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CONNECTIONS BETWEEN EQUIPMENT AND STRUCTURES SUBJECT TO SEISMIC LOADING -- PRELIMINARY BIBLIOGRAPHY

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Connections are treated in their role as a component in an overall dynamic system including equipment or machinery, connections, structure, and foundations.

Over 700 reference citations are presented including over 450 references on general analysis and design and over 250 references on equipment and machinery.

Findings of the survey are that literature specifically treating the connections of concern is scarce, especially with regard to earthquake problems.

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ABSTRACT

Literature on earthquake and dynamic response, analysis, and design approaches for connections between equipment or machinery and structures are covered in this comprehensive bibliographic survey. The equipment or machinery involved includes a wide range of units found in typical industrial installations such as materials processing plants, chemical plants, petroleum refineries, and fossil fuel power plants.

Connections are treated in their role as a component in an overall dynamic system including equipment or machinery, connections, structure, and foundations. The interaction of several components of the dynamic system is identified as the main problem in connection design.

Over 700 reference citations are presented including over 450 references on general analysis and design and over 250 references on equipment and machinery. Subdivisions of the portions on general analysis and design cover damage, codes, damping, details and decision analysis. Among the categories of equipment and machinery are generators, motors, pumps, pressure vessels, piping, tanks, stacks, electrical equipment, furnaces, bins, conveyor systems, mixers, precipitators and cranes.

Findings of the survey are that literature specifically treating the connections of concern is scarce, especially with regard to earthquake problems. Persons seeking design information must interpolate and extrapolate from information gathered from other related areas. Synthesis of the references into a state-of-the-art report will be done in a separate paper.

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1. INTRODUCTION

Earthquake effects on a structure and the equipment or machinery connected to it are very much dependent on earthquake ground motion and on the mechanical and dynamic properties of the structure and equipment and their connecting elements. The most important of these properties are the strength and energy absorbing capacity of the entire load carrying structure and of the connections joining the equipment to the structure.

In order to establish the proper relationships between equipment and the rest of the structure, the so-called systems approach may be used. Then, any structure whether it is an industrial plant, a commercial building, or a public building can be considered in terms of a combination of components or subsystems. These subsystems are (see, for instance, Figs. 1 and 2):

(1) Soil-Foundation System

(2) Main Structural System

(3) Non-Structural System (curtain walls, ceilings, cladding, etc.)

(4) Equipment or Machinery and their Connecting Systems

The connecting system includes "connections" as a component. In general, connections are made up of fasteners, detail material added to accommodate fasteners or to stiffen the joint, and any parts of a machine or structure which are extended to accommodate fastening. Within the context of this report, connections are also assumed to be composed of machinery or equipment supports, shock absorbing and damping elements

(pads, springs, viscoelastic layers), hanging or suspension systems, mounting platforms, pedestals, etc. (A more precise definition of the connecting system will be introduced in Sec. 3.) This report will be primarily concerned with the literature related to the dynamic response of equipment and connections to earthquakes.

Equipment and machinery for purposes of this report, will include machines used in industrial processes as well as other associated apparatus, equipment, and devices. Any class of equipment or machinery is included if it might be subject to earthquake hazard by virtue of its own size and mass distribution or if it might contribute to the earthquake hazard of a structure housing it.

In the past, the prime objective of earthquake resistant design was to maintain overall integrity and safety of the structure itself during and after an earthquake, without much concern for the response of "non-structural elements" or "equipment and machinery systems" attached to the structure.

This design approach assumes that the non-structural elements will take care of themselves with negligible damage if the load carrying structural system or structural elements survive the earthquake shock and motion. However, more recent investigations and evaluations conducted in the aftermath of recent earthquakes clearly indicate the real extent and magnitude of damage suffered by the non-structural elements and equipment or machinery. For instance, in the 1971 San Fernando earthquake, electrical and mechanical equipment suffered damage which rendered it inoperable, even though many buildings containing such equipment suffered negligible structural damage.

Therefore, the damage incurred by the equipment or machinery and its consequent effect on the safety of the building's occupants and contents and the economic loss due to down production time, repair, and replacements can not be neglected. Furthermore, damage to equipment or machinery which is part of the so-called "life-line" systems (i.e., power plants, communication facilities, hospitals) may result in unacceptable consequences for a modern society.

The literature available on structural connections for equipment or machinery is limited and is scattered among several disciplines and areas and, in some cases, among the design manuals and handbooks of manufacturers and consulting engineers. Therefore, the present authors approached the subject in a three-pronged way:

(1) an in-depth literature survey

(2) a direct industry survey through a "questionnaire" sent to the professionals in industry and in consulting engineering firms working in the subject area

(3) visits and discussions with the professionals in industry and consulting engineering firms.

Currently, the initial phase of the literature survey has been completed and is the subject of this report. The direct industry survey is at the finishing stage and the responses are being sorted out and evaluated. The results will be included in a forthcoming state-of-the-art report.

2. OBJECTIVES

The main objectives of the current investigation are:

(1) to review the state-of-the-art in earthquake resistant design of connections for equipment or machinery

(2) to consider and describe briefly the general principles and and analytical models employed and upon which the current design practice is based

(3) to review the related codes, specifications, standards and guides

(4) to define the gaps and research needs for safer and more economical design of connections.

The emphasis here is to be on connections associated with the equipment or machinery in industrial installations. These installations are primarily fossil fuel power plants, petroleum refineries, chemical plants, and materials processing plants. The results would be applicable to other installations which involve at least some facilities similar to those listed in this report. Nuclear power plants, however, are beyond the scope of this report since they are the subject of many other investigations. However, pertinent literature on some nuclear plant equipment of a nature similar to equipment or machinery in other industrial installations will also be taken into account.

The purpose of this report is to present the initial part of the literature survey and study as a preliminary bibliography on the subject (see Sections 5 and 6 of this report). A critical review of the available literature and knowledge gathered from other sources will be presented in the form of a state-of-the-art report and also an intensive review of the

related codes, specifications and standards will be the subject matter of subsequent technical reports. A final bibliographic report which is to include further relevant references is planned.

3. MAIN PROBLEMS

Any item of equipment or machinery is usually joined to a main structural system by means of a system of connecting elements. In the current engineering and technical literature there is no common name or definition used for these connecting elements. For the sake of clarity and simplicity, the system of connecting elements will be defined here as the "connections" and will be considered as a part of an overall dynamic system. This overall dynamic system can be considered to be composed of the following physical components:

(1) Equipment or Machinery System

(2) Connections

(3) Connecting Sub-Structure

(4) Structural Member System

A typical configuration of these dynamic systems is given in Fig. 3.

The problem to be considered in the analysis of the equipment together with the rest of the structure for seismic effects is mainly the "interaction" of several elements in a dynamic environment. The most general problem is the three-dimensional problem of "Foundation-Structure-Equipment Interactions".* However, the problem stated this way poses analytical and computational difficulties and can only be handled successfully in rare and simple

*Here, the word foundation is meant to include not only the foundation of the structure itself but also the soil and its effects.

cases. Several sub-problems may be defined to simplify the main problem. To a large extent each of these subproblems must consider the interaction of equipment or machinery with:

(a) foundation or supports,

(b) structural elements,

or (c) connections.

The subproblems may be divided further depending on the type of supports such as supporting platform, hanging platform, pedestal, or types of foundation.

In the formulation of the above problems, the types and combinations of the connections used and their configurations have to be taken into account in each individual case. Consequently, any particular design problem encountered in practice eventually has to be reduced into one or more of the above mentioned types on the basis of engineering judgement, 'experience', analytical and numerical difficulties involved, and the physical parameters to be studied.

The above classification of the subproblems is derived from a purely analytical point of view. These and other sub-problems will be considered in great detail in the subsequent state-of-the-art report.

Much of the information associated with the various aspects of seismic analysis and design of connections available in the open engineering and technical literature is scattered among many disciplines. A certain amount of the pertinent literature covers analysis and design in general, whereas other papers cover individual kinds of machinery and equipment. The treatment on connections within this literature may be incidental to the

main problem and is rarely reflected in the titles. Some of the more prominent sources of literature covered in this survey are the Seismological Society of America, the chemical and hydrocarbon process industries, the Nuclear Regulatory Commission, the Power and Structural Divisions of the ASCE, the Pressure Vessel and Piping Division of the ASME, various building code committees, and the various international committees on earthquake engineering.

Over 700 reference citations are included in Sections 5 and 6. Section 5 contains over 450 references on general analysis and design further subdivided into sections on various general aspects of analysis and design. Section 6 contains over 250 references on equipment and machinery broken into fourteen categories which appear in a wide variety of industrial installations. The major subdivisions of both reference lists are enumerated in the table of contents. Where a given reference gives substantial information on two or more of the selected subtopics, duplicate reference listings are provided in each of the subdivisions lists of Sections 5 and 6.

4. SUMMARY AND OUTLOOK

The bulk of literature available on the subject of seismic design of connections for equipment and machinery is unevenly distributed among several major categories. For example, an abundance of information exists on the seismic analysis and design of building structures. However, there is substantially less information available on the seismic response of buildings' contents and of structures other than building structures. These are areas for which more information would be extremely valuable in design practice.

Literature in the field of civil engineering with respect to structural connections is also abundant. However, only a very small percentage of it is associated with earthquake-resistant design; and literature with respect to the design of structural connections for equipment (industrial or otherwise) is almost non-existent in the civil engineering field.

Most of the information on the design of structural connections for industrial equipment, which is not plentiful by any means, exists in the literature of the chemical and hydrocarbon process industries. Unfortunately, any consideration given to seismic loading in the design procedures presented is purely incidental.

Regardless of this lack of information in some crucial areas, the bibliography presented herein will serve as a nucleus around which to organize an appraisal of the state of the art. Moreover, the bibliography will serve as a source of references for individuals confronted with design problems in this area.

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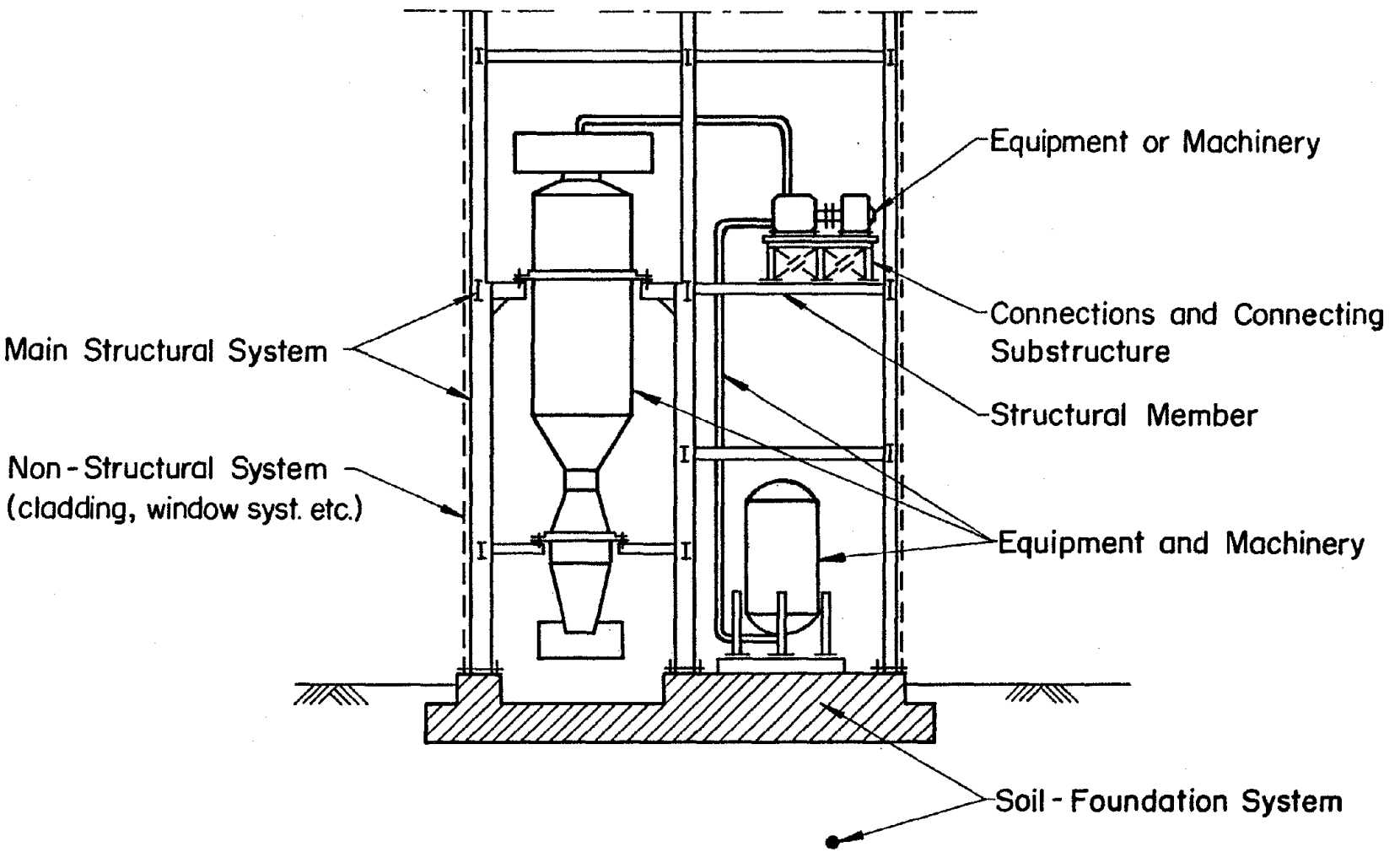

Fig. 1 Industrial Plant and its Physical Components

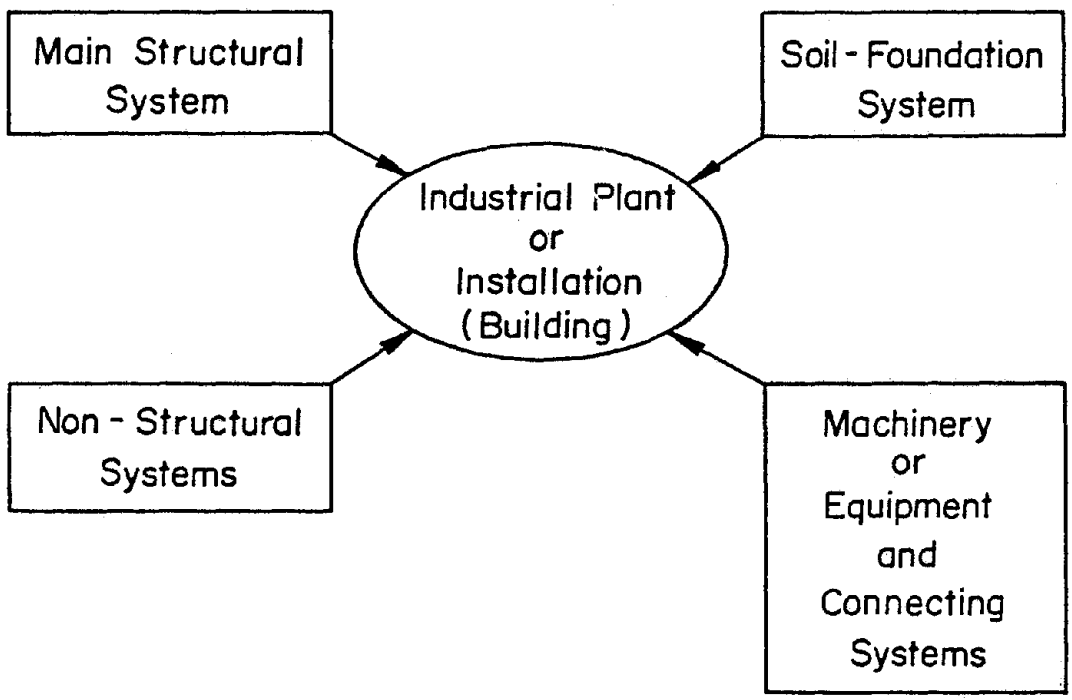

Fig. 2 Systems Representation of an Industrial Plant

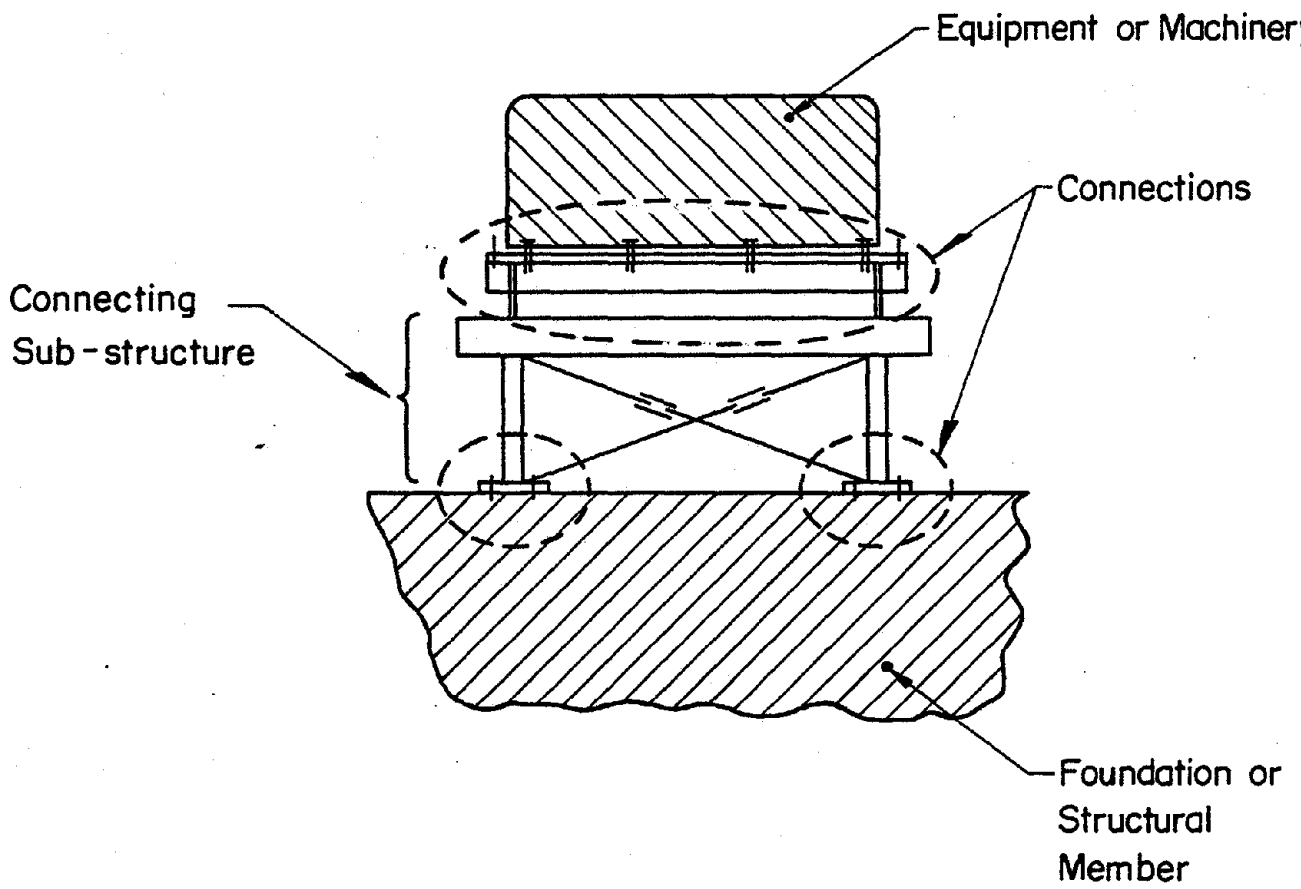

Fig. 3 A Typical Configuration of an Equipment Dynamic System

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16. Abstracts

Literature on earthquake and dynamic response, analysis, and design approaches for connections between equipment or machinery and structures are covered in this comprehensive bibliographic survey. The equipment or machinery involved includes a wide range of units found in typical industrial installations such as materials processing plants, chemical plants, petroleum refineries, and fossil fuel power plants.

Connections are treated in their role as a component in an overall dynamic system including equipment or machinery, connections, structure, and foundations.

Over 700 reference citations are presented including over 450 references on general analysis and design and over 250 references on equipment and machinery.

Findings of the survey are that literature specifically treating the connections of concern is scarce, especially with regard to earthquake problems.

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