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INDUSTRIAL FACILITIES AND EARTHQUAKE ENGINEERING

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SUMMARY

Design standards for earthquake engineering have traditionally been lacking depth, clarity and consistency, with respect to design of industrial facilities and structures The objectives of this paper are: a) to examine the cross discipline impact in a post earthquake scenario, b) to review some codes of practice in the context of non-building and industrial structures, and c) review within the context of a performance based approach some considerations associated with the objectives and performance levels that may be required by a business or a client for industrial facilities.

INTRODUCTION

Existing buildings have been shown to sustain significant over-stress, local, and global failures when subjected to moderate and strong intensity earthquakes. Recent earthquakes such as the 1989 Loma Prieta (California), the 1994 Northridge (California) and the most recent 1995 Hyogo-ken Nanbu (Japan) earthquakes showed that steel buildings are still vulnerable to moderate and strong earthquakes. The 1995 Hyogo-ken Nanbu earthquake produced a large number of damaged steel buildings. In fact, 1247 steel buildings were reported to be damaged, of which 286 had collapsed or were in danger of collapsing during aftershocks, as per Tremblay et al. [1].

From an industrial facilities/buildings view point, the 7.4 magnitude 1999 Izmit (Turkey) earthquake impacted numerous industrial facilities such as: a) heavy manufacturing facilities, b) refineries and petrochemicals processing plants, and c) light manufacturing plants. In a survey done by M. Rahnama and G. Morrow [2], 24 industrial sites were visited and their performance summarized.

In the Izmit earthquake, damages were different in type and nature. A base buckling of tanks caused, for instance, oil leakage which was ignited by sparks resulting in fire. Failure of cooling tower supports and base connections led to complete collapse and destruction of the cooling towers. Failure of pipe racks cantilever supports due to ground settlements led to the collapse of a 12” diameter pipeline carrying crude oil. Extensive damages to pump stations and water pipelines disrupted the water supply. This heavily impaires the firemen efforts to put out fires. Separation of a glass furnace from its surrounding equipment lead to leakage of molten glass.

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Other failures in structural elements were noted. The latter consisted of : a) failure of silo concrete columns leading to the total failure of the silos, b) failure of stacks at their base that led to the complete collapse of the stacks and neighboring equipment, c) failure due to weak axis bending of steel beams supporting steel tanks.

From the above, it is clear that unless structural engineers work hand in hand with other discipline engineers such as piping, electrical, mechanical and process engineers, contractors and manufacturers, the performance of industrial facilities will always be subject to the performance of the structural system itself and/or the equipment attached to it. It is therefore imperative that design codes not only cover areas such as building systems but also areas such as non-building structures and equipment.

Implementation of performance based design will be difficult. Also, the understanding of non-linear analytical methods, procedures and the inclusion of cumulative damage methods are of prime importance for good implementation of performance based design.

CODES OF PRACTICE

Considerable changes occurred in the seismic requirements of the National Building Codes since their earliest editions. For instance, earthquake loads specified in the earliest editions of the National Building Code of Canada [3] are considerably lower than the 1990 and 1995 editions. In Some instances the ratio of base shear of the latest editions can be as high as twice that of the earliest editions. This often means that buildings built back then, had in most instances, wind loads governing the design process. It should also be noted that industrial buildings receive, in general, numerous structural modifications over the years. In some instances, it has been observed that bracing members were removed to accommodate equipment. In other instances, the basic system is modified to accommodate specific production requirements; example of this type of intervention is the removal of a building column for a larger entrance. Other examples of important modifications show up in the form of additional substantial mass being installed in the structures such as new conveyors, new bunkers, and new heavy equipment etc. All the above leads to a modified structure with geometrical, stiffness and mass distribution characteristics that are totally different from the structure originally designed.

Industrial plants are inherently process driven in their design, because of the specialized nature of the process and equipment residing in the structures. The post-earthquake risks associated with storage of toxic materials, high pressure and or high temperatures for instance makes the industrial type of structure fundamentally very different in nature compared to regular building structures.

Most codes of practice set out procedures for determining minimum seismic loads on structures, which are in general buildings. Non-building structure housing minor equipment, attachments, architectural elements and services are sometimes covered in a very limited fashion in this group of codes. Beyond their scope of provisions are special structures such as nuclear power plants, electrical power plants, high risk equipment, industrial facilities and unusual structures. Codes for instance that belong to this first group are: National Building Code of Canada [3] and Australian Standard [4].

Other codes that cover building structures, attempt also to cover in a limited manner such areas as non-building structures, industrial buildings, transportation structures, and hydraulic structures. The procedures set out in these codes are however either relatively complex, very general in nature and do not have an in-depth coverage of design rules and procedures. Example of the latter codes is the Russian code

[5], the 2000 international building code [6], the 1997 Uniform Building Code [7], or the SEAOC Blue book [8].

Another category of design codes and guidelines pertain specifically to special type of structures such as industrial structures, nuclear structures or power plants and dams. These are especially important since in case of failure, they may put a great number of people at risk or may lead to exceptionally high economic losses. An example of such standards is the ASCE4-98 standard covering the seismic analysis of safety related nuclear structures [9] and related structures such buried pipes, above-ground tanks, raceways and earth-retaining walls. Another one is the Chilean Standard covering the seismic design of industrial structures and installations [10].

From the limited review of the above mentioned codes of practice, it is still clear that developing seismic design methodologies for industrial structures is still limited in type and nature. The lack of clarity in the scope of coverage of some codes and the fact that their compliance is enforced in some instances makes their application confusing. The above has been highlighted in studies such as by E. Arze-Loyer [11] and R. Evison and A. Mowat [12], but only recently an effort to develop a code for non-building structures has been undertaken [13].

PERFORMANCE LEVELS

From an industrial building owner's point of view, the major objective is people's safety and the continuous operation of its plant. For life safety, the collapse performance level is evidently to be achieved at all cost. Also to save life, the structural engineer should closely work with other engineers to ensure that services inside an industrial building are designed and manufactured to behave adequately for a specified performance level, and that equipment is properly anchored to the main lateral earthquake resistant system, and /or behaves in a compatible fashion. For instance, what could be a tolerable drift from a structural point of view, could also be an intolerable movement for a Carbon Monoxide pipe that could crack and lead to potentially disastrous consequences. A minor settlement that is acceptable from a structural point of view may not be acceptable to an in-ground water pipe that is cooling a furnace, or a pipeline carrying crude oil in a refinery plant. A minor ground settlement or deformation of a structural element may lead to failure of an equipment in an electric substation, servicing a hydroelectric power house.

Performance based design has been in use in various engineering disciplines and sectors such as manufacturing and to a limited extent in structural engineering for many years now. In fact numerous design codes have used and are still using one form or another of performance based design. Within the context of a limit state design, two levels of designs exist: a) the first level consists of serviceability limit state, and b) the second level covers the member strength limit state. The advent of recent strong earthquakes brought Performance Based Design to the forefront. Performance Based Design and its performance levels and corresponding objectives are well covered in documents such as ATC-40 [14], FEMA-273 [15] and SEAOC Blue book [8].

The following table shows performance levels and the corresponding basic objectives, essential/hazardous objective and safety critical objective levels associated with performance based design:

Event	Recurrence Interval	Probability of Exceedence	Fully Operational	Operational	Life Safe	Near Collapse
Frequent	43 years	50% in 30 years	●	❍	❍	❍
Occasional	72 years	50% in 50 years	■	●	❍	❍
Rare	475 years	10% in 50 years	❖	■	●	❍
Very rare	970 years	10% in 100 years		❖	■	●

Where:
● : is for basic objective
■ : is for Essential/Hazardous Objective
❖ : is for Safety Critical Objective

In most cases, the objective of maintaining an operational plant would span from the Fully Operational level to the Near operational level, where a major shut down has to be planned and executed. This should be achievable when planning for a new facility, and would only account for a small percentage of the capital cost.

For an existing structure, this line of thinking will in most cases not be achievable. Protecting against the full spectrum of performance levels will either be too stringent, exhaustively expensive or not practical since it will hinder production or operation in the facility. The project team should thus put together a list of priorities that could include structural considerations as well as non-structural considerations. For instance, a chemical tank falling and spilling its content might be more dangerous than the consequences of a collapse of a member, which has no bearing on the overall structural system stability.

ANALYSES PROCEDURES

In consulting offices, it is accepted practice to design new structures and evaluate/assess existing structures using two and three-dimensional equivalent static analyses. The analysis uses code specified lateral loads applied to a structure modeled with an elastic linear stiffness. The results of this linear elastic static analysis will be internal forces and displacements whose magnitudes are approximately those of the design earthquake. However, it should be mentioned that the nature of industrial type of structures presents plane and vertical irregularities that makes the use of the static analysis inappropriate in most cases; hence the necessity of using the dynamic method.

For the reasons above mentioned linear time history dynamic analysis and linear response spectrum analysis found their way in design offices. To use these two methods, the structure is also modeled with an elastic linear stiffness. The advantage of these methods of analyses over the static linear analysis resides in a better distribution of forces that takes into account system irregularities and mass distribution. But the shortcomings reside in the fact that material and geometrical non-linear effects and cumulative damage are not included.

Since the advent of performance based design, non-linear static (or pushover) analysis and dynamic analysis became the tools of choice for analysis and evaluation for the identification of areas where there is a lack of stiffness and ductility, or weaknesses in the member or connection. The FEMA-273 and ATC-

40 are two documents where modeling techniques, guidelines for use of ground histories and acceptance criteria can be found. The static non-linear procedure is used on structural models with non-linear moment-rotation (or force-deformation) relationships. Gravity loads are first applied, then the lateral loads are progressively increased and a load-deformation envelope for the whole structure is obtained. The non-linear time history dynamic analysis is similar to the linear time history dynamic analysis except that non-linear force-deformation relationship is included in the modeling.

Low cycle fatigue due to cumulative damage and its resulting cracks in connections of moment resisting frames could also have equal disastrous consequences from a strong motion earthquake compared to consequences from a repeated number of moderate motion earthquakes. For this reason, models for cumulative damage assessment by Daali & Korol [16], and Daali [17] should be part of non-linear static analysis and non-linear dynamic time-history analyses.

CONCLUSIONS

It is evident that the industry standards are still lacking the consistency needed in terms of design approaches and the philosophy behind it. While this paper has a limited coverage of the issues and topics found in the design of industrial buildings and structures, it is nonetheless hoped that the idea of a need of a consolidated building code for industrial buildings is conveyed.

A strong interaction and coordination between the structural engineers and the other discipline engineers such as process, electrical, mechanical and piping is clearly and fundamentally very important in delivering a project that has a consistent approach in terms of earthquake design, i.e., the performance level desired by their owner is achieved in its entirety rather by each discipline operating in isolation.

A clear and simplified consolidated building code for industrial structures, will avoid all the confusions encountered in the present building codes

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