal swaying modes and the torsional mode. For the second mode, the front vertical plane frame vibrates in the first mode and the side vertical frame vibrates in the second mode.

This study has given some insights into the dynamic behavior of a complex steam generating structural system. The results have also given some guidelines and comparative basis for the development of the simple dynamic models which are needed in the power industry.

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Figure Captions

Fig. 1. An elevation view of the steam generator.

Fig. 2. A rough three-dimensional sketch of the steam generator and the 11 ties.

Fig. 3. A three-dimensional outside view of the steel framing structure.

Fig. 4. Description of a three-dimensional beam finite element.

Fig. 5. Lumped mass and rigid bar model for the steam generator.

Fig. 6. The photograph of the balsa wood model for the supporting frame structure.

Fig. 7. The central portion of the supporting structure for the initial analysis.

Fig. 8. The first mode shape of the central structure without both bracing members and the steam generator (frequency = 0.4299 Hz).

Fig. 9. The first mode shape of the central structure without the steam generator but with the bracing members (frequency = 0.5517 Hz).

Fig. 10. The first mode shape of the central structure with the steam generator but without the bracing members (frequency = 0.1556 Hz).

Fig. 11. The second mode shape of the central structure with the steam generator but without the bracing members (frequency = 0.1987 Hz).

Fig. 12. The first mode shape of the central structure with both the steam generator and the bracing members (frequency = 0.2060 Hz).

Fig. 13. The first mode shape of the steam generator supported by central structure with bracing members.

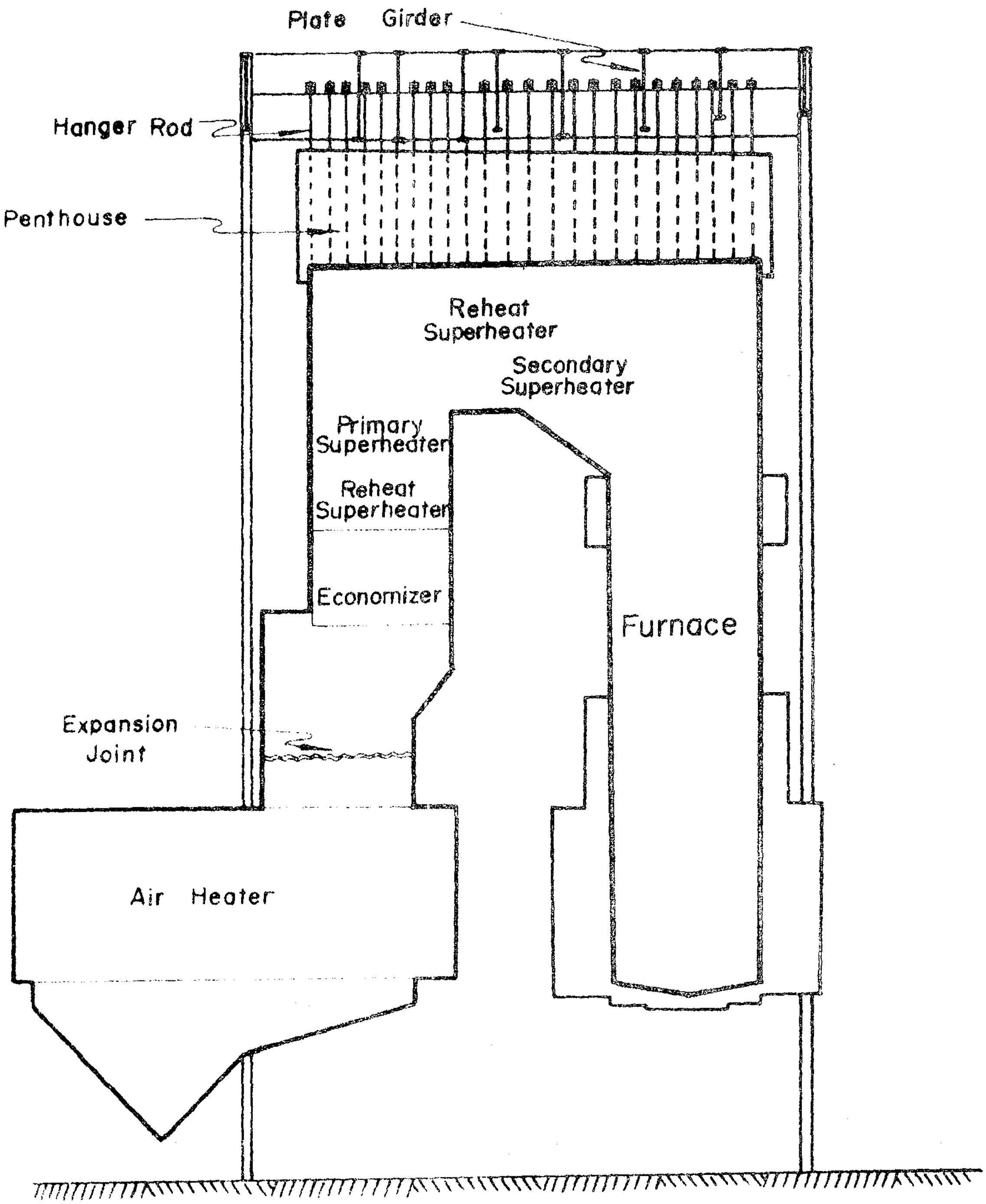

Fig. 1. An elevation view of the steam generator.

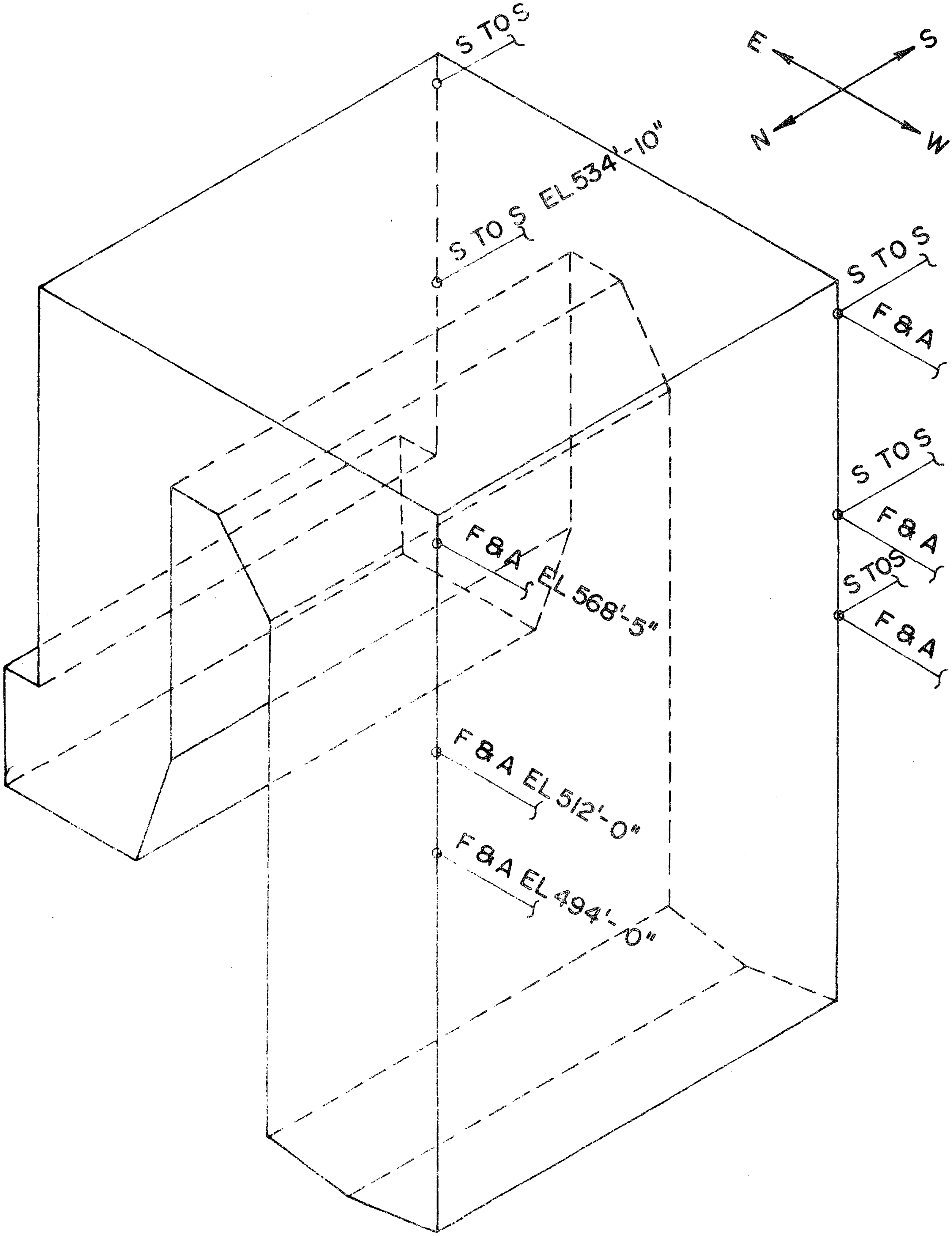

Fig. 2. A rough three-dimensional sketch of the steam generator and the 11 ties.

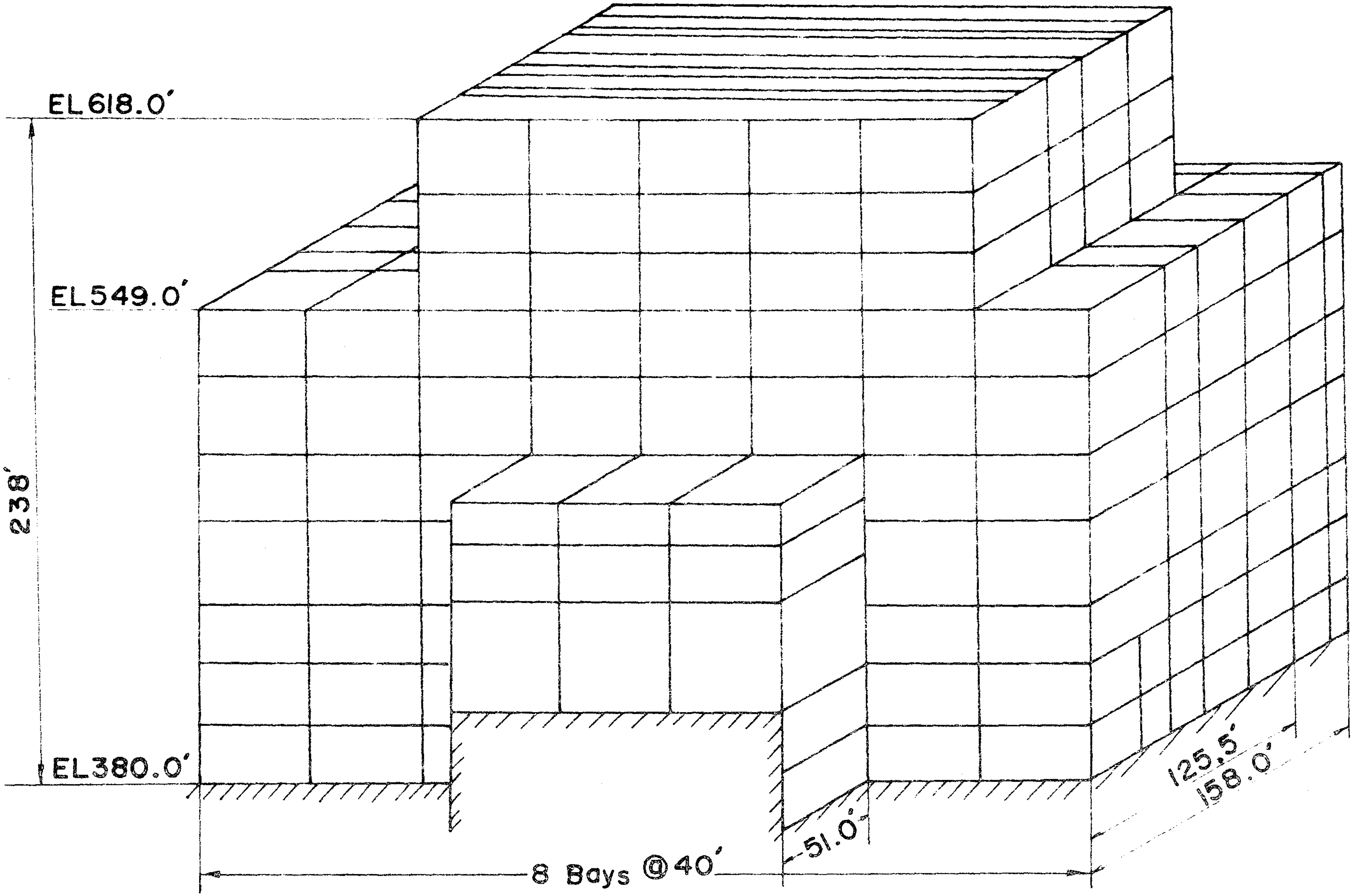

Fig. 3. A three-dimensional outside view of the steel framing structure.

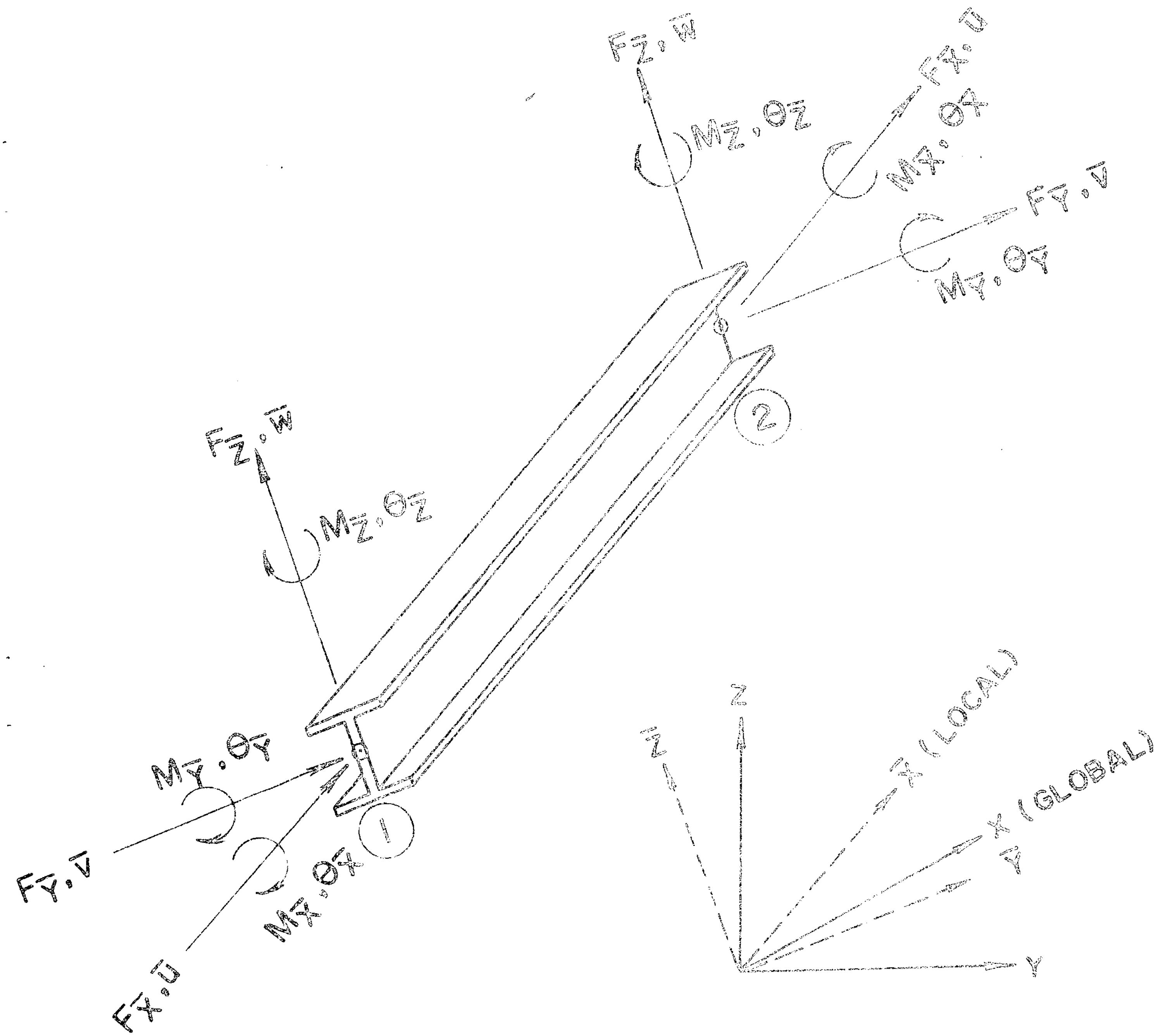

Fig. 4. Description of a three-dimensional beam finite element.

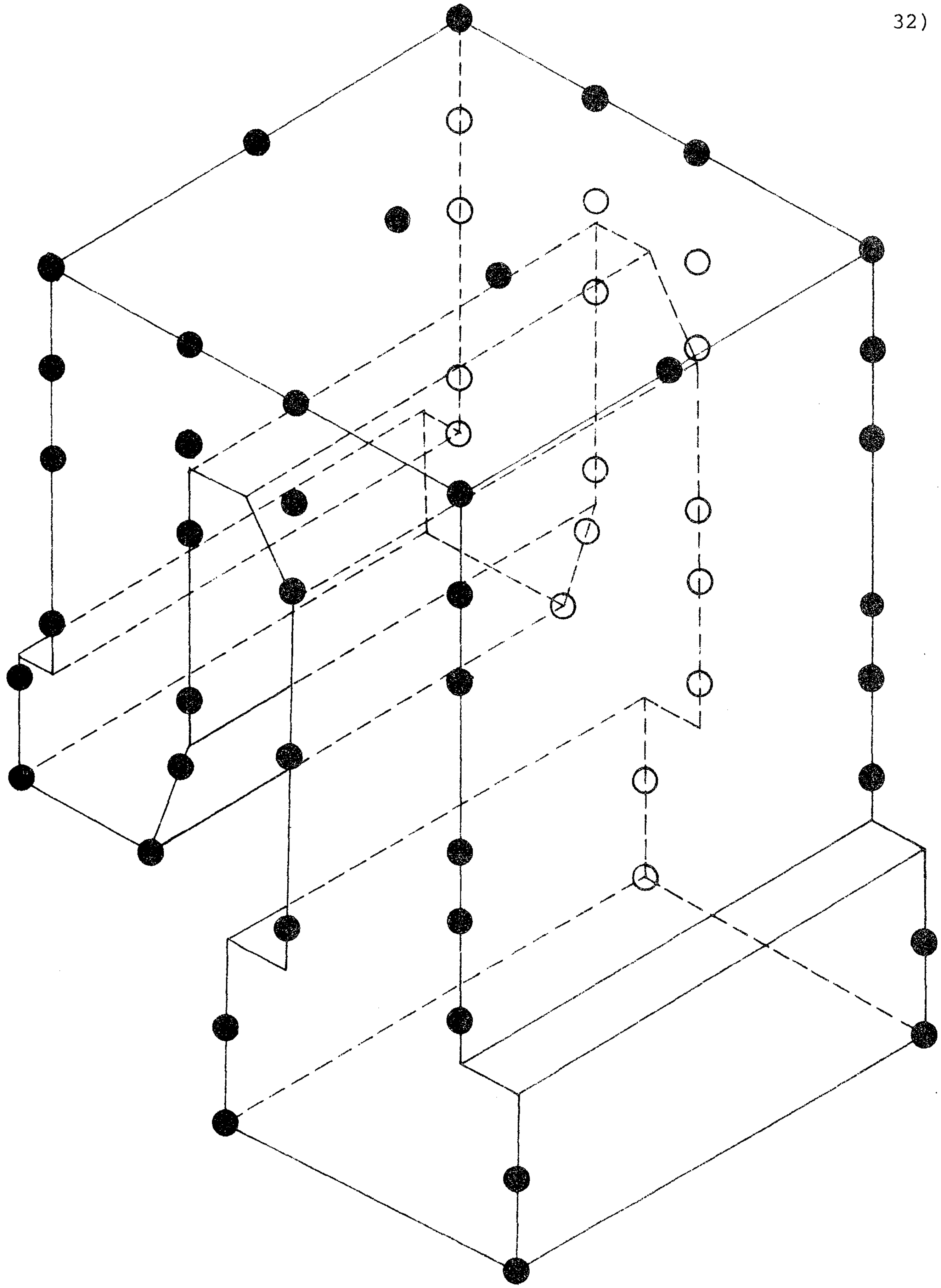

Fig. 5. Lumped mass and rigid bar model for the steam generator.

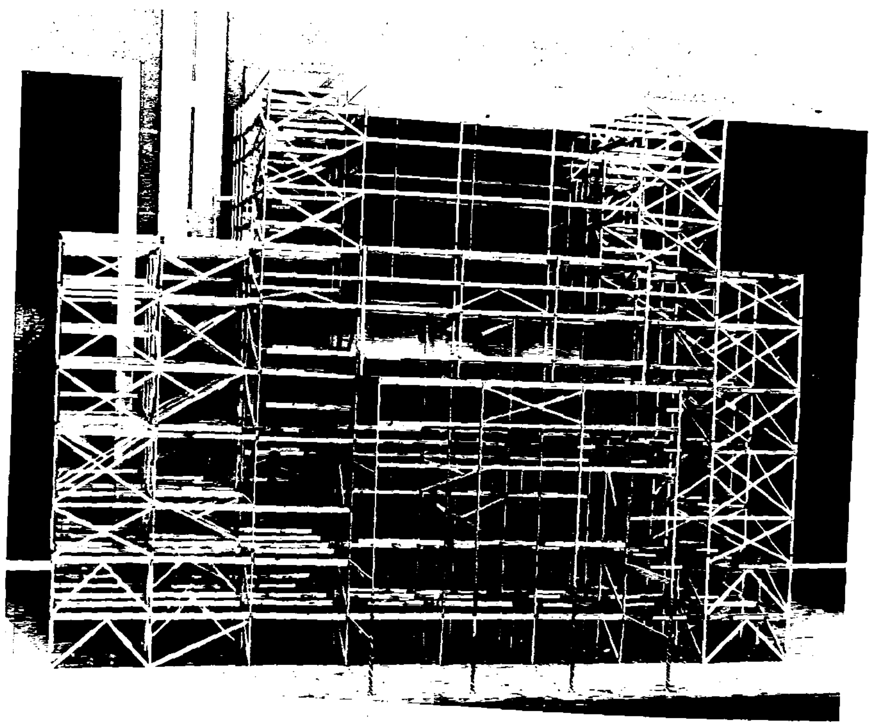

Fig. 6. The photograph of the balsa wood model for the supporting frame structure.

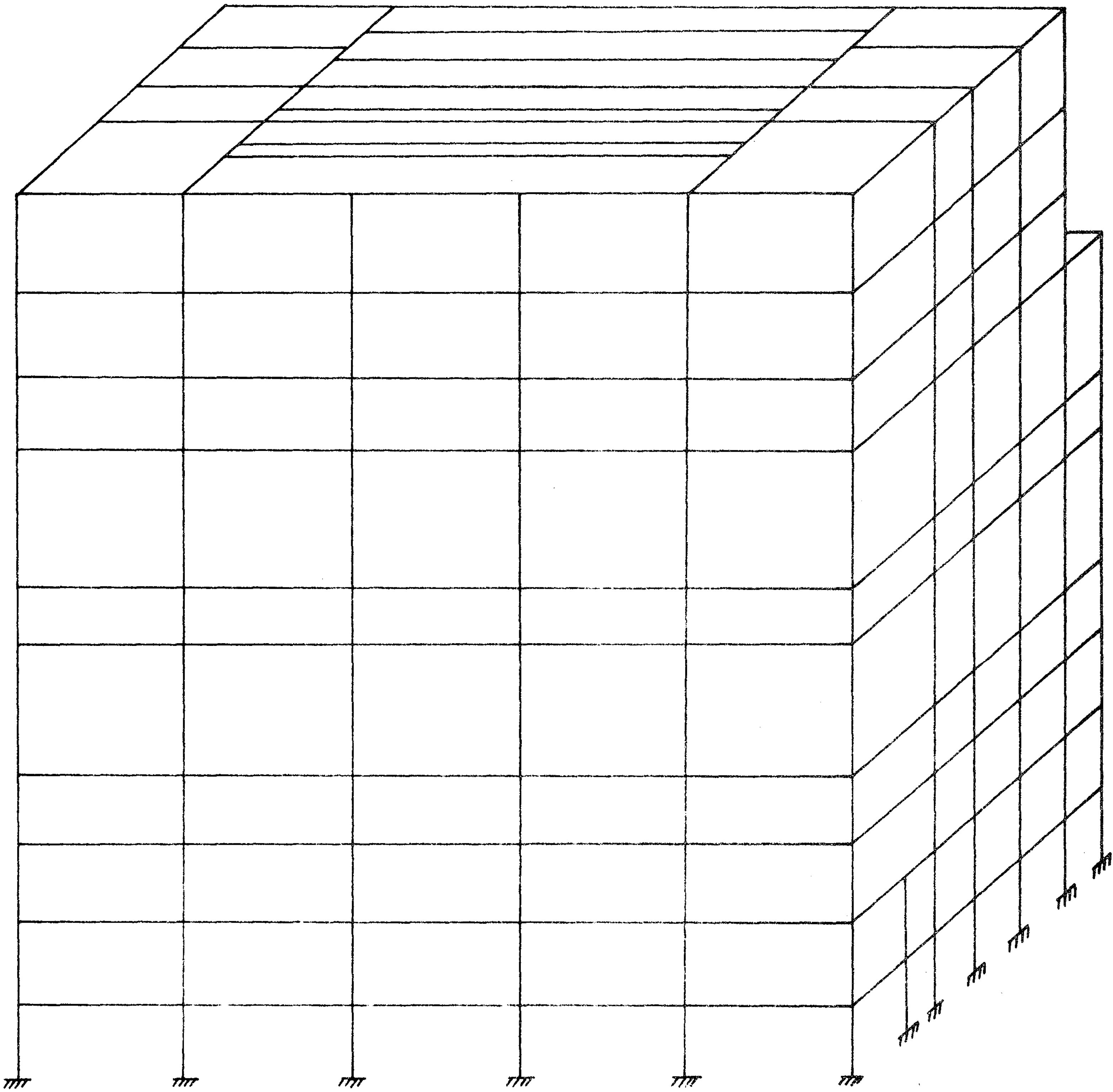

Fig. 7. The central portion of the supporting structure for the initial analysis.

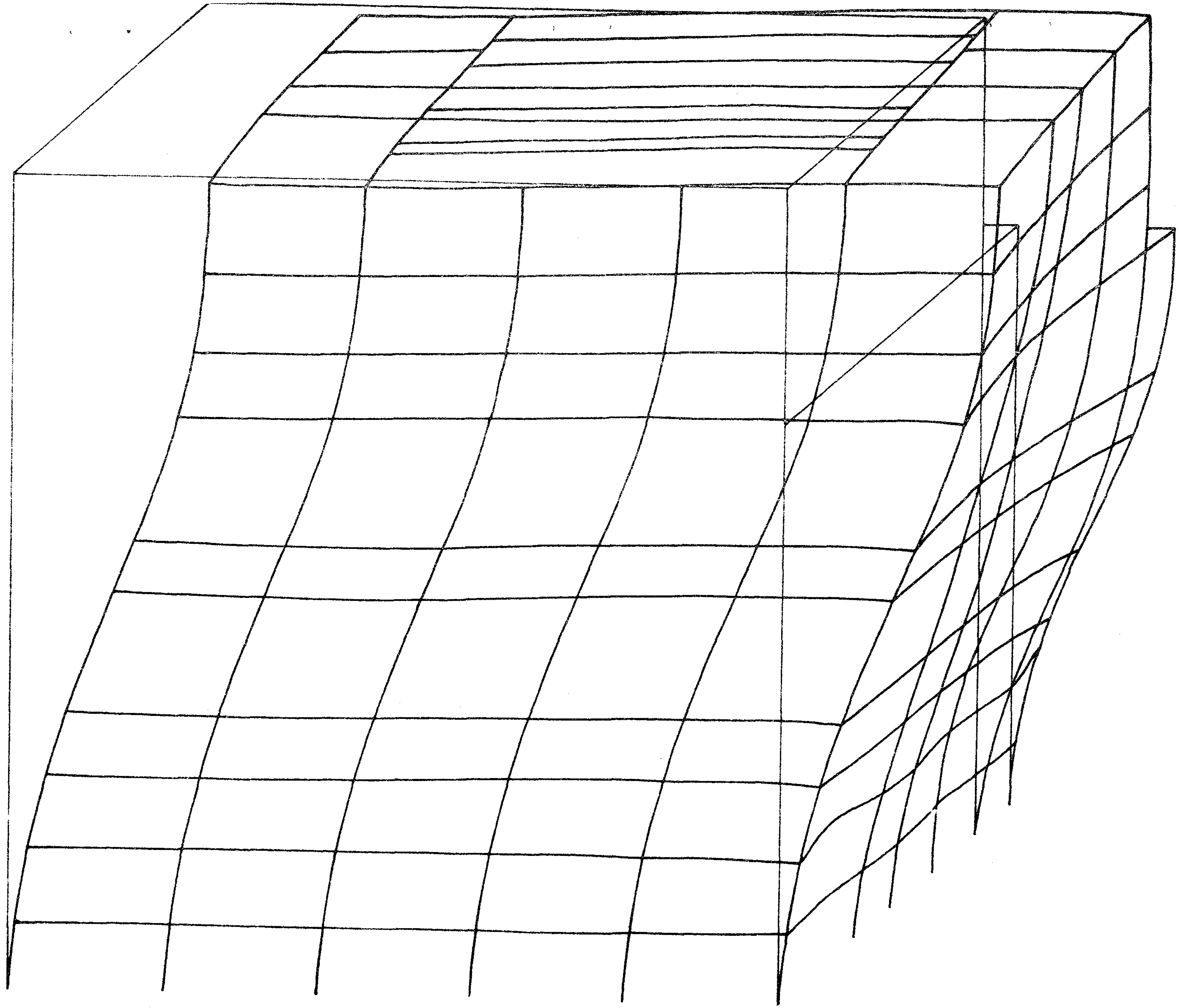

Fig. 8. The first mode shape of the central structure without both bracing members and the steam generator (frequency = 0.4299 Hz).

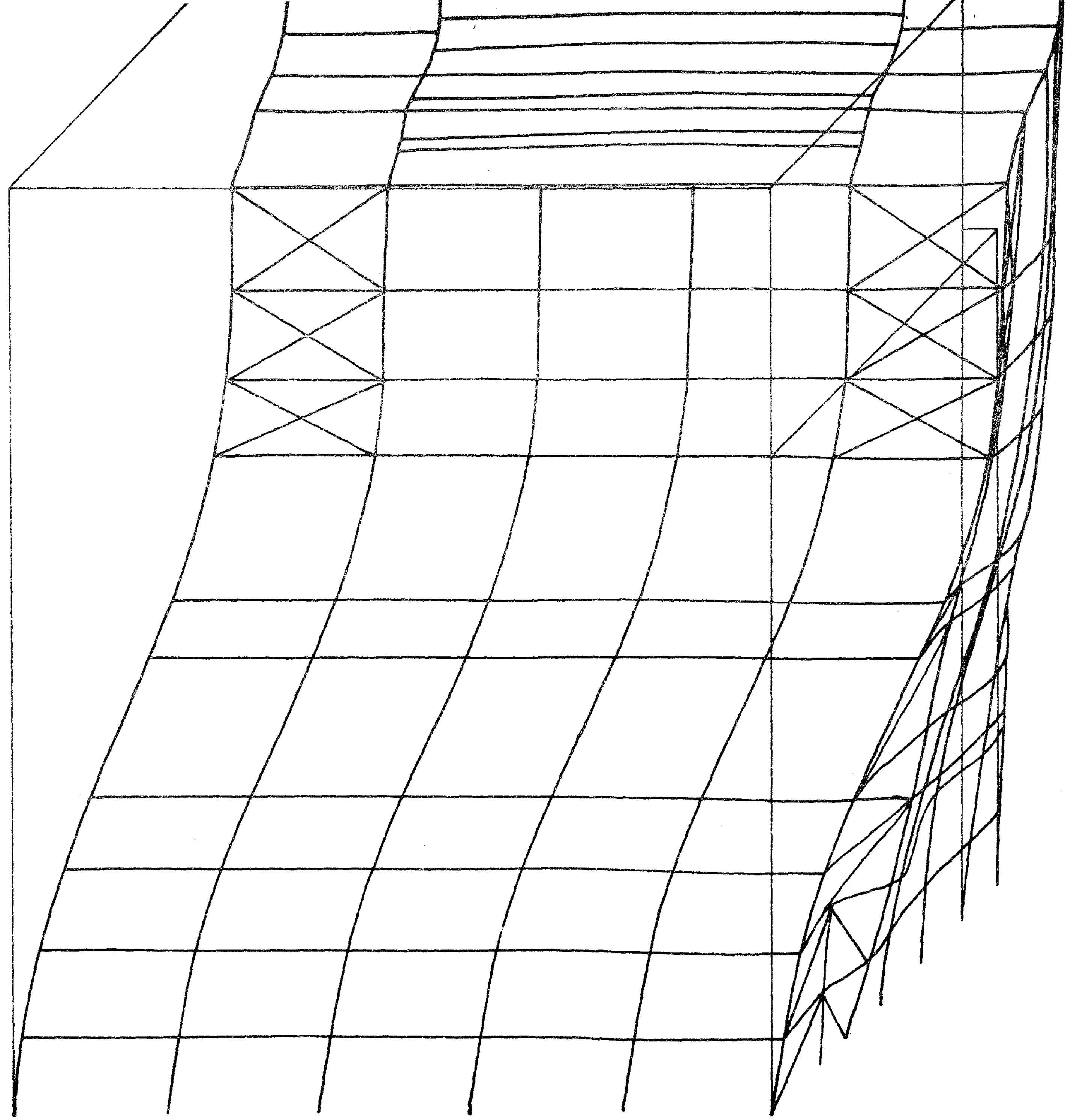

Fig. 9. The first mode shape of the central structure without the steam generator but with the bracing members (frequency = 0.5517 Hz).

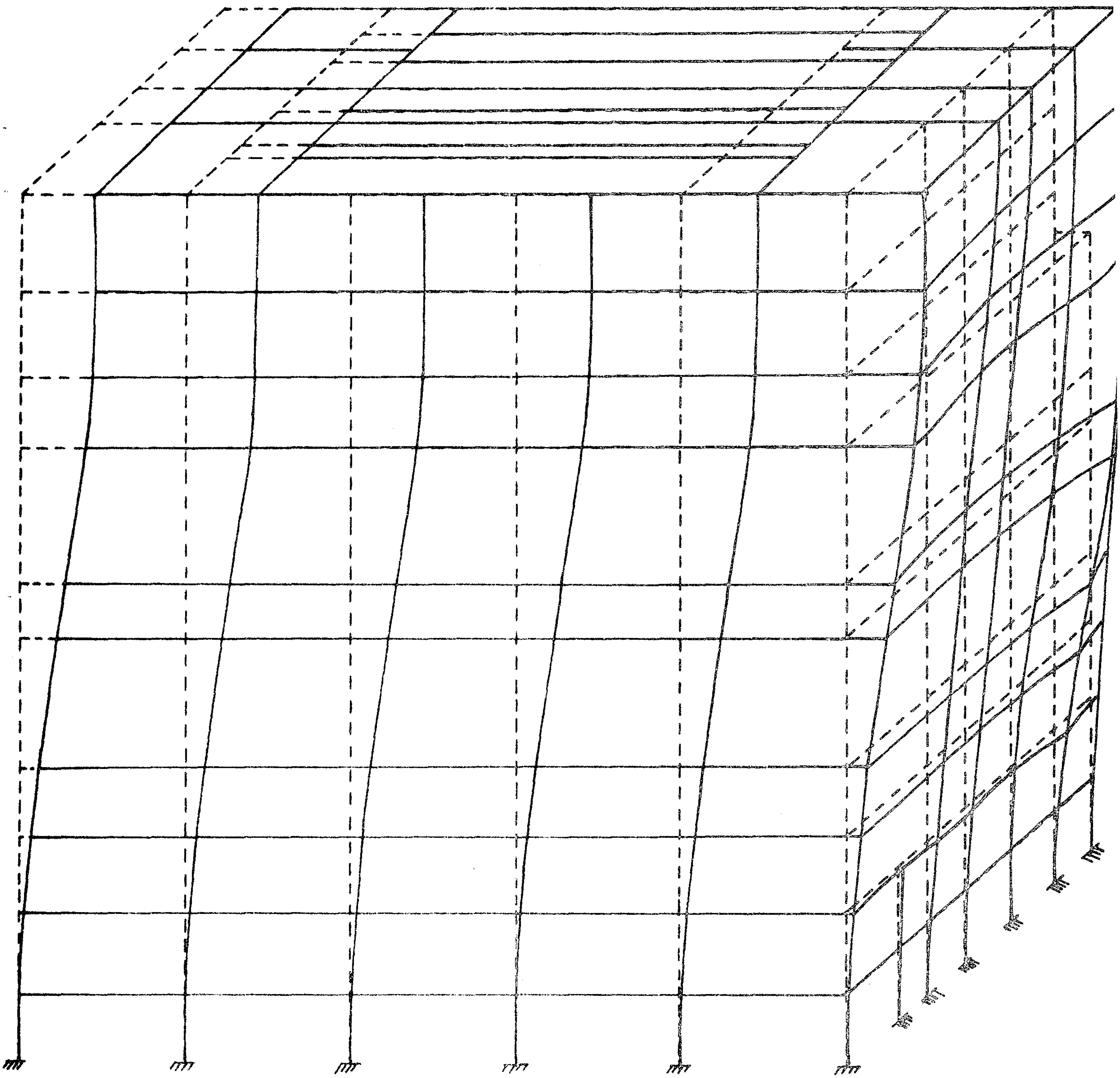

Fig. 10. The first mode shape of the central structure with the steam generator but without the bracing members (frequency = 0.1556 Hz).

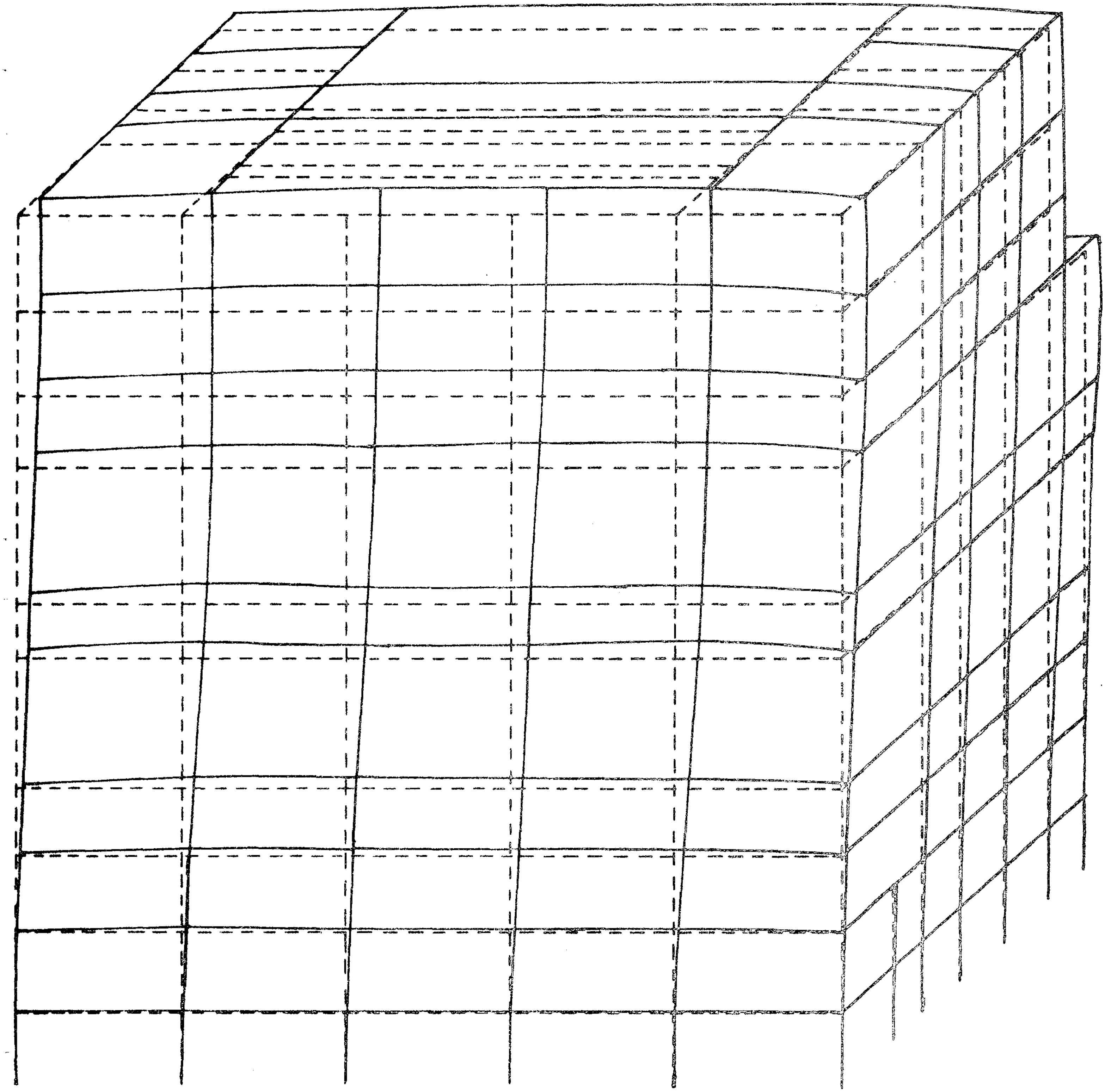

Fig. 11. The second mode shape of the central structure with the steam generator but without the bracing members (frequency = 0.1987 Hz).

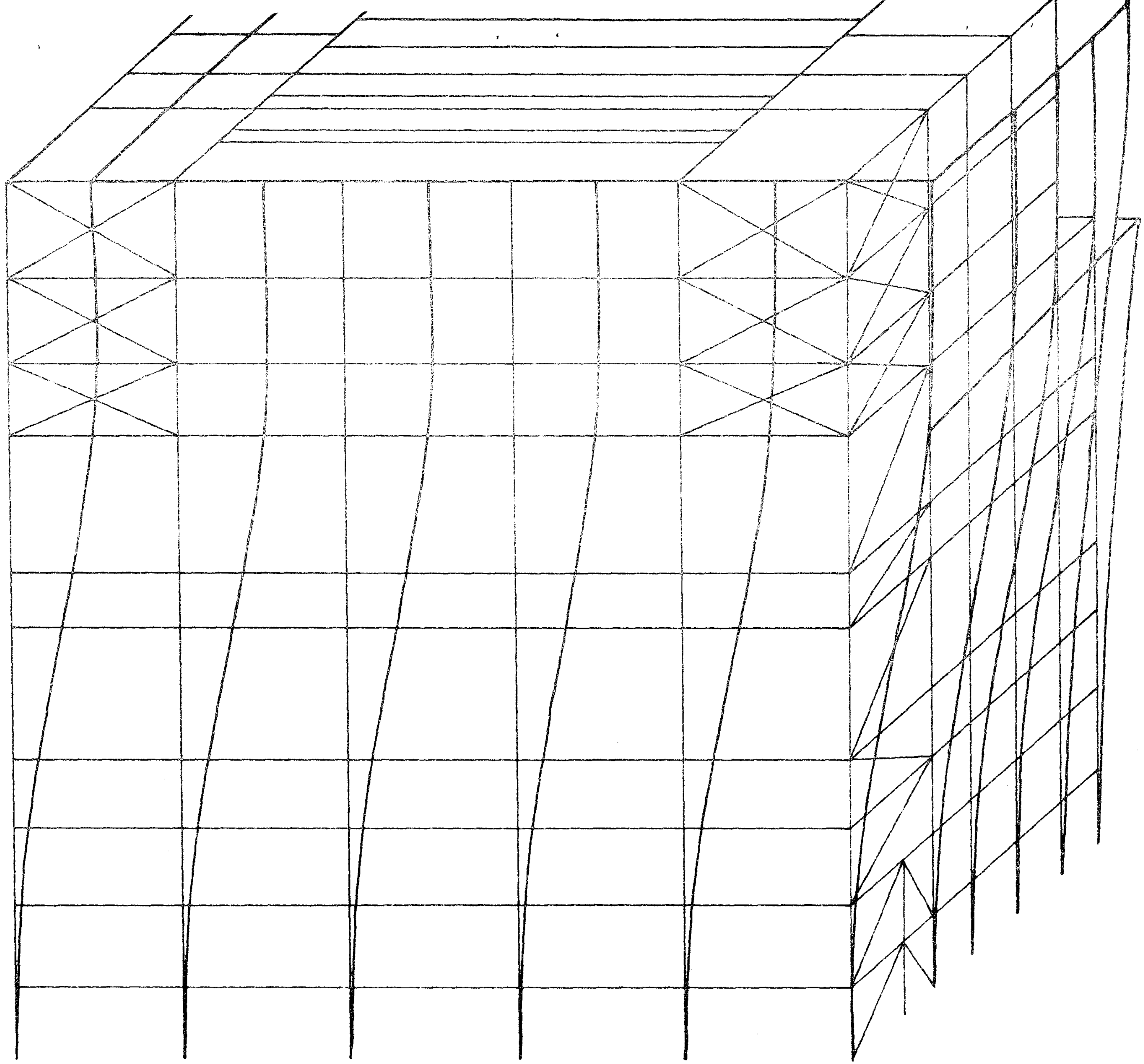

Fig. 12. The first mode shape of the central structure with both the steam generator and the bracing members (frequency = 0.2060 Hz).

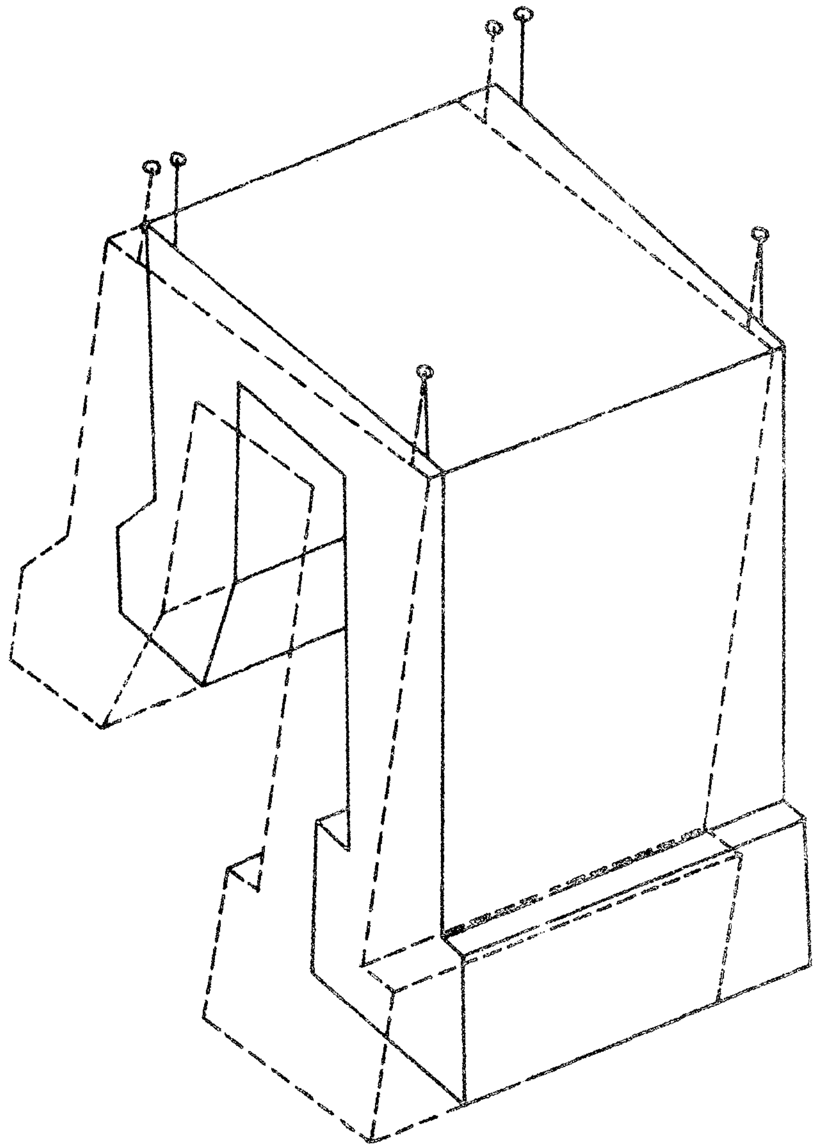

Fig. 13. The first mode shape of the steam generator supported by central structure with bracing members.

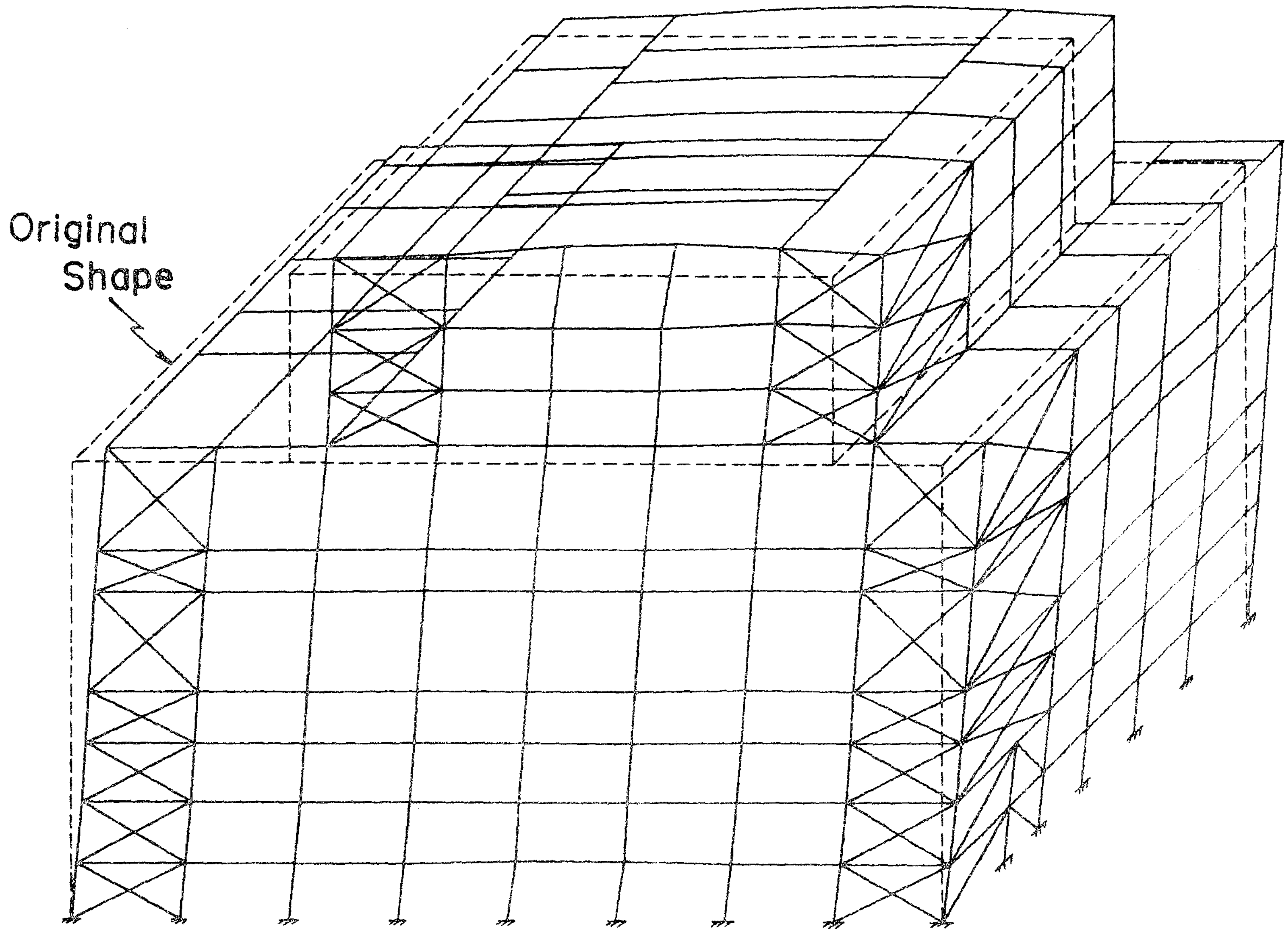

Fig. 14. A three-dimensional outside view of the total structure vibrating in the first mode.

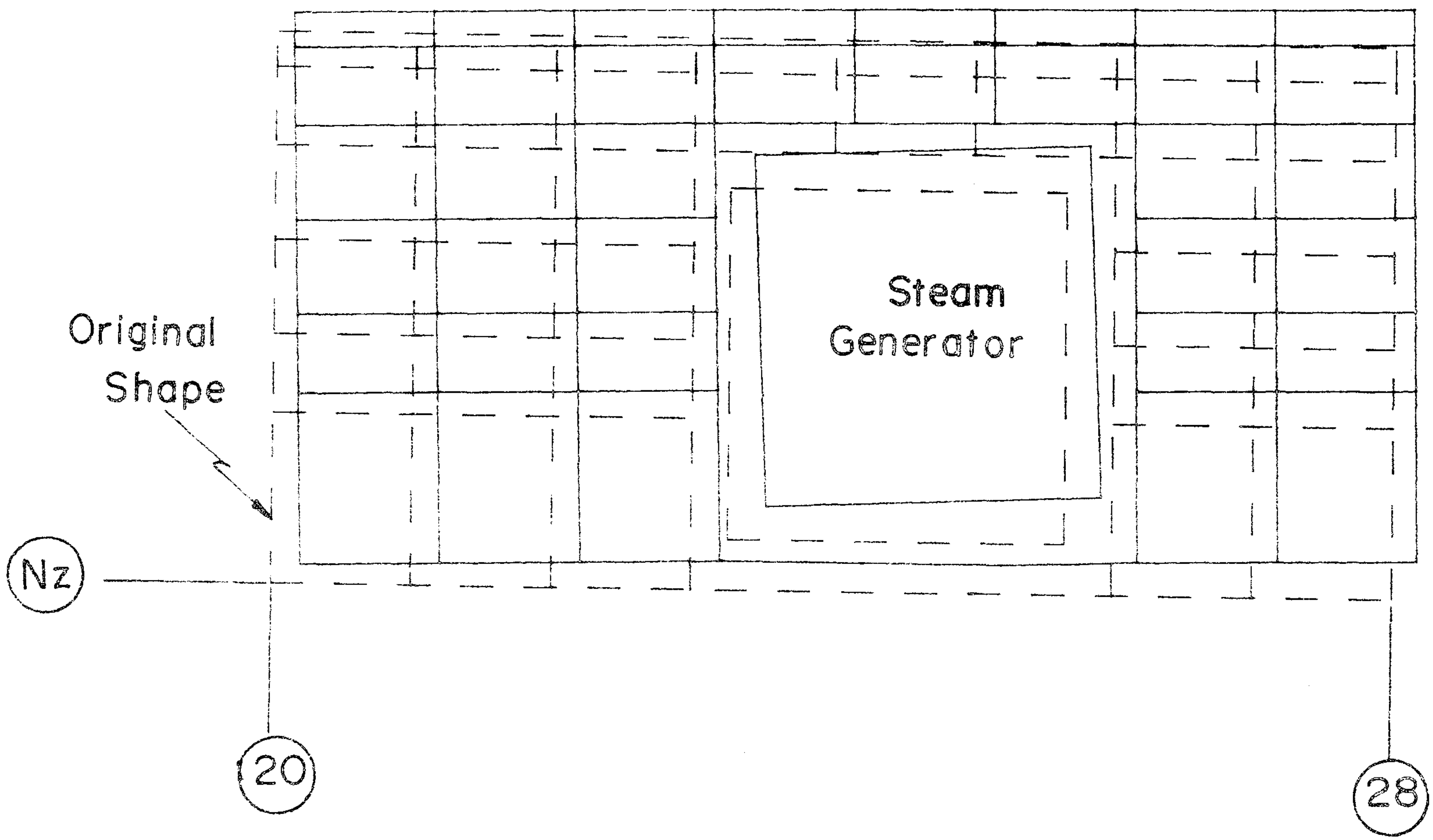

Fig. 15. A top view of the horizontal section at 169 feet above ground vibrating in the first mode.

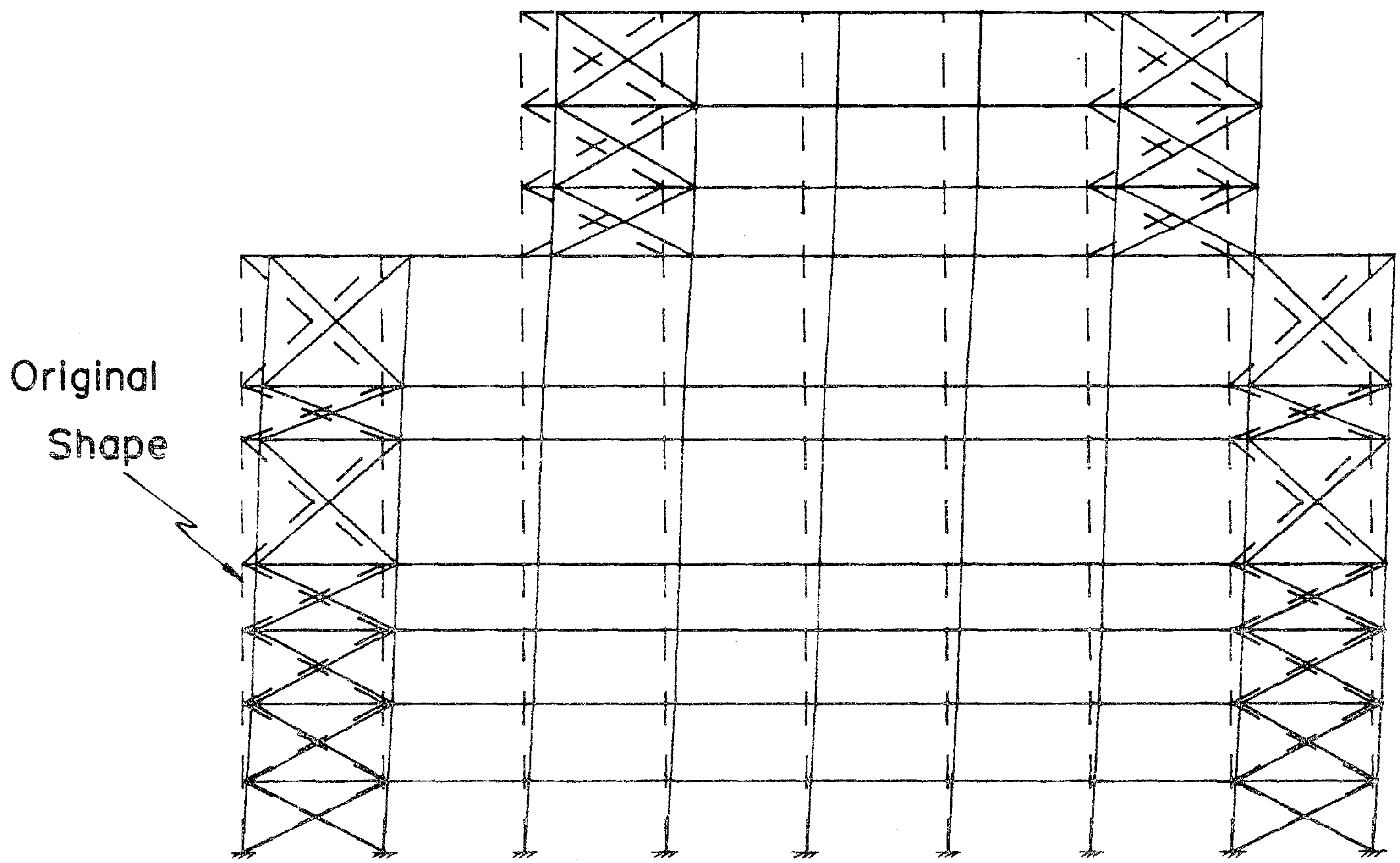

Fig. 16. A front view of the vertical frame along line Nz vibrating in the first mode.

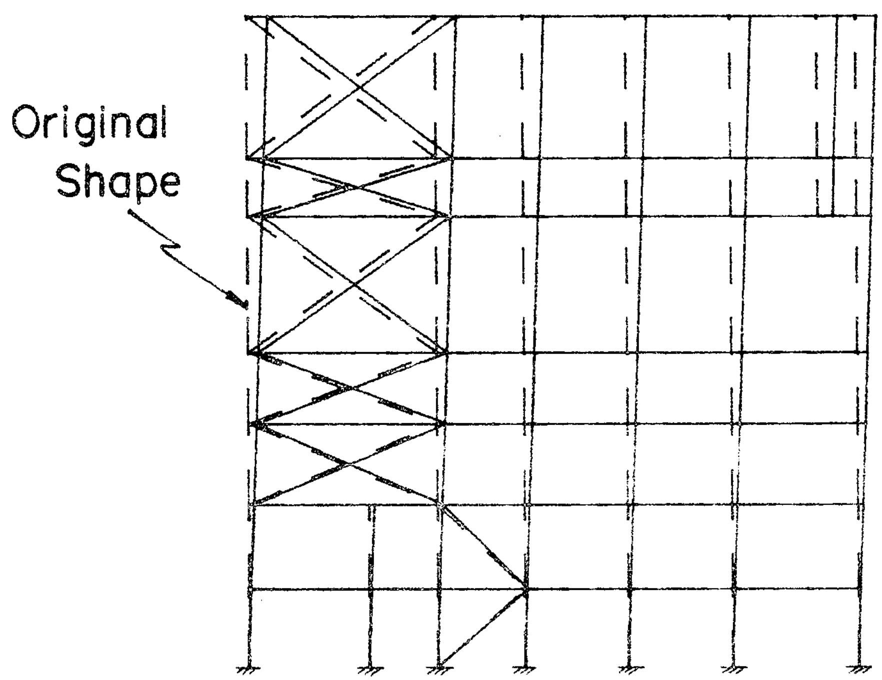

Fig. 17. A side view of the vertical frame along line 20 vibrating in the first mode.

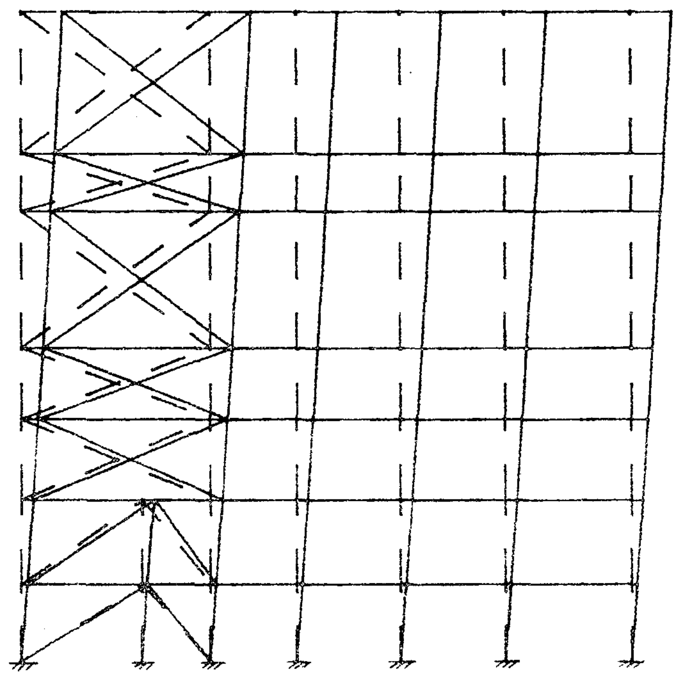

Fig. 18. A side view of the vertical frame along line 28 vibrating in the first mode.

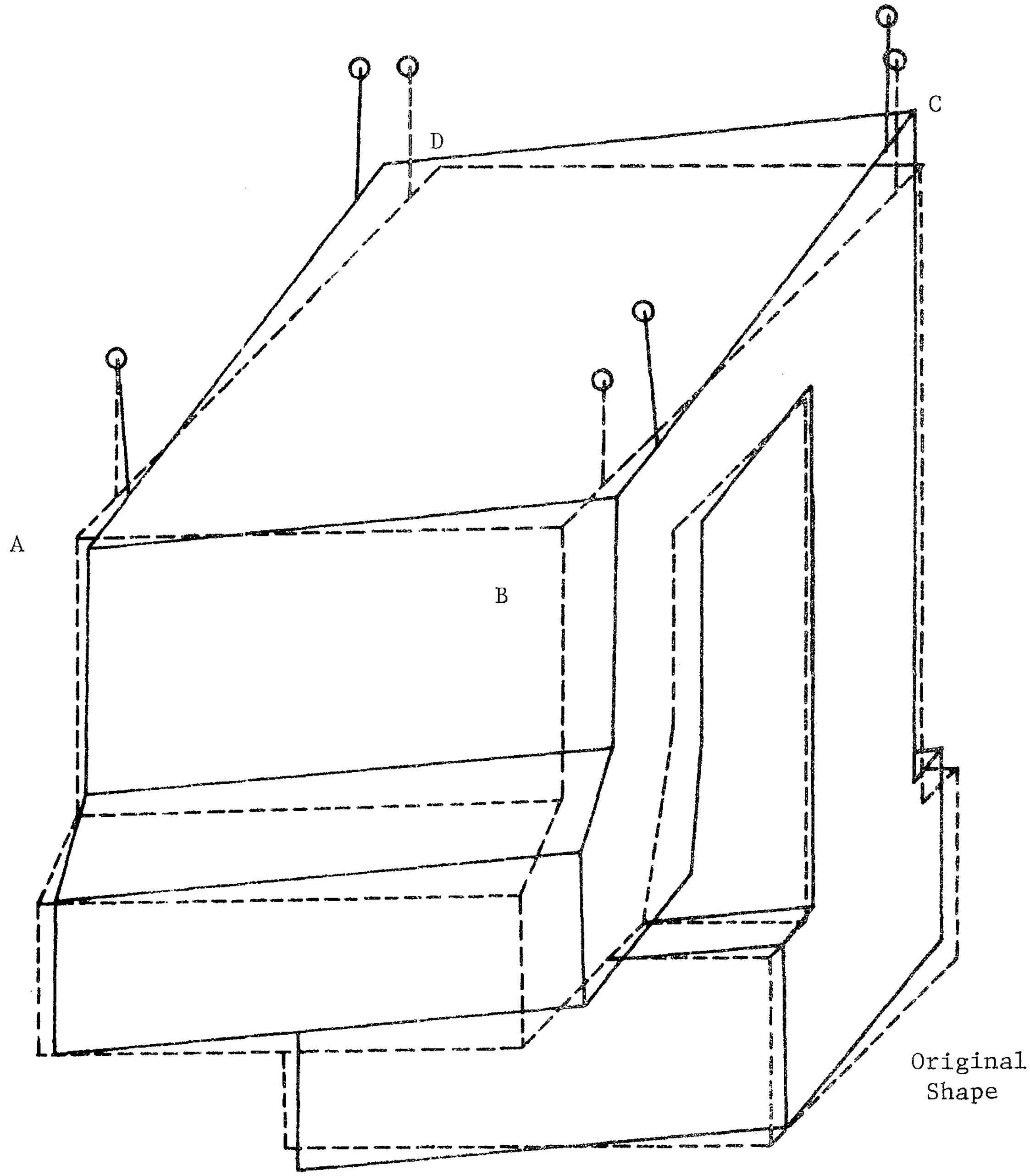

Fig. 19. A three-dimensional view of the steam generator vibrating in the first mode.

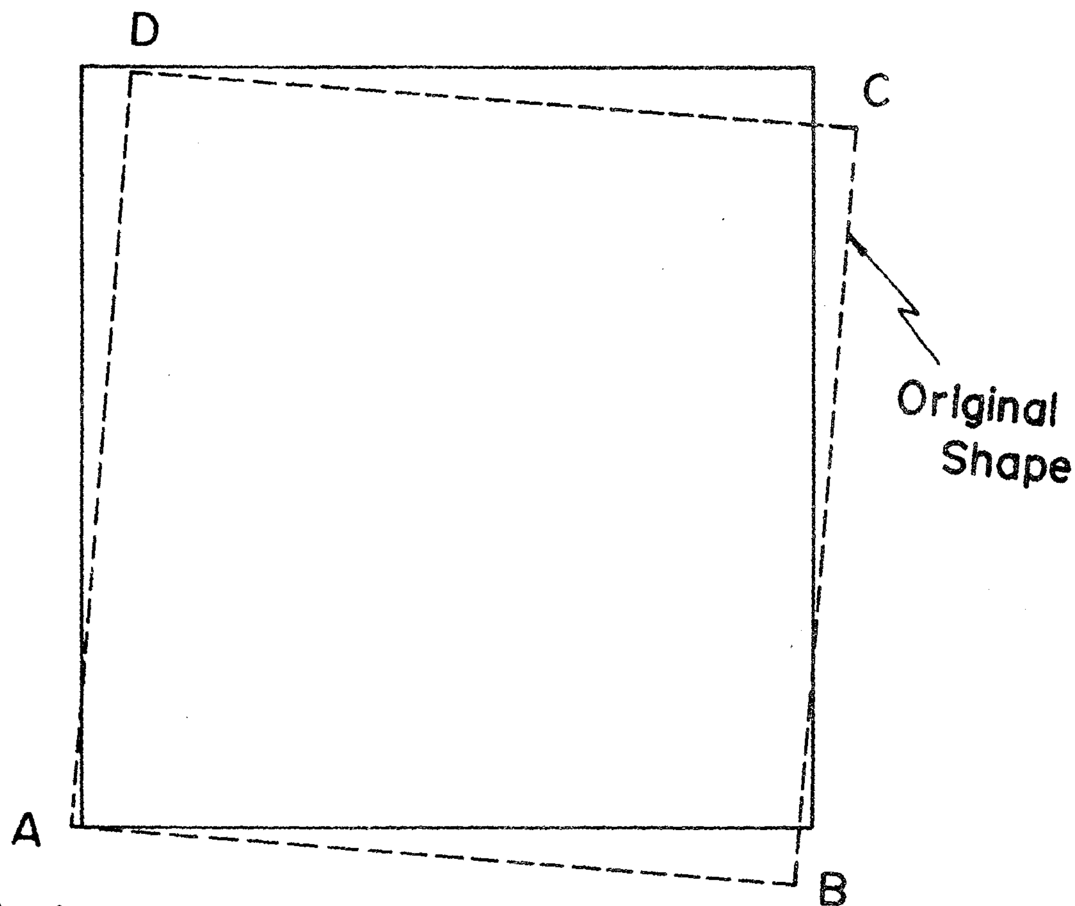

Fig. 20. A top view of the horizontal section at the top of the steam generator vibrating in the first mode.

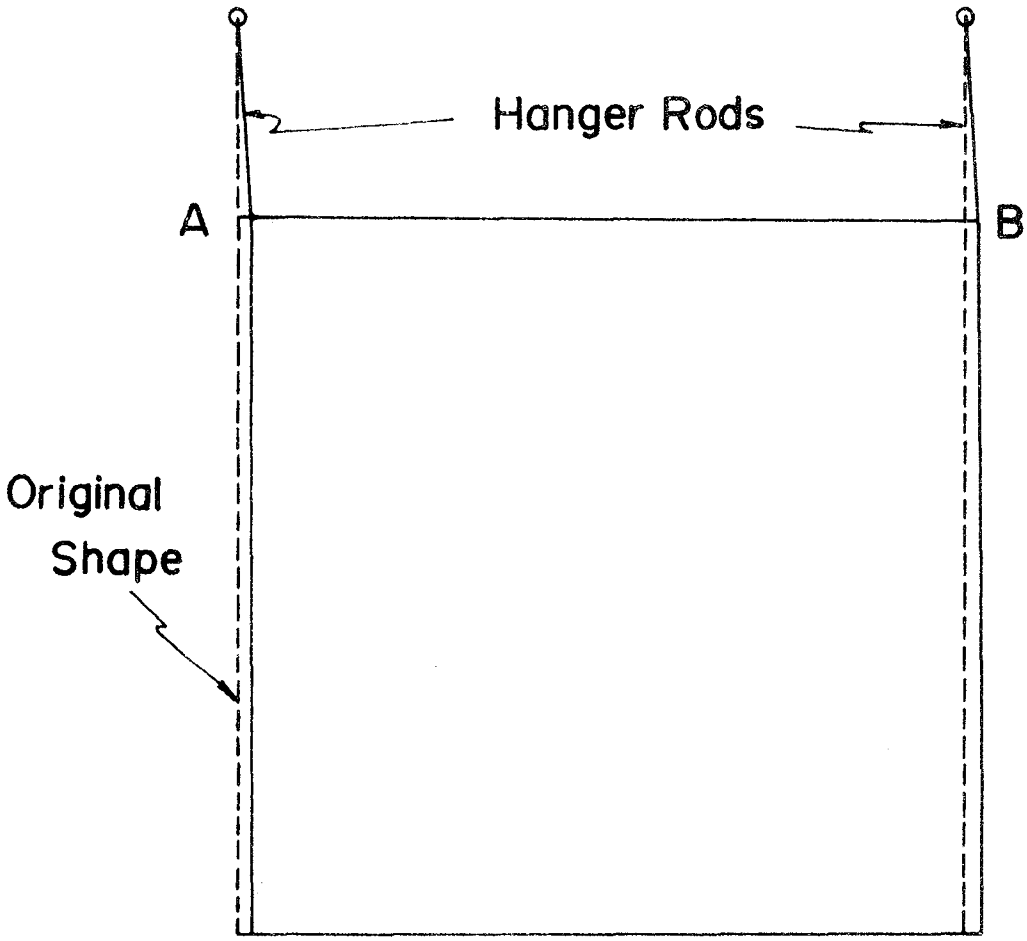

Fig. 21. A side view of the steam generator wall along line AB vibrating in the first mode.

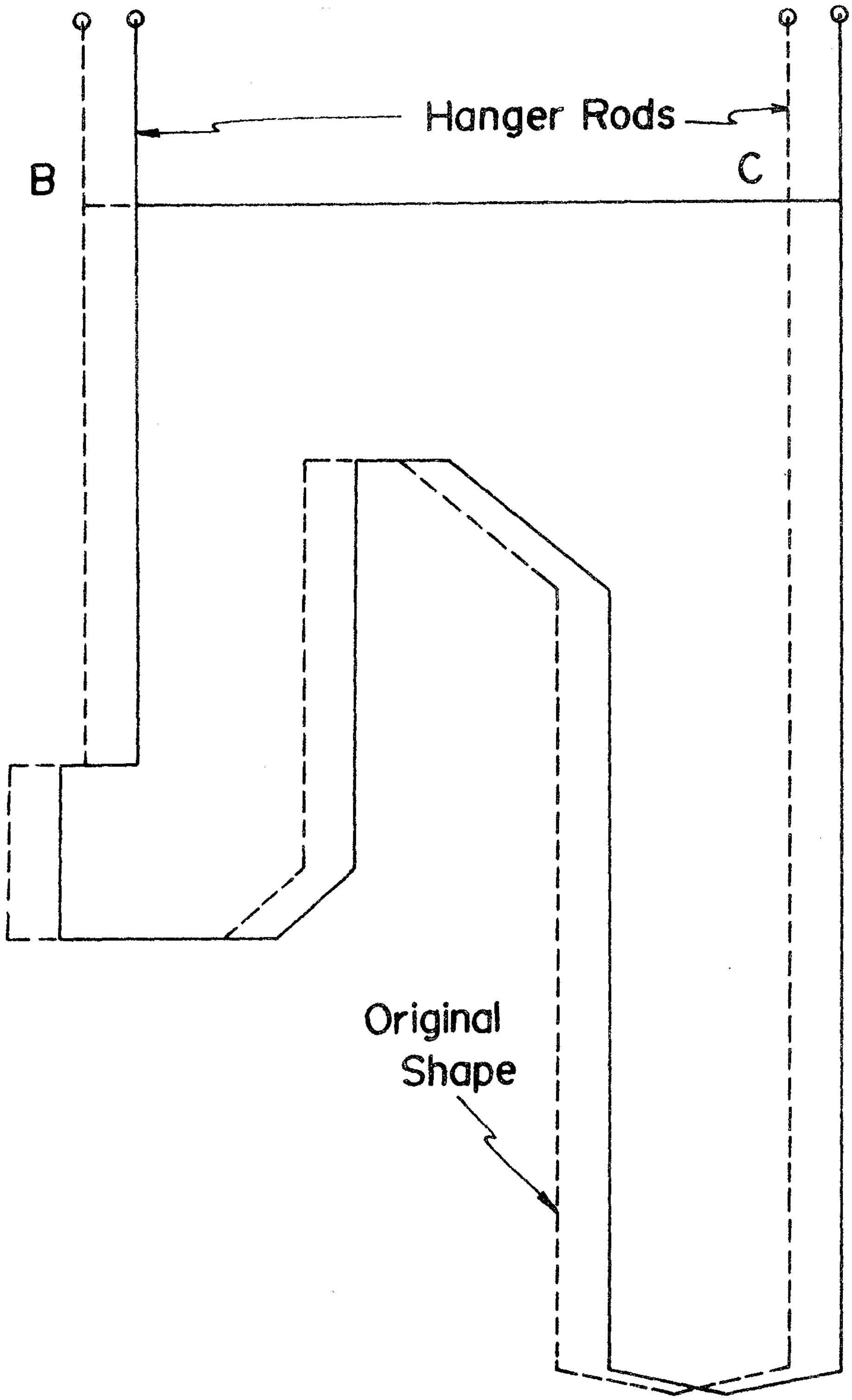

Fig. 22. A side view of the steam generator wall along line BC vibrating in the first mode.

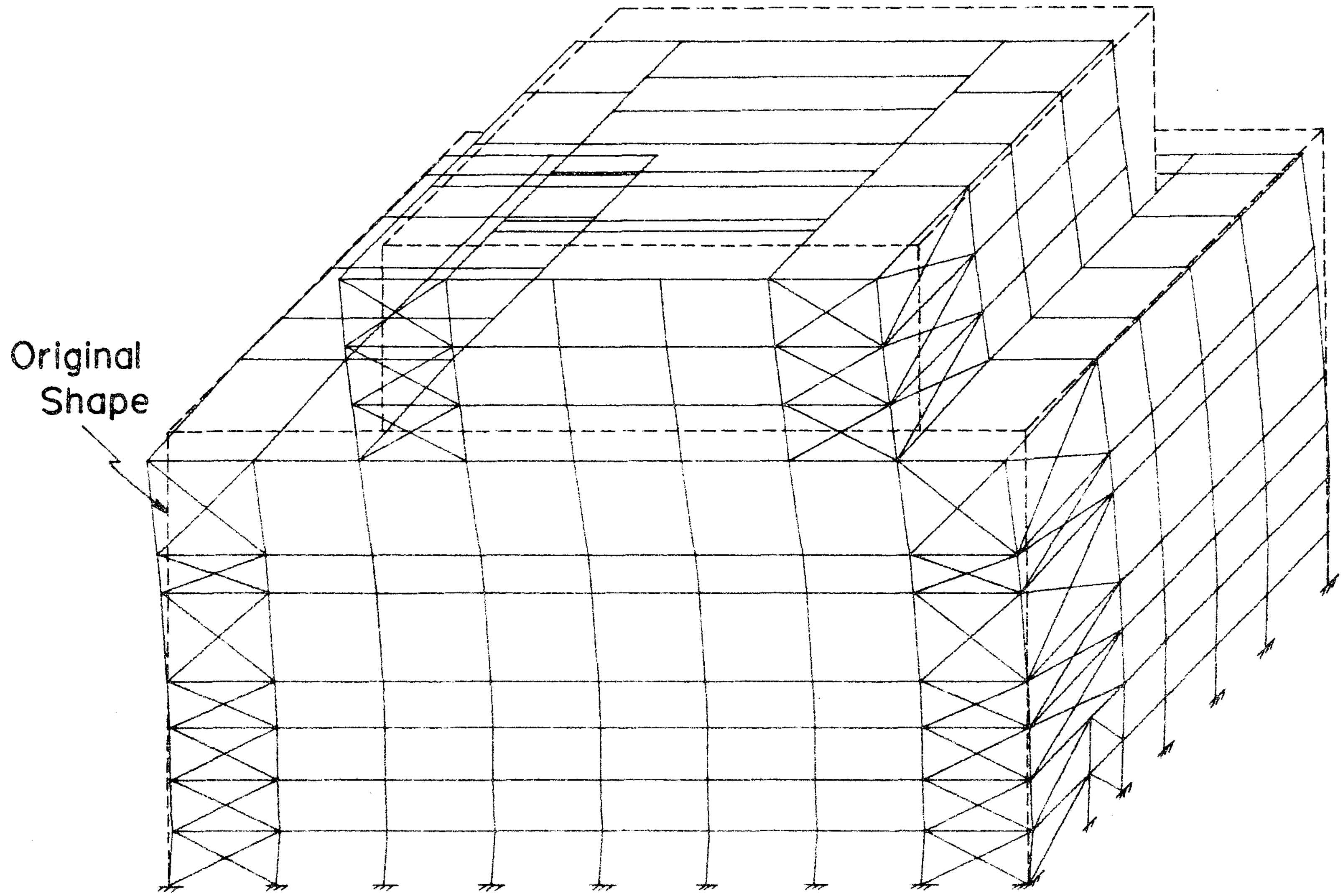

Fig. 23. A three-dimensional outside view of the total structure vibrating in the second mode.

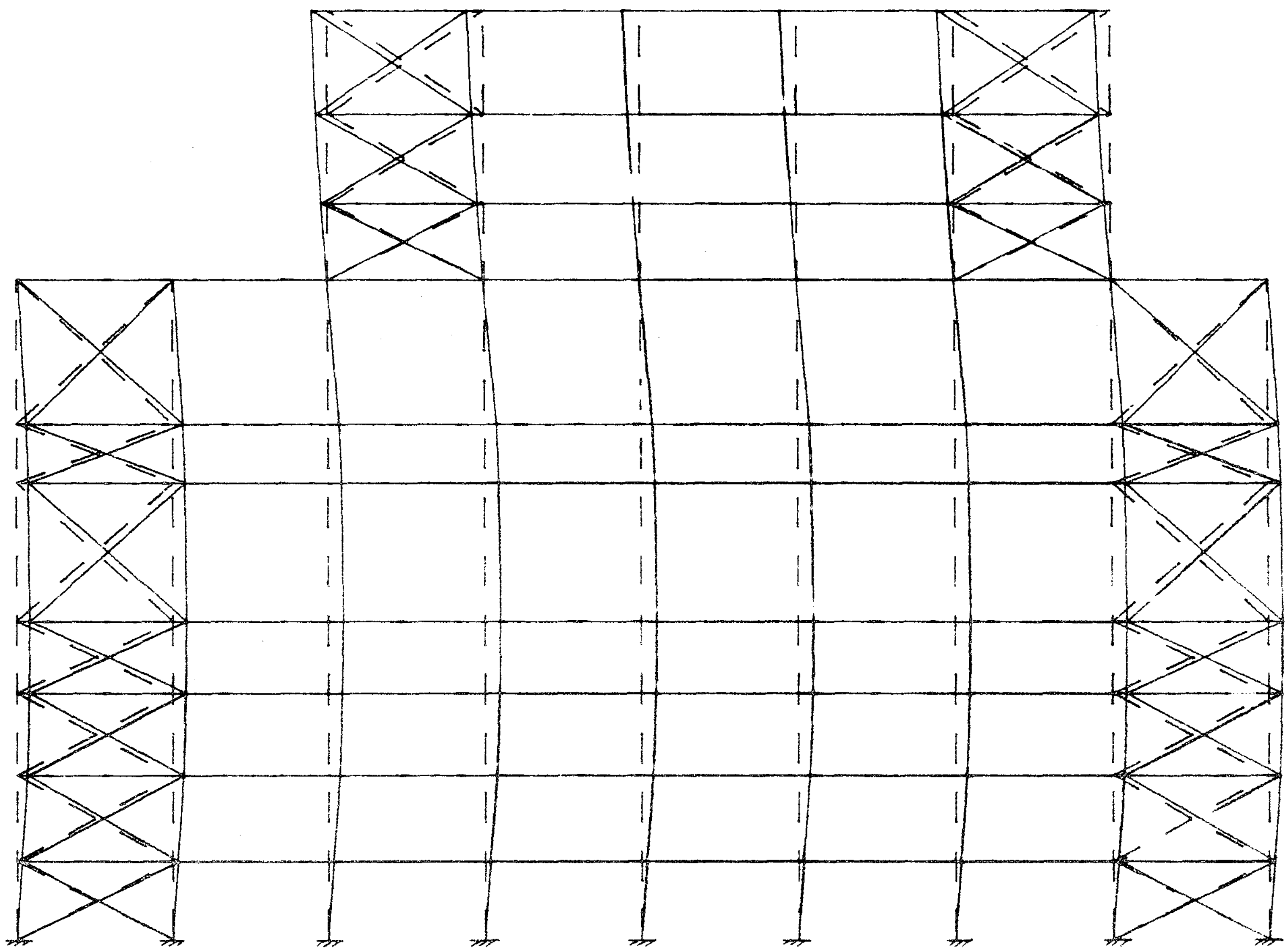

Fig. 24. A front view of the vertical frame along line Nz vibrating in the second mode.

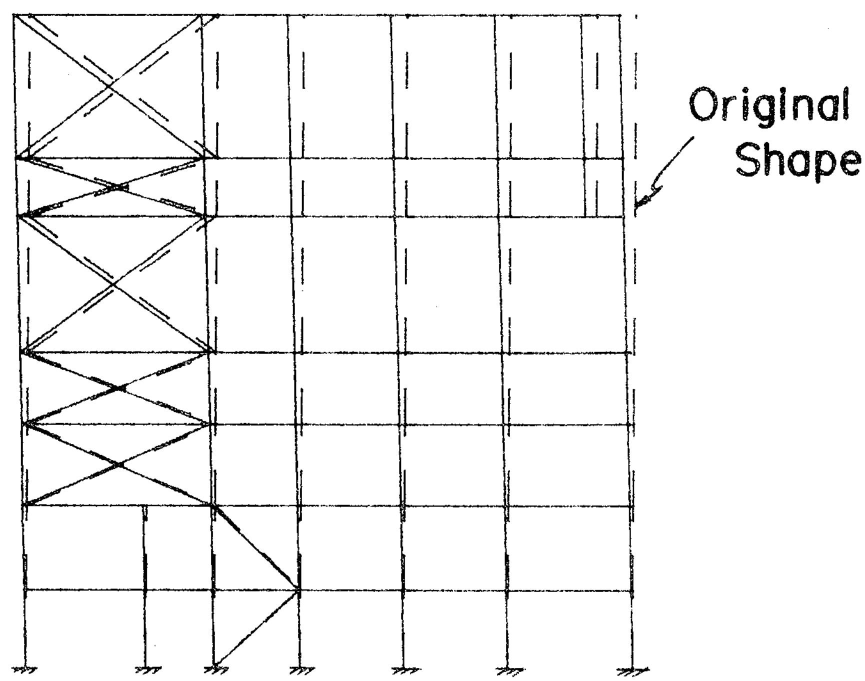

Fig. 25. A side view of the vertical frame along line 20 vibrating in the second mode.

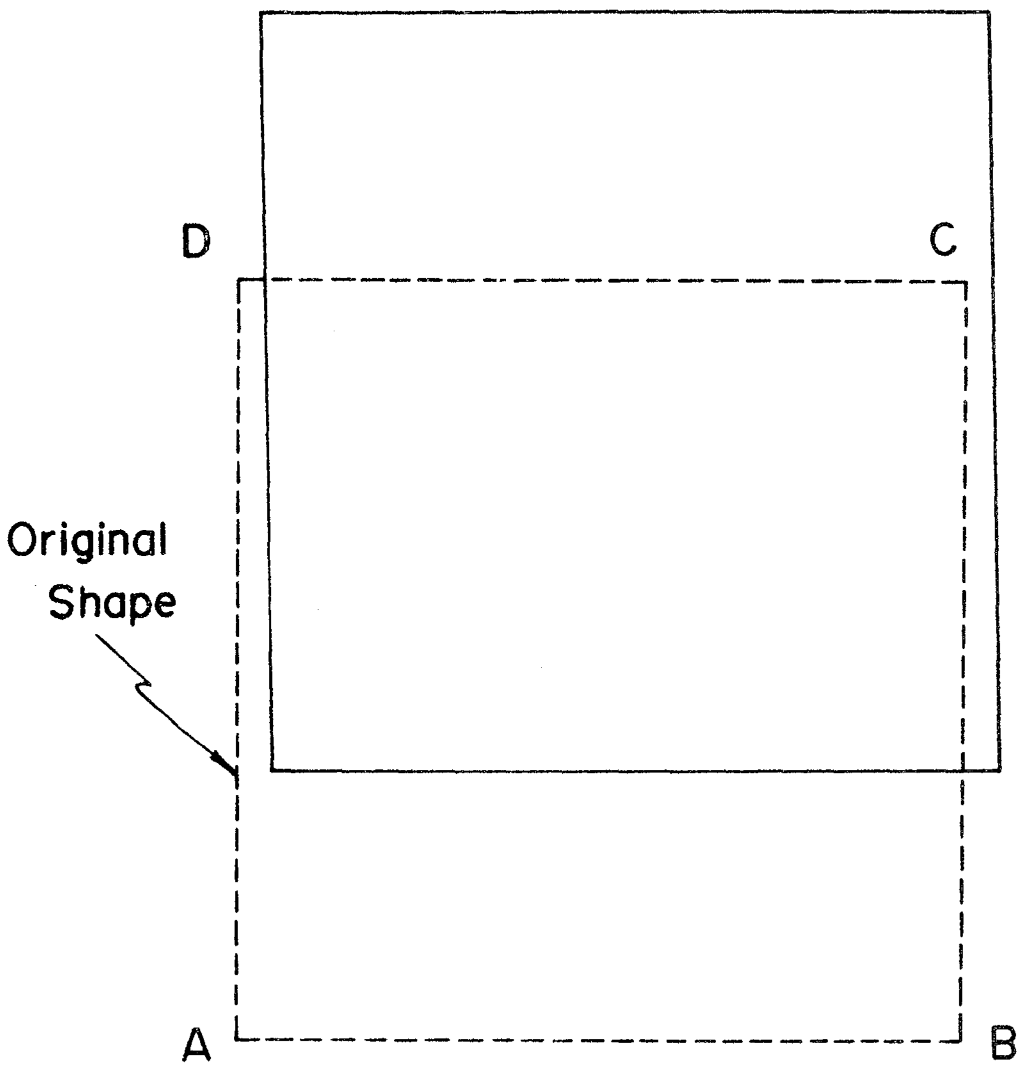

Fig. 26. A top view of the horizontal section at the top of the steam generator vibrating in the second mode.

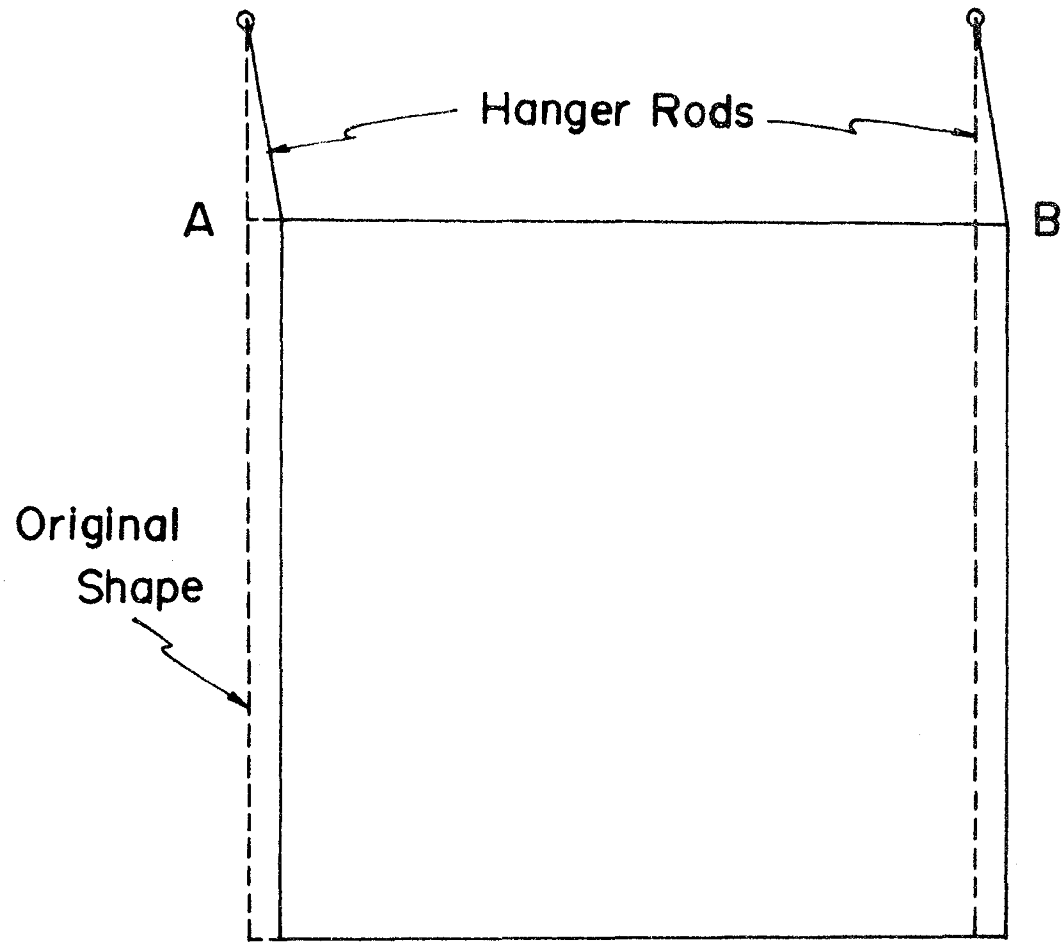

Fig. 27. A side view of the steam generator wall along line AB vibrating in the second mode.

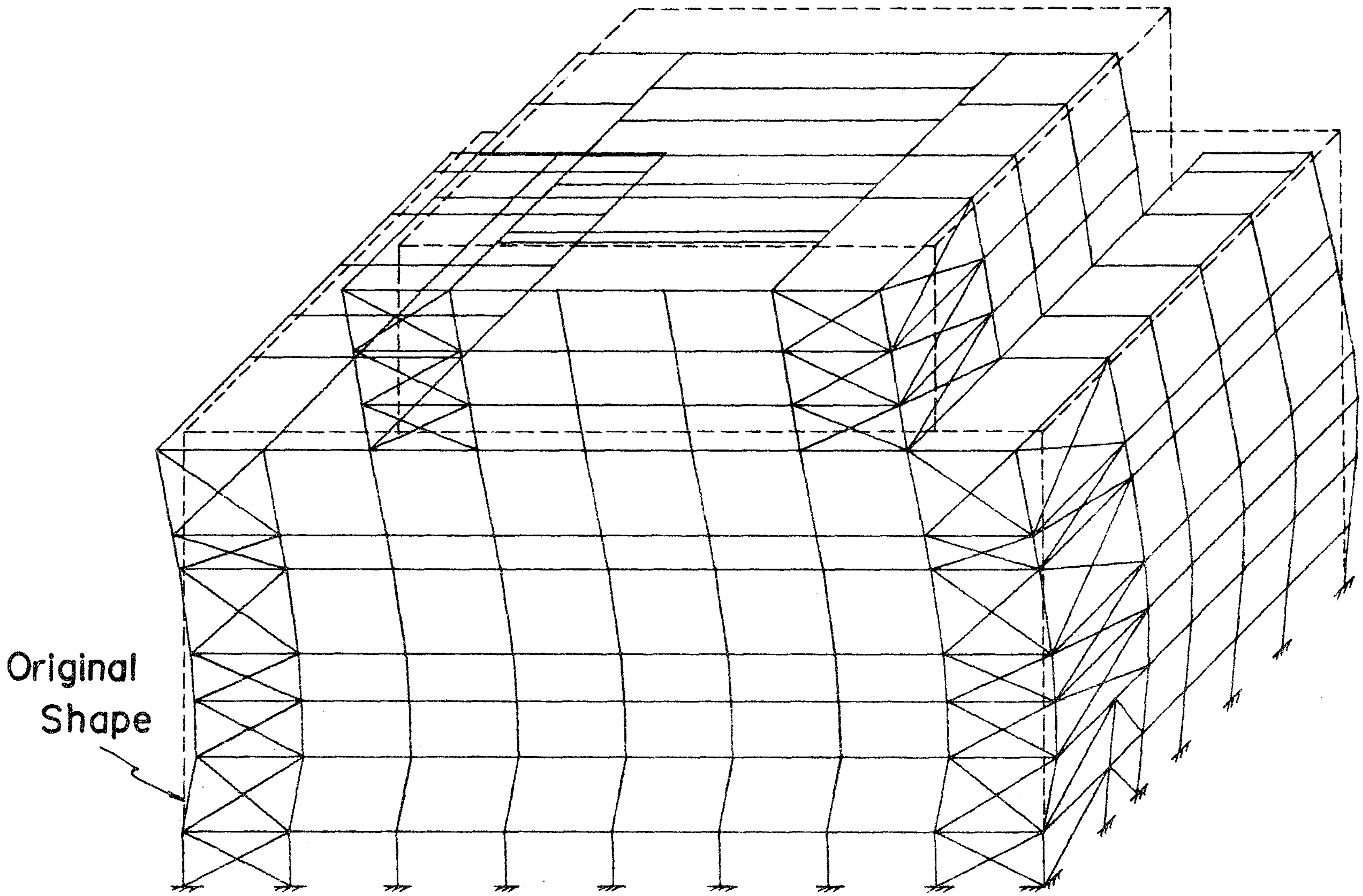

Fig. 28. A three-dimensional outside view of the total structure vibrating in the third mode.

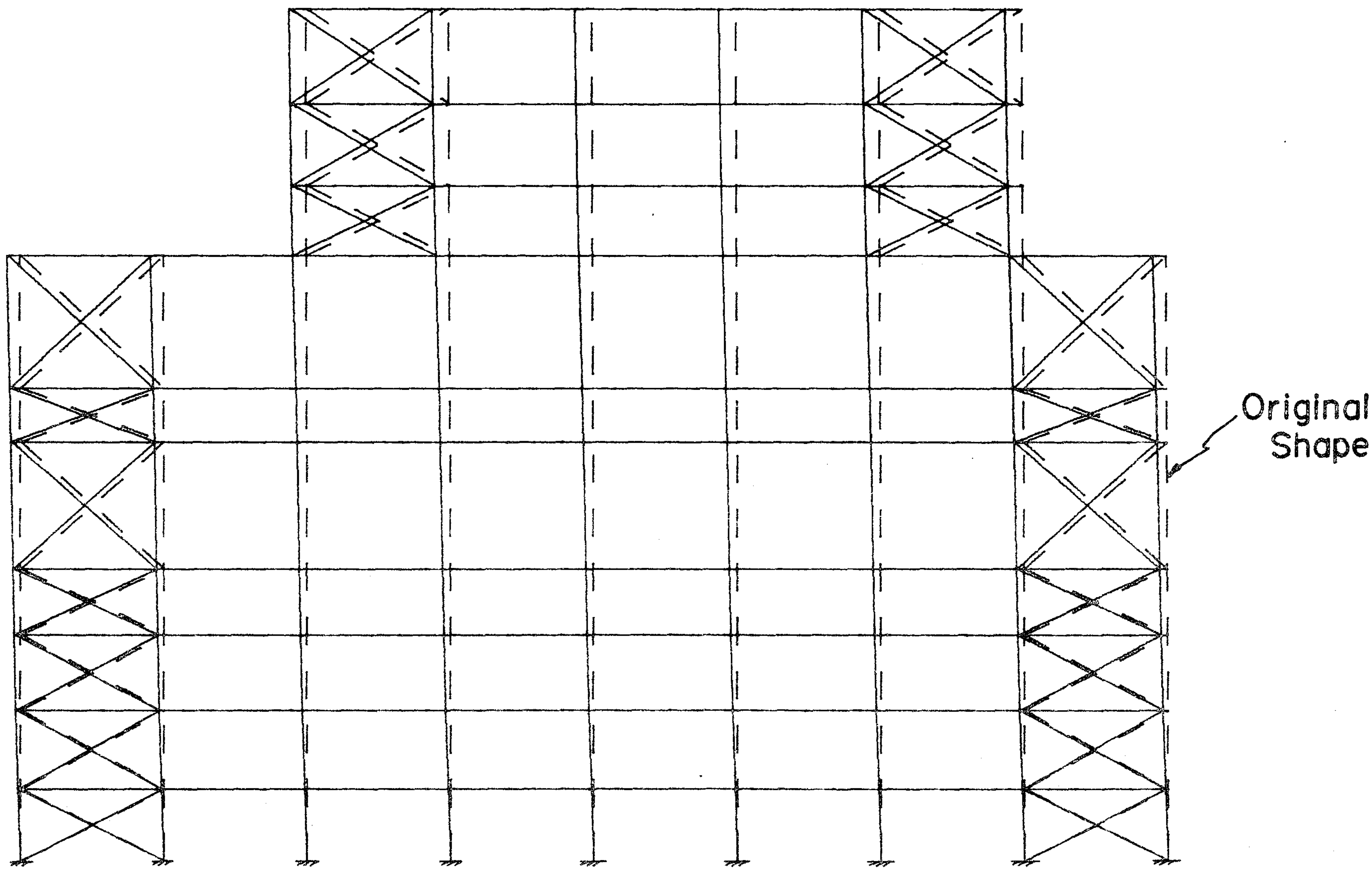

Fig. 29. A front view of the vertical plane frame along line Nz vibrating in the third mode.

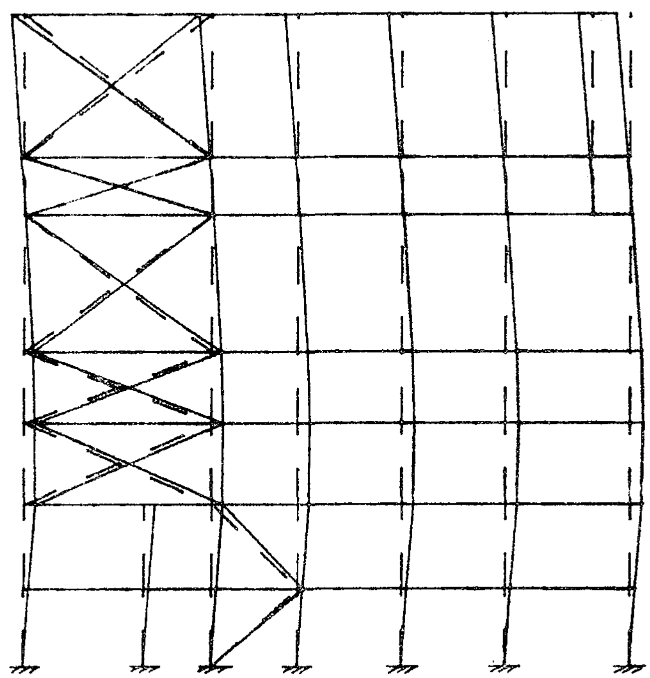

Fig. 30. A side view of the vertical plane frame along line 20 vibrating in the third mode.