DYNAMIC BEHAVIOUR OF CONCRETE STRUCTURES

REPORT OF THE RILEM 65 MDB COMMITTEE

Edited by

G.P. TILLY

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Chairman, RILEM 65 MDB Committee

ELSEVIER

Amsterdam — Oxford — New York — Tokyo

1986

ELSEVIER SCIENCE, PUBLISHERS B.V.
Sara Burgerhartstraat 25
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Distributors for the United States and Canada:

ELSEVIER SCIENCE PUBLISHING INC.
52, Vanderbilt Avenue
New York, NY 10017 U.S.A.

Library of Congress Cataloging-in-Publication Data

Dynamic behaviour of concrete structures.

(Developments in civil engineering ; 13)
Bibliography: p.
Includes index.
1. Structural dynamics. 2. Concrete construction.
I., Tilly, G. P., 1937- . II. Series: Developments
in civil engineering ; v. 13.
TA654.D93 1986 624.1'834 86-4475
ISBN 0-444-42624-8

ISBN 0-444-42624-8 (Vol. 13)
ISBN 0-444-41715-X (Series)

Printed in The Netherlands

PREFACE

This publication comes at a very good time because the engineering development of concrete structures has just reached the stage where dynamic behaviour could be critical to design. Hitherto dynamic behaviour has been a preoccupation of steel designers because of the lighter weight, lower flexibility and lower damping of steel assemblages. Also steel has been used for the more demanding applications where there is less margin for error. However, this is now changing and with the introduction of higher strength materials and more advanced designs, concrete is becoming used in situations that would previously have been the preserve of steel. For example, highway bridges of spans greater than about 200m would automatically have been constructed in steel up to a decade ago; in 1983 the Barrios de Luna Bridge in Northern Spain was constructed in concrete with a main span of 440m. This is not only the longest concrete span but is the longest cable stayed span of steel or concrete in the world at the time of writing. In the North Sea the first generation of platforms was steel but they were quickly followed by advanced concrete structures. Currently there are plans to build more massive concrete structures particularly in the Arctic.

The different structures discussed in this publication are bridges, buildings, offshore platforms, offshore cranes, dams, wind turbines, chimneys, TV towers, bell towers and transmission towers.

During preparation of the text it quickly became evident that there are too many topics to be considered in the one publication and it was necessary to miss out or deal only superficially with many of them. It was decided that the emphasis should be on the analysis, testing and performance of structures. Design is dealt with in a generalised manner and methods of reducing dynamic response (by increased stiffness, added damping, etc) have had to be missed out altogether. Each section of the report is self sufficient so that there are some topics that have of necessity been repeated. Such repetition has however been minimised as much as possible. Cross references have been made where appropriate.

The combination of disciplines and structures has provided an opportunity to generate a unique overview which brings together the different approaches. An interesting example of differing approaches is the way that the equations of fatigue have been developed for steel and concrete. For steel the acceptance of fracture mechanics, particularly for welded connections, has led to the usage of simple power law relationships between stress (S) and endurance (N) to represent the so-called S-N or Wohler curves of fatigue performance. Concrete has been researched along rather different lines and the application of fracture mechanics has only recently been considered. The relationships between stress and endurance are usually represented semi-logarithmically, i.e. by linear-S and logarithmic-N. In this instance there is a good case for concrete using the same type of representation as steel because it is based on the science of fracture mechanics and therefore has more significance than an empirical relationship.

The text is divided into six chapters, starting from basic definitions and going on to the special problems and technologies of different structures.

In Chapter 1, Mr Cantieni has addressed the question of when to treat a design or analysis problem as being one of statics or dynamics. The chapter goes on to deal with dynamic loads and definitions.

In Chapter 2, Professor Dyrbye has dealt with the fundamental principles of dynamic analysis. Single and multi-degree-of-freedom systems are defined and described in the two main sections. In an appendix to Chapter 2, five worked examples of dynamic systems are given. This Chapter is self sufficient and can be used by a student of the subject who wishes to become acquainted with the underlying mathematics of dynamics.

In Chapter 3, a general account of loading and effects is given. In cases of individual structures more specific information is given later in Chapter 5. The types of loading given special attention are those caused by mechanical plant (rotating, oscillating or longitudinally acting), wind, waves and earthquakes. The effects that are considered are those of structural fatigue and human tolerance to vibrations.

In Chapter 4, eight specialists have written about dynamic experiments and related data analysis techniques. This is a huge topic to cover in one chapter and it has therefore been necessary to limit it to eight sections dealing with the more important aspects of the subject. The first sections of the Chapter deal with the techniques of data acquisition and signal analysis. Laboratory techniques are discussed but there is an emphasis on field work and methods of exciting structures. Other sections deal with beam tests, vector response diagrams, seismic loading of components, structural models of offshore components and wind tunnel testing.

In Chapter 5, eleven specialists have written about the dynamic behaviour of different types of concrete structures. The types of loading relevant to the structure in question are outlined as are the different types of dynamic response and the design philosophies. Wherever possible typical examples of the dynamic characteristics are given: these include the natural frequencies (usually the first three bending frequencies), the values of damping (expressed as logarithmic decrement) and the responses to loading expressed as amplitudes of deflection or acceleration. In the section on buildings by Dr Jeary, the temptation to reduce the data has been resisted because it forms such a valuable collection of information.

In Chapter 6 the conclusions to be drawn from the earlier sections are brought together. Typical values of dynamic characteristics are listed and recommendations are made where appropriate. The latter include suggestions for further research where the needs have been identified.

The effects of the differing limit states vary according to the structure. For example, the wind loading of buildings causes the designer to be concerned mainly (but not exclusively) with the question of whether the resulting movements are within the limits of human tolerance whereas for wind loading of bridges the main concern is with structural damage through fatigue cracking or collapse.

The different structures can experience similar loadings and exhibit similar effects but the relative intensities differ. Human tolerance is a recurring theme which requires further attention to be applicable to a wider range of situations. The approach used to assess footbridges is quite different from that for buildings. This is not surprising because people crossing footbridges are exposed to the vibrations for relatively short periods of time but the movements are much greater. On the other hand people in buildings can be exposed for long times to small movements and, moreover, are usually seated and therefore more perceptive.

The other recurring theme is fatigue. This can be caused by low numbers of high loads, for example earthquakes, or high numbers of low stress cycles, for example wave loading of offshore platforms. Despite the extensive research to date, there remains further work to be done because there is a need to bring together and rationalise the methodology of fatigue, particularly in relation to Design Codes.

It is intended that this publication should be useful to designers, researchers and students. It is hoped that the unique mix of disciplines and structures will provide an invaluable source of information which will remain relevant for many years.

The work has been carried out by the RILEM 65 MDB committee and there have been special contributions by others, as acknowledged on page XIII. It is my pleasure to thank all these contributors for their hard work and patience.

G P TILLY

Developments in Civil Engineering

Vol. 1 The Dynamics of Explosion and its Use (Henrych)
Vol. 2 The Dynamics of Arches and Frames (Henrych)
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Vol. 11 Structural Dynamics (Vértes)
Vol. 12 The Selection of Load-Bearing Structures for Buildings (Horváth)
Vol. 13 Dynamic Behaviour of Concrete Structures (Tilly, Editor)

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ACKNOWLEDGEMENTS

Contributions have also been received from specialists outside the Committee and their assistance is gratefully acknowledged:

- Dr N I Cook, Building Research Establishment, provided the sections on wind tunnel testing and wind loading.
- Mr J S Hay, formerly of the Transport and Road Research Laboratory, provided the sections on measurements of wind.
- Mr Peter Simpson, Wind Energy Group, assisted in the preparation of the section on wind turbines.
- Mr J A D Balfour, Heriot-Watt University, provided information and results for the section on offshore cranes.
- Miss Joyce Smith, Heriot-Watt University, prepared the final typescript.

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Chapter 1

INTRODUCTION TO THE DYNAMICS OF STRUCTURES IN RELATION TO DESIGN

1.1 STATICS, DYNAMICS AND TIME

Any strict attempt to separate static and dynamic phenomena is beset with difficulties. If the concepts "static" and "dynamic" are described as "time invariant" and "time variant" respectively the question immediately arises: are there really any phenomena (loads, forces, deformations) which do not vary with time? A Buddhist philosopher would certainly answer in the negative: Nothing is invariant! A physicist would perhaps admit that gravitational acceleration is constant at a specific location on the earth's surface. There, for example, the weight of a body would be time invariant, as long as its mass was not altered through physical or chemical processes. However, implicit in this concept of time invariance are several conditions. For example the time frame includes only the period in which the earth exists in its present form and in which the mass of the body remains constant. Furthermore, changes in location are not allowed. For an engineer who is involved with structures that are, in one way or another, fixed to the earth's surface, these conditions are likely to be fulfilled. Thus, with a good conscience, he can assume that the dead load of his structure is time invariant, i.e. a static quantity. There now remains, with answers of interest to the engineer, the question: where does the boundary between static and dynamic phenomena lie? A proper definition of this boundary is imperative in order to correctly assess the load-carrying capacity and serviceability of structures. Obviously, time is a very important factor in the differentiation of static and dynamic phenomena.

Stated simply, time manifests itself in two quantities, namely the period (or frequency) with which a load (or a support motion) varies and the period (or frequency) of a mode of vibration of a structure. Whether a problem is to be treated by static or dynamic methods cannot be assessed through a consideration of just one of these two quantities. Rather the relationship between them must be considered. The situation can be formulated as follows: a problem must be treated by dynamic methods if the forces caused by the load evoke a dynamic response of the structure. This will take place if the periods of the load variation and a natural period of the structure are close together or equal.

In many practical cases loads occur with a range of frequencies and the structure may have several modes of vibration. Therefore, the more general concepts of "load spectrum" and "transfer function" will be used in the following discussion. First though, these terms must be defined. The "load spectrum" shows the distribution of the frequencies of the load application together with the amplitude or power at each of these frequencies. It is usually plotted as a graph of load power against frequency. The "transfer function" of a system is a mathematical relationship between the output (or response) and the input (or excitation) of the system. It is usually given as a complex function of frequency. Using these definitions the above formulation may be stated more generally: a problem must be treated by dynamic methods if peaks in the load spectrum nearly coincide with peaks in the transfer function of the loaded structure. If the frequencies of the load are substantially lower than the fundamental frequency of the structure then the problem can be solved by static methods. This applies to most structures in which no vibrations occur. If the load frequencies are substantially higher than the highest natural frequency of concern in the structure, then the dynamic response will be insignificantly small. In all other cases, dynamic methods must be employed to determine the structural response correctly (see Chapter 2).

To avoid confusion, the concept of the "dynamic method" will be clarified below. The basic principles of static structural analysis are, of course, not invalidated by the fact that the structural response is dynamic. The same relationships between deflection and stress apply under both dynamic and static conditions. Dynamic analysis consists primarily of the determination of the time variation of deflection, from which stresses can be directly computed. In the following example it will be shown that it is not meaningful to qualify a given load as "static" or "dynamic", independently of the dynamic properties of the structure involved: although it is thoroughly justified to treat the effects of wind loads on low, squat structures (buildings) with static methods, it must be taken into account that the same loads can cause resonance phenomena in high, slender structures (tall buildings, towers, etc). As long as the fundamental frequency of a structure is high enough so that it does not respond to wind gusts, it is sufficient to base the analysis and design upon a maximum wind force, acting statically. It must be realised that the boundary between statics and dynamics is not invariable. It depends upon the load spectrum as well as the properties of the structure. This fact can lead to problems.

It is the tendency in civil engineering to treat loads as far as possible on the basis of static load models and avoid burdening the design engineer with dynamic analysis. On the other hand, modern structures are tending to be more and more slender and flexible. Thus, the peaks in the load spectrum and the peaks in the transfer function of the structure are coming closer together, and the danger of dynamic problems occurring in a structure is becoming correspondingly greater. It is understandable that the use of static load models is preferred in loading codes for the following reasons:

(1) These models have proved reliable over many years;
(2) The proportion of dynamic to static load is often relatively small;
(3) Measurement results which can serve as the basis of dynamic load models are not always available in sufficient quantity and reliable form;
(4) The educational background of civil engineers usually concentrates on the treatment of static design methods;
(5) Dynamic calculations can be carried out by hand only for simple systems or models of real systems.

Fortunately, parallel to the increase of dynamic problems in structures, there has been a rapid development of measurement, data processing and analysis methods. As a result, the treatment of dynamic problems today is much easier than it was 10 or 20 years ago.

In the following paragraphs the various load types will be discussed so as to classify the ensuing responses as either static or dynamic. In addition to the dead load, which can certainly be considered as static, certain other actions may be mentioned where no dynamic problems are to be expected due to their slow variation with time:

(1) Creep, shrinkage, relaxation;
(2) Temperature effects;
(3) Prestressing and its side effects;
(4) Effects of settling of foundations;
(5) Immovable live loads such as soil pressure and snow loads (assuming that dynamic forces are not produced in the structure during application of these loads).

Load types in which the load spectrum and the transfer function of the structure may have peaks in the same frequency range can be summarised as follows:

(1) Forces excited through the direct influence of natural phenomena such as wind, waves, ice drift;
(2) Forces induced by support movements (e.g. earthquakes);
(3) Structures loaded with moving masses or vibrational systems (pedestrians, road traffic, rail vehicles);
(4) Structures subjected to alternating forces caused by oscillating machinery;
(5) Impulse-type loads, mostly produced by human action, such as for example, aircraft crashes, pressure waves from explosions or vandalism.

If these load types are examined more closely, then one finds differences not only with respect to cause and spectrum, but also with respect to the proportion of static to dynamic load and the average duration of influence.

For example, an earthquake generally results mainly in dynamic forces whereas moving traffic on a bridge results in static as well as dynamic forces. In addition, the duration of influence, for example of sea waves, cannot be compared with that of impulse type loads. Consequently, it is always necessary to consider various aspects before deciding whether to analyse a structure by static or dynamic methods. These aspects are:

(1) *Relation between load spectrum and transfer function of the structure;*

(2) Damping of the structural vibrations;

(3) Duration of the dynamic loads;

(4) Variability of the parameters describing the load and force functions;

(5) Magnitude of the force amplitudes produced in the structure (including absolute values of the forces as well as the proportion of dynamic to static forces);

(6) Number of load cycles per unit time and during the intended life of the structure (as a function of the amplitude).

Furthermore, it should be considered whether the load carrying capacity or the serviceability of the structure would be endangered by dynamic loads and what the consequences would be if the structure collapsed or became unusable. In many cases, it is not possible to predict the loading (and consequently *stress) histories of a structure exactly. As a result, probability theory is* being employed more and more both in transforming dynamic into static load models and also in actual dynamic analysis. Such theoretical approaches are only possible if they are founded upon a sufficient amount of reliable measurements.

Although the methods of measuring the load function, transfer function and system response are selected to meet the specific problem on hand, the further processing of these dynamic signals always makes use of the same basic methods. Physics (statics and dynamics) and mathematics (deterministic and stochastic) are equally valid, regardless of whether a bell tower or an offshore structure is under discussion.

1.2 EFFECTS OF DYNAMIC LOADS

Dynamic forces can endanger the load carrying capacity or the serviceability of structures. Since the loss of load carrying capacity can have drastic consequences, structures are nowadays designed with quite a small probability of failure due to fatigue or collapse. Either the static substitute loads provided by the codes are set sufficiently high (this remains the most common approach) or dynamic analysis is required. However, an absolute protection against the effects of catastrophic events such as strong earthquakes, hurricanes, etc, is of course not possible. The study of problems relating to the load-carrying capacity of structures has a long tradition, and even today