New trends in model research on large structures

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New Trends in Model Research on Large Structures

Nouvelles tendances dans la recherche sur modèle pour grandes structures

Neue Tendenzen in Modelluntersuchungen für grosse Bauwerke

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1. FOREWORD

The design of a civil engineering structure of importance usually goes through two successive stages.

In the first stage, the basic choice of the structural scheme to be adopted in relation to the technical problem under consideration is carried out, so as to set then roughly up the sizes of the structure. The designer, at this time, thus operates on a structure that is set up only along general lines and is, therefore, likely to be changed and improved in its component parts.

Thereafter, a detailed check of the behavior of the structure up to determining, if possible, its factor of safety is performed on one or several alternative designs already well defined on the basis of the above study.

At the outset, therefore, only mathematical analysis and especially personal experience are available to the designer. In fact, quite obviously a model study, though useful, is at this stage rather costly (both in time and money) and is seldom appropriate in the design of a structure which is still undergoing modification.

Instead, it is during the second stage that experimentation is profitably associated with the most refined mathematical methods.

Recently both experimentation and mathematical analysis have greatly advanced. In fact, on the one hand, efficient calculation procedures based on the finite elements method and made possible by the advent of the new digital computers have been developed. On the other hand, the introduction of the modern electronic techniques has enormously improved the measurement accuracy, while the use of small process computers has made possible the handling of large quantities of data.

It seems, therefore, appropriate to try to define, even in so rapidly an evolving situation, the perspectives and application field of the experimental method as compared with the analytical one by both summarizing the operational techniques and available facilities, and illustrating two recent model studies carried out at the ISMES.

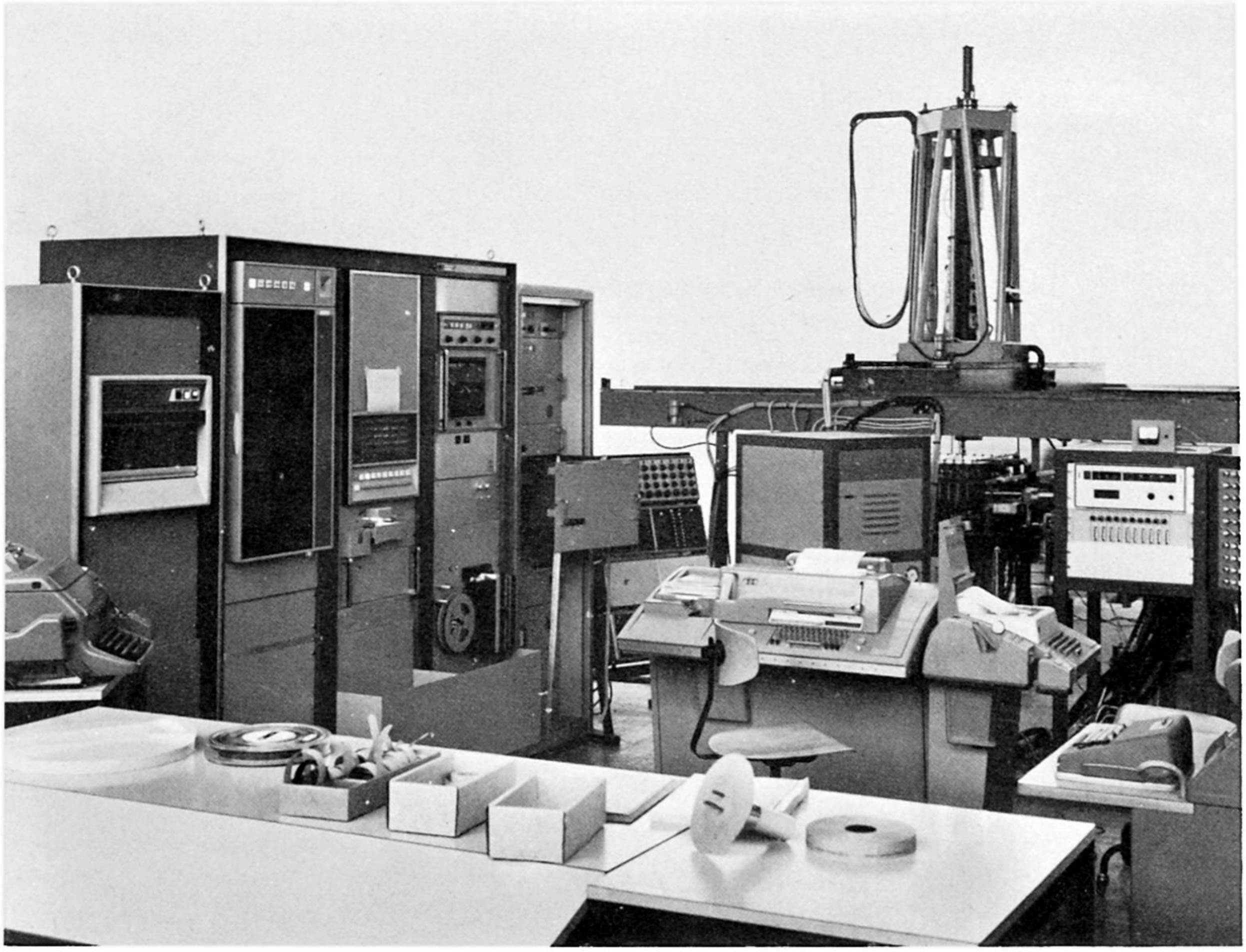
2. TESTING EQUIPMENT

A thorough understanding of the possibilities and also present-day limitations of the experimental techniques requires at first a description, though a brief one, of the equipment presently available to the experimenter.

The criterion followed below consists in mentioning, on the basis of their functions, the various component parts used. We thus have:

Loading equipment

The loading is applied, using a conventional technique, by one or more oil-controlled jacks.



However, it is today possible to have an automatic control of the loading by means of a force transducer inserted between the structure and the jack. The transducer generates a feedback signal which, compared with a reference one, then acts on a servopump that controls the pressure of the oil and, hence, the load value.

The accuracy of this system is nowadays enormous; suffice it to consider the performances of the materials testing machinery operating in a like manner.

Data acquisition instrumentation

Data acquisition instruments (transducers) of any type, size and characteristics are presently available in commerce. Their accuracy is very high (about 1%).

For example, the displacement measurement problems are solved by using capacitance or inductance type transducers. Strains are easily measured by various types of extensometers (foil grid strain gages for a great stability or semiconductor strain gages for a large sensitivity).

Moreover, a wide variety of electrical instruments sensitive to different mechanical quantities (force, pressure, moment, etc.) is based on the use of extensometers.

In the dynamic field, the use of materials with piezoelectric properties has brought about lightweight accelerometers, force pickups, etc., working very well in any environment (in water, under pressure, at high temperature or in the presence of radiation).

Each transducer then is connected to a data logger by means of a signal-conditioning device whose task it is to raise the level of the electric signal of the transducer to a value that is sufficient for the following processing and datum acquisition phases.

The data logger commutates the various signals at the input of a digital reading instrument which furnishes a numerical indication of the performed measurement.

The data acquisition time substantially depends on the adopted scanning method, on the reading system and on the type of instrumentation available for the data storage. It generally ranges from a few points per second to a few hundred ones.

Data processing instrumentation

The operator who elaborated a few data has now been replaced by the process computer.

This computer is charged with all the test control operations. In particular, it regulates the various loading cycles, it controls the data logger in the commutation phase (with possible selection of the gage point), it orders the measuring system to read the datum and, finally, it commits the indication to memory.

3. EXPERIMENTAL TECHNIQUES ON ELASTIC MODELS

a) Test criteria in the static field

In elastic range tests, the conventional procedure usually required a complicated equipment capable of reproducing simultaneously over the entire structure a certain loading condition (e.g., dead load, working loads, live load, wind effect, etc.). This equipment, made up of a reacting frame and a series of jacks, was constructed to be used on a model of a given size and shape, and necessarily had to be redesigned if the model under study was changed and sometimes even when the type of loading applied varied.

It is, therefore, obvious that under such conditions the number of tests was kept as low as possible and, likewise, the cost of a manual data elaboration limited the number of instruments used.

The present trend, sponsored by Hossdorf, is rather to use a more general method consisting in determining appropriate influence coefficients. When these coefficients are known, it is simple to calculate the "response" of the structure to any system of acting forces.

The method can be summarized as follows.

A series of n points capable of describing accurately enough the state of deformation (or stress) of the structure is chosen. The structure is then loaded only by one jack in the position i, while the measuring equipment reads, for all the n points, the value of the quantity δ_i under study (displacement, strain, moment, shearing stress, etc.). The influence coefficients

$$\delta_{ji} = \frac{\delta_j}{F_i} \qquad (j = 1,n)$$

are thus obtained.

The jack is then applied to each of the remaining points.

The set of n · x values of δ_{ji} forms the matrix $[\delta]$ of the influence coefficients for the given quantity. The values $\{x\}$ of this quantity for a certain loading condition P is then given by

$$\{x\} = [\delta]\cdot\{P\} \tag{1}$$

Quite clearly, this investigation method is very efficient, especially when the rapidity with which the testing equipment can determine the matrix $[\delta]$ is taken into account.

However, it seems appropriate to point out some disadvantages which in practice may limit its use.

1) The method makes use of the principle of superposition of effects and is, therefore, applicable only to structures with a linear behavior. It cannot rigorously be used in all those cases where, though the stress remains in the elastic range, the strain is not proportional to the acting load because of the geometry of the structure (e.g., suspension bridges).

2) For a number of massive structures (such as dams, nuclear reactor vessels, etc.) the possibility of measuring accurately enough the influence coefficients depends on the possibility of increasing the applied load without locally damaging the model. This possibility is determined solely by the elastic properties of the model material and frequently does not exist.
Difficulties in evaluating the influence coefficients appear also in all the cases where it is necessary to measure a mechanical quantity that is superposed by an undesired quantity of the same type having a very high value. Such cases are found, for instance, when it is necessary

to measure the displacement in a certain direction while a large displacement exists in the orthogonal direction (case of a diverted flexure or a flexure accompanied by torsion) or when the axial stress in a cross-section loaded also by a large moment is to be found.

3) The final result of the analysis is always obtained, on the basis of equation (1), as the sum of the results of numerous independent measurements. Quite obviously, this sum contains the errors of all the measurements made and, therefore, this method is intrinsically less accurate than the conventional one.

b) Test criteria in the dynamic field

The experimental study of the dynamic behavior of a structure is correctly made when the dynamic actions on the prototype (or the anticipated ones) are applied to a model faithfully simulating all the essential details.

In such a study, the difficulty of having an excitation equipment reproducing the characteristics of utmost interest (spectral density function, probability density function, r.m.s. value) of the dynamic actions is added to the difficulty of manufacturing a model responding to the similitude laws.

The instruments available at present (shaking tables, electrodynamic or electrohydraulic exciters, etc.) have partly met the request but are very expensive and require skilled operators.

On the other hand, modal analysis theory shows that the dynamic behavior of a structure in the elastic range is entirely known when its vibration modes (i.e., natural frequency, shape and damping of each mode) are determined. It is, therefore, natural that the experimenter prefers to look for the principal vibration modes and then obtain by calculation the response of the structure to any excitation, rather than simulate such an excitation on the structure.

The evaluation of the principal "modes" is presently based on the following considerations.

The oscillations of a structure, produced by a system of external forces, can always be expressed as the sum of the oscillations relative to the various modes. It is also obvious that a particular choice of the excitation forces can render negligible or even nullify the contribution of a single mode to the response of the structure.

Therefore, the problem of exciting a dynamic system according to one only vibration mode is reduced to determining the particular force system for which the response of all the modes, except the desired one, is nil.

The problem cannot be solved directly because it would require an advance knowledge of the frequency and shape of the mode under examination. Nevertheless, a technique has been developed, based on an iterative process which permits at each successive step to render ever more negligible the response of the undesired modes.

In practice, each iteration permits, on the basis of the results obtained in the previous test, to apply a certain number of exciters (capable of generating sinusoidal forces having a frequency equal to the one of the supposedly known desired mode) to the most suitable points of the structure, and, at the same time, to regulate the value of the force generated by them. It should be:

$$\{F\}^{(i)} = [m] \cdot \{\ddot{x}\}^{(i-1)}$$

where $\{\ddot{x}\}^{(i-1)}$ are the accelerations resulting in the (i - 1)th iteration.

Although extremely efficient, this method requires complex equipment and is not too easily applicable, especially when the higher vibration modes are also to be determined.

At present, in this field, too, the advent of the test techniques described under point 3 a) has produced a considerable simplification and a cost reduction.

Suffice it to observe that the influence coefficients for the displacement are but the coefficients of the structure's flexibility matrix. Therefore, when the structure is considered as a lump system of springs and masses (concentrated in the points chosen for the experimentation), the problem of the mode determination is turned into the rather simple problem of calculating the eigenvalues and eigenvectors relevant to the matrix $[m] \cdot [\delta]$, where $[\delta]$ is not affected by calculation or schematization errors as it has been obtained experimentally.

The dynamic problem has thus been changed into a statical one and, therefore, can be handled by numerous laboratories.

Some limitations of this type of analysis will be pointed out here, too. They are:

1) the structure has to be schematized by a lump system of masses. This involves inevitable errors which experience alone can reduce to a minimum;

2) the number of masses (or degrees of freedom) of the system chosen to schematize the structure must be fixed in function of the modes which one wishes to derive. An accurate description of the modes may, therefore, require a large number of masses, and this very much increases the amount of work necessary to determine the flexibility matrix;

3) the flexibility matrix must be known very accurately. In fact, the errors affecting the coefficients greatly influence the calculation of the higher modes.

4. TEST CRITERIA BEYOND THE ELASTIC RANGE UP TO FAILURE

The superiority of the experimental method over the analytical one is unquestionable when the structure's behavior has to be checked beyond the elastic range until determining its factor of safety. However, serious problems still exist about the construction of a model reproducing the prototype with complete faithfulness. In this case, the data acquisition and processing techniques have not basically changed the testing scheme in a way similar to the one of experimentation in the elastic range.

The main reason is that, because of the impossibility of applying the principle of superposition of effects, the operator is not free to choose the type and value of the loadings, which must be the same as those predicted for the prototype.

Nevertheless, the computer can in this case, too, be of a very great use, mainly because the rapid elaboration on line of the acquired data enables it to readily indicate the arising of yielding zones, fractures, etc.

However, the greatest developments of the experimental technique are to be expected in the modeling field by producing materials most responding to the similitude laws.

5. EXAMPLES

The above techniques are illustrated below by two examples, one high-rise building and one suspension bridge, recently tested at the ISMES in the elastic range under seismic action.

a) Parque Central building, Caracas, Venezuela

Fig. 2 shows the 1 : 40 scale resin model. The number of gage points chosen was 32, and the model was successively loaded in each of them so as to furnish a series of deformed surfaces (fig. 4). Simultaneously with the displacements, recordings were made also of the indications of numerous strain gages applied to the base.

The results obtained permitted to calculate the vibration modes (fig. 3), and these were later found experimentally by placing the model on a shake table excited in resonance.

At this point it was possible to check the seismic performance of the structure by calculating the response of each mode to the design earthquake and determining the resulting distribution of the forces of inertia. Having thus obtained the system of horizontal forces P equivalent in its effect to the earthquake, it was easy to also calculate the stresses at the base as a superposition of effects.

b) Bosphorus suspension bridge

A 1 : 200 scale resin model was made, using appropriate artifices for a correct reproduction of all the parameters of interest (fig. 5).

As the influence coefficient method could not be applied to this structure, a first test was made to determine the importance of the nonlinearity of behavior. The conclusion was that in this case, too, the load-deformation curve, for loads of not too great a magnitude, could in a first approximation be assimilated to a straight line.

The above-described criteria were, therefore, used by determining at first the deformed surfaces of the deck (fig. 6) and also of the cables for different positions and directions of the load and, hence, the natural vibration modes (fig. 7).

7. CONCLUSIONS

In concluding the above considerations, a comparison between the experimental and analytical investigation methods can be attempted.

As is known, the analytical method deals with a structure whose behavior has been schematized by well-defined mathematical laws. In general, both by the conventional solution methods and the one of the finite elements, one arrives at a system of linear algebraic equations which in a matrix form is of the type:

$$[K]\cdot\{x\} = \{B\} \tag{2}$$

System (2) contains the following three matrices:

1) "column matrix" $\{x\}$ whose elements form the unknowns of the problem (sometimes the displacements and sometimes the forces);
2) matrix $[K]$ whose coefficients depend on the geometry of the structure and the elastic properties of the material;
3) column matrix $\{B\}$ of the known terms containing the data of the problem (external loads, restraint settlements, temperature variations, etc.).

The solution of system (2) leads to the relation

$$\{x\} = [K]^{-1}\cdot\{B\} \tag{3}$$

Relation (3) shows that the investigation of the unknowns is, in any case, directly or indirectly connected with the problem of inverting the matrix $[K]$.

The detailed description of the solution procedure shows that the most serious and significant problems are as follows:

a) Formation of matrix $[K]$

The calculation of the coefficients of the matrix $[K]$ can in the simplest cases (beams, plane or space frames, etc.) be easily set up. It is more complicated for three-dimensional structures, and the simplifications which must be introduced make frequently the results little reliable.

b) Inversion error

As was already mentioned, there is, explicitly or implicitly, the problem of inverting a matrix.
However, as the number of unknowns increases, this inversion may become too laborious even with computers of great power. This is so because the propagation of the rounding-off errors, when the direct solution methods are used, or the "cutoff errors" when the "iterative methods" are resorted to, make in any case the final error sometimes so appreciable as to annul the advantage of a better schematization.
The attempt to obviate these inconveniences by conducting the calculations with a great number of significant figures can lead to economically almost prohibitive computation times.

c) Cost

The treatment of complex problems in which an accurate description of the structure requires a large number of unknowns involves not only solution difficulties but also great cost increases in using the computer for both forming and inverting the matrix $[K]$.
It should also be pointed out that, in the case of unusual structures, very heavy economic problems may arise in adapting existing programs (especially as regards the input and output of the data) and in checking the quality of the adopted schematizations.

In the experimental method, the construction of the model is the equivalent of the matrix $[K]$. It should, however, be observed that, at least in the elastic range, no particular difficulties exist and the similitude laws can easily be complied with when a suitable material and geometric scale are chosen.

Of utmost importance is, moreover, the fact that, in this case, there is no matrix inversion problem.

The model functions as an analogic computer and furnishes the exact solution (if the model is exact) with no approximations of any kind.

The cost of the model test is rather high even in simple cases despite the fact that the new data acquisition equipment has appreciably reduced the time required.

Likewise expensive is still the construction of the model, on whose accuracy and fidelity of operation depends the quality of the results.

In view of all the above, we may conclude that the experimental and analytical methods have complementary fields of employment. The problems relating to structures that are plane or symmetrical with respect to their axis, and to plane or space frames will advantageously be studied on a computer, whereas recourse to model testing will be more economical (and accurate) for complex structures.

SUMMARY

Some general considerations on the usefulness of model studies in both the design and verification stages of large tridimensional structures are first outlined.

The new testing techniques in both the static and dynamic fields, based on the use of modern data acquisition systems in association with a computer, are then analyzed. As regards the dynamic field, emphasis is placed on the considerable simplification of the excitation equipment with consequent cost reduction.

In this connection, the results of some elastic model tests conducted at ISMES, Bergamo, Italy, by using the above criteria are illustrated.

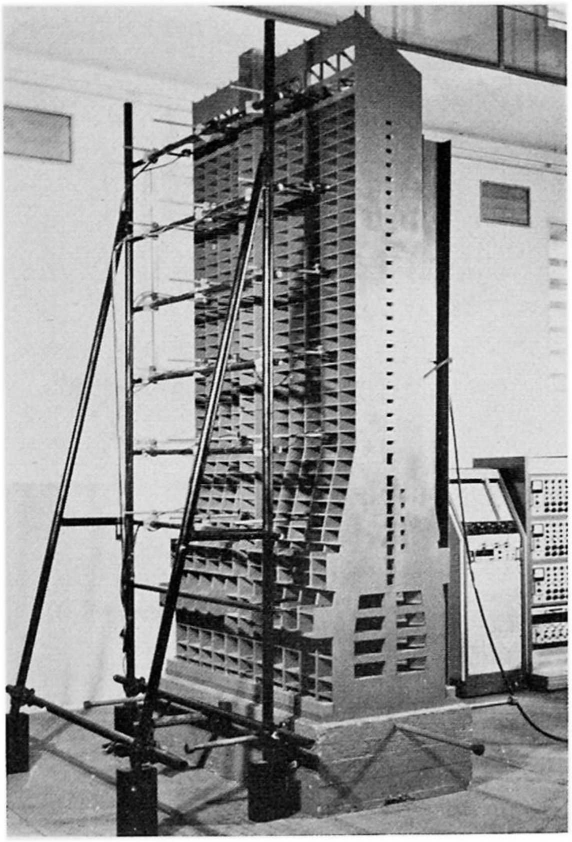


Fig. 2

FIRST VIBRATION MODE

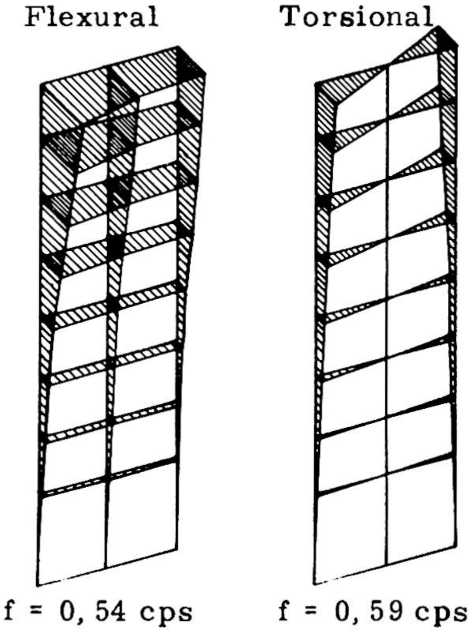


Fig. 3

DEFORMATIONS FOR HORIZONTAL LOAD IN POSITIONS

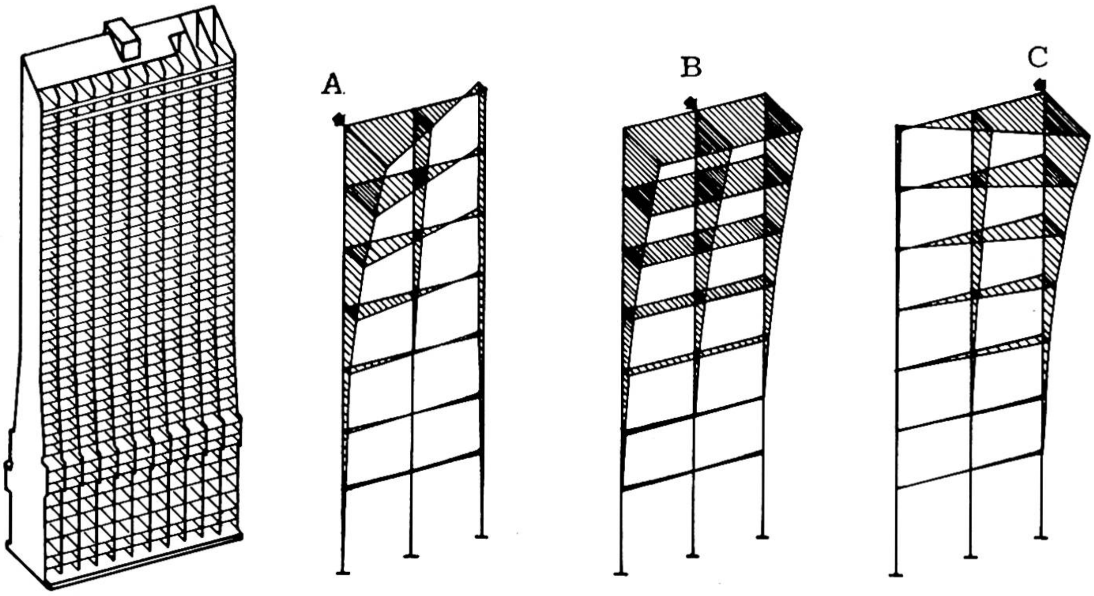


Fig. 4

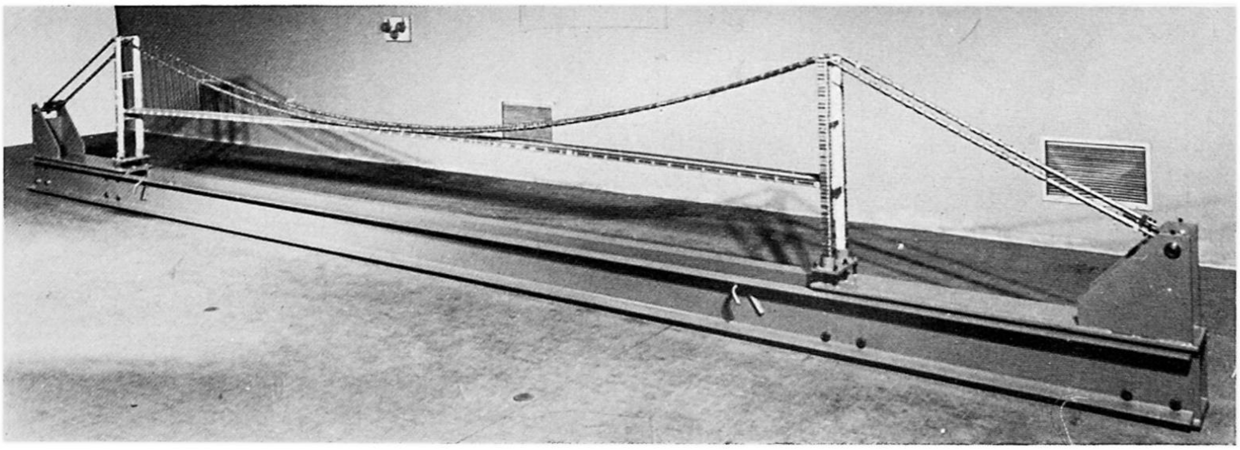


Fig. 5

DECK DEFORMATIONS FOR VERTICAL LOADS

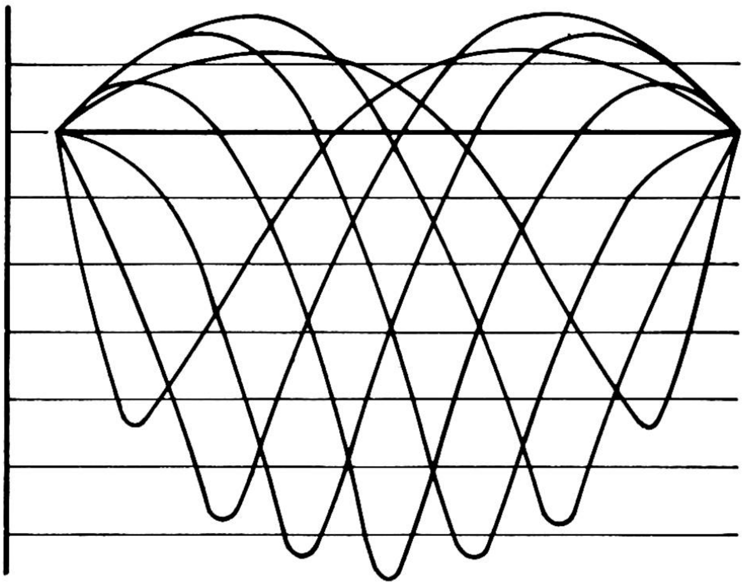


Fig. 6

VIBRATION MODES

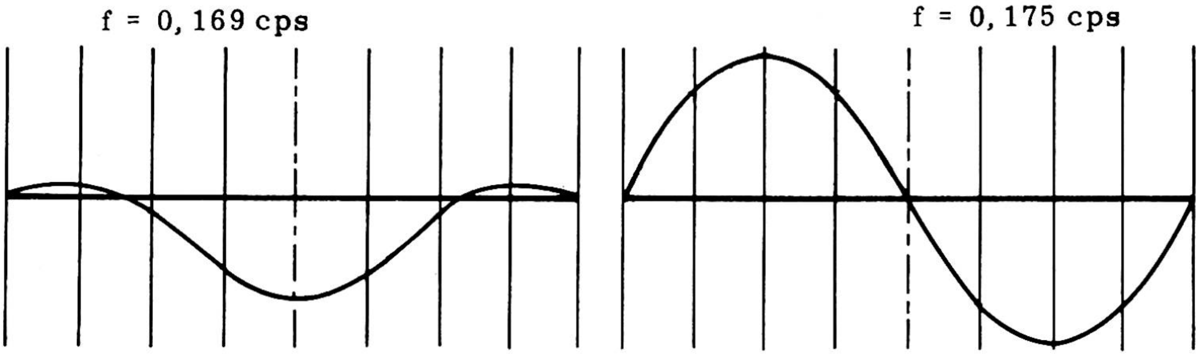


Fig. 7

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