Vienna Congress on Recent Advances in
Earthquake Engineering and Structural Dynamics 2013 (VEESD 2013)
C. Adam, R. Heuer, W. Lenhardt & C. Schranz (eds)
28-30 August 2013, Vienna, Austria
Paper No. 125

Structural performance objectives in seismic design of industrial constructions and equipments

T. Uzunoglu[1], **R. Saragoni H.**[2], **A. Ansal**[3]

[1] convex ZT GmbH, Graz, Austria
[2] Department for Civil Engineering, Universidad de Chile, Santiago, Chile
[3] Özyegin University, Faculty of Engineering, Istanbul, Turkey

Abstract. In industrial construction, the consideration of operability after an earthquake is a major design topic. It requires an overall assessment of the facility, its function and the interlocking of mechanical, electrical and structural components. The objective of this paper is to discuss ways for improving the characterization of performance and their link to calculated structural response parameters in particular for industrial constructions. In this respect, Turkish and Chilean seismic design codes are reviewed with respect to their applicability for performance based seismic design (PBSD).

Keywords: Performance Based Seismic Design; Industrial Construction; Equipment

1 INTRODUCTION

1.1 Consideration of operability after an earthquake

The consideration of operability after an earthquake requires the following:

- The project specific definition of operability.
- The project specific definition of related structural response parameters.
- The project specific definition of limit values of the structural response parameters.

Maintaining operability after an earthquake might be either:

- A requirement by the applicable codes and regulations for facilities that are considered as life-line structures.
- A project specific requirement by the Owner.

As an example for a code requirement, the Turkish Seismic Code for Coastal and Harbor Constructions, Railway, Airport Constructions (Turkish Seismic Code, 2008) defines qualitative seismic performance criteria. The seismic performance is related to the repair time that is required after an earthquake to put the facility back into operation. In this context, four damage levels are defined.
As an example for a contractual requirement, in the contract from a thermal power plant currently in construction in Turkey, it is foreseen that:

- For a small-to-moderate size earthquake, the power plant should be able to be quickly restarted.
- For the maximum size earthquake to be considered, the power plant should be safely shut down without endangering human lives and the safety of the environment.

In both cases, the main task with respect to structural design is to define the structural response parameters resp. their limit values that correspond with performance level to be achieved. Requirements related to seismic performance in codes and/or in contracts are mostly qualitative, and leave room for interpretation. These requirements need to be transformed in quantitative performance parameters, first on facility/equipment level, and in the following on structure/member level.

The engineering proof of operability after an earthquake requires performance based seismic design (PBSD); as the usual seismic design does not cover serviceability limit state checks. Current codes provide minimum provisions for design and construction of structures to resist seismic loading without major structural failures and loss of life, but not to limit damage or maintain function.

The difficulty in engineering practice is that due to qualitative performance objectives and code provisions that are not specifically associated with any particular performance level, design issues remain ambiguous. This leads to wide variation in results, and in commercial competition, the related costs are difficult to evaluate.

The engineering proof of operability of an industrial construction and of an equipment after an earthquake requires a strong interdisciplinary co-operation between process, mechanical, electrical and civil engineering. In current projects, the main parameters for mechanical and electrical engineers are:

- Acceleration during earthquake.
- Deformation of structures during earthquake, to which equipment is attached.
- The resistance of the equipment anchorage against earthquake loading.

In many cases, limits for these values are not given, however indirect requirements lead to the desired effect. For example, if movements/displacements during earthquake need to be limited, response modification factors may be limited. If acceleration during earthquake needs to be limited, the equipment may be mounted on spring/damper devices.

2 PERFORMANCE BASED SEISMIC DESIGN

2.1 Use of construction and of equipment considered

PBSD requires categorization of the seismic performance level desired. This is necessary to ensure design to demand without losing design economy.

Current PBSD based design codes provide categorization of the performance level for constructions depending on their use. For example, the SEAOC Blue Book, Appendix G (SEAOC Blue Book, 1999) recommends the following seismic performance levels:

- Safety critical performance level: For facilities with large quantities of hazardous materials (such as toxins, radioactive materials, explosives), that have significant damage potential to the construction and significant external effects.
- Essential performance level: For facilities with critical post-earthquake function (such as hospitals, communication centers, police, fire stations, etc.) and facilities containing hazardous materials with limited impact outside of immediate vicinity (refinery, etc.).
- Basic performance level: For all other structures.

Current PBSD based design codes provide also categorization of the performance level for equipments depending on their use. For example, the IEEE Recommended Practice for Seismic Design of Substations (IEEE 693, 2005) foresees the following seismic qualification levels:

- High seismic level: Equipment, that must remain completely undamaged and shall continue to function after a defined earthquake.

- Moderate seismic level: Equipment that may have little damage, but shall continue to function acceptably after a defined earthquake.
- Low seismic level: Equipment that may have damage and may fail to function after a defined earthquake.

In industrial construction, the selection of the required seismic performance level of construction and of equipment is the decision of the process/plant designer.

2.2 Differentiation in earthquake loading

PBSD requires categorization of the earthquake loading to be considered.
Current PBSD based design codes provide categorization of the earthquake loading depending on its recurrence interval and the associated probability of occurrence. For example, the SEAOC Blue Book, Appendix G (SEAOC Blue Book, 1999) proposes the following four levels:

- Frequent seismic hazard, with a recurrence interval of 43 years and probability of exceedence of 50% in 30 years.
- Occasional seismic hazard, with a recurrence interval of 72 years and probability of exceedence of 50% in 50 years.
- Rare seismic hazard, with a recurrence interval of 475 years and probability of exceedence of 10% in 50 years.
- Very rare seismic hazard, with a recurrence interval of 970 years and probability of exceedence of 10% in 100 years.

The earthquake probability of occurrence should be considered with regard to the service life of the construction and/or the equipment:

- The seismic hazard may occur several times during service life.
- The seismic hazard may occur one or more times during service life.
- The seismic hazard may be a rare and unusual event as large as any experienced in vicinity of site.

In industrial construction, the selection of the earthquake loading, for which the operability has to be maintained, remains at the Owner’s discretion. A common approach is a two-tiered performance based approach with an Operation Based Earthquake (OBE) and a Maximum Credible Earthquake (MCE) with the following probability of occurrence:

- OBE with a probability of exceedence of 50% in the lifetime of the facility (usually between 25 – 50 years in industrial construction).
- MCE with probability of exceedence of 2% in 50 years (usually the design earthquake as per local code).

2.3 Differentiation in operability

PBSD requires categorization of the operability level after an earthquake.
Current PBSD based design codes provide categorization of the operability level after an earthquake. For example, the SEAOC Blue Book, Appendix G (SEAOC Blue Book, 1999) recommends the following operability levels:

- Fully Operational: Negligible damage, facility continues operation.
- Operational: Minor damage and minor disruption in nonessential services, facility continues in operation.
- Life Safe: Damage is moderate to extensive, life safety is substantially protected.

- Near Collapse: Structural collapse is prevented and damage is severe, life safety is at risk.

In industrial construction, the selection of the operability level after the earthquake might be partially indicated in codes and disaster management plans, and mainly remains at the Owner's discretion.

3 STRUCTURAL ENGINEERING ISSUES

3.1 Methodology

The engineering proof of operability after an earthquake requires a particular design approach. The structural engineering cannot be restricted only to the structural analysis of the load bearing structure. In order to design a structure with a defined seismic performance, the following factors need to be considered (based on provisions of SEAC Blue Book, Appendix I, Part A):

- Site selection: A site may not be suitable with respect to a performance objective, as not all adverse site hazards can be mitigated in the design (for example: vicinity to an active seismic fault).
- Characterization of earthquake: A site specific probabilistic seismic hazard assessment shall be carried out, providing site specific elastic response spectra.
- Soil-structure interaction: The role of soil-structure interaction in seismic response of structures requires a site specific consideration, as its negligence may lead to erroneous conclusions.
- Material and primary load bearing system selection: The design shall not be restricted to the selection lateral load-resisting system, but shall include the consideration of seismic isolation and/or passive energy dissipation systems.
- Continuity of load path: In industrial construction, structures have often irregular mass and stiffness distribution, which cannot be altered, as the form has to follow the function.
- Secondary load bearing system: The inclusion of secondary load bearing structures for equipments is mandatory to find out a realistic seismic performance.
- Consideration of equipment: The seismic acceleration, to which equipment is subjected, shall be calculated based on the dynamic properties of the equipment (rigid or flexible) and on its location in the facility (elevation and dynamic properties of the structure it is mounted on).
- Consideration of design quality: A peer review by an independent, authorized third party shall ensure an accurate design; and is mandatory in some countries, for example in Chile.
- Consideration of construction quality: The quality of construction plays an important role in Probable Maximum Loss (PML) assessment of facilities, and must be ensured by continuous inspection.

In industrial construction, the load bearing system is subordinated to the process. Adverse conditions have to be mitigated by design, as far as possible. Performance objectives have to be linked to quantitative criteria of structural response. If objectives cannot be met, this must be clearly communicated to the overall design responsible.

3.2 Analysis of construction

In principle, two methods are applicable when performing structural analysis for performance based seismic engineering:

- Strength design: Strength criteria are established by relating the response modification factor to the required performance level.
- Force-displacement design: The non-linear force-deformation characteristic of the structural system is determined in order to verify that the performance criteria are met.

The analysis method applied may also differ:

- With respect to the dynamic characteristic of the seismic loading, pseudo-static, response spectrum, or time history design type analysis may be applied.
- With respect to material behavior, linear, non-linear, or capacity design type analysis may be applied.
- With respect to soil-structure interaction linear or non-linear type analysis may be applied.

In general, the capacity design philosophy is adopted as the underlying principle of performance based seismic design. In capacity design, the inelastic behavior of the structure is controlled by proportioning the structure to yield at predetermined ductile “fuse” locations. These system yield mechanisms have to be designated; and designed such that they provide controllable and acceptable inelastic deformation patterns in seismic condition (SEAC Blue Book, Appendix G).

In order to ensure that the performance criteria are met; PBSD codes recommend limitations to structural materials and systems, to horizontal and vertical irregularity, to drift and to methods of analysis, depending on the performance level to be achieved. In addition, elastic and inelastic system displacement limits and damage ratio limits are given for each performance level.

In industrial construction it is often difficult to fulfill the limitations, as the process requirements dominate the design process; and the structure has obey to and comply with load and geometry specifications given by the process, mechanical and electrical engineering. Drift limits, given as percentage of building heights, are not representative for non-building type structures, that are common in industrial construction.

Capacity design requires realistic input of load data. However, in industrial construction, load data provided by the other disciplines does often include a high margin of safety. In addition, serviceability requirements under normal operating conditions lead already to structures that are overdesigned compared to regular structures. Hence, such structures may remain mostly elastic in OBE condition, and such, compromise capacity design features.

3.3 Analysis of equipment

The consideration of equipment itself (and not only of its anchorage) is of vital importance in PBSD. Generally, it should be discerned between the following:

- Non-structural components: Complete entities of architectural, mechanical or electrical objects.
- Non-building structures similar to structures: Self-supporting structures that carry gravity loads.
- Non-building structures not similar to structures: Self-supporting structures that carry gravity loads.
- Equipments: Single architectural, mechanical or electrical objects, permanently mounted on primary or secondary load bearing structures.

Non-structural components and equipments will affect the seismic response of the primary structure, and shall be considered with their mass and stiffness characteristics in the structural system. Exemptions of this rule can be made if the weight of the supported object is less than 25% of the combined weight of the supported object and supporting structure (ASCE 7-05, Section 15.3).

During the determination of the design earthquake force of non-structural components and equipments, the following shall be considered:

- If the component/equipment is considered as rigid, a pseudo-static analysis may be carried out, whereby the seismic acceleration is associated with the mounting location.
- If the component/equipment is considered as flexible, a response spectrum analysis may be carried out, whereby its seismic interaction with the supporting structure and all other connected components/equipments shall be accounted for.

Non-building structures, either similar or not-similar to structures shall be analyzed similar to structures, as their seismic response is directly depended on their eigenperiods.

In industrial construction, earthquake experience data from realized projects can be of guidance to judge, which components/non-building structures/equipments are susceptible to earthquake loading, and which not (EPRI, 2007). For example, post-earthquake assessments of thermal power plants show that turbine-generator units, air cooled condensers and heat recovery steam generators perform very well; whereas substation, transformers and large diameter tanks that are not anchored are susceptible to seismic loading.

For supporting structures of heavy equipment; seismic deformation limitations of the supporting structure and seismic acceleration limitations at equipment level can conflict each other. Deformation limitations lead to very rigid supporting structures, where, in turn, seismic accelerations at equipment level are strongly amplified and may exceed equipment specific, permissible values. To overcome such situation, seismic isolation systems may be used.

4 ENGINEERING PRACTICE IN INDUSTRIAL CONSTRUCTION

4.1 Difficulties encountered in engineering practice

PBSD requires setting of performance objectives and engineering verification, that they can be met. In this context, in current engineering practice, difficulties are encountered.

Seismic performance objectives with respect to operability are descriptive (e.g. continued operation, safe shut-down) and leave room for interpretation. This may lead to contractual problems if the desired performance is not achieved after an earthquake. Depending on prevailing site characteristics, it can be impossible to reach a certain seismic performance level. This may lead to contractual problems, particularly for retrofit projects.

Engineering verification of seismic performance criteria requires the structural modeling of the entire system, including foundations, primary and secondary superstructure, and equipment. However, in industrial constructions, the overall project is subdivided in parts, and different parties are responsible for each scope. Reinforced concrete works for foundations are considered as “civil works”; whereas supporting steel structures are often designed by the system supplier, and hence considered as “mechanical works”. As a consequence, there is an interface in design, where stiffness and loading data has to be exchanged. Each party makes conservative assumptions, in order to be on the safe side. In such a configuration, it is difficult to obtain realistic results of seismic performance.

In industrial construction, foundations and supporting structures are first to build, considering the project schedule. However, equipments/components are often ordered in the last possible moment, in order to save pre-financing costs. Interconnecting piping design is also dependent on equipment/component data and not yet completed in early stages of the project. Hence, the structural design has to be made with conservative assumptions of load data, thus hindering an economic performance based seismic design, exploiting non-linear material capacities.

In industrial construction, there are numerous load cases that must be superimposed in order to find out the worst case load combination. The consideration of non-linear material characteristics does not allow simple superposition anymore; which constitutes a serious problem in daily engineering business using state-of-the-art commercial software.

Industrial construction projects are cross-country projects, where engineers have to consider local engineering practice. Conservative assumptions in structural modeling of soil-structure interaction (for example, not allowing for combined pile-raft foundations) may result in less accurate prediction of seismic structural response.

Earthquake experience data shows that in industrial facilities, the insufficient or not existent anchorage of peripheral equipment leads to considerable damage. The seismic design of this anchorage is often neglected, as the delivery of the anchorage is with the equipment supplier; and the design requirements are not within the expertise of these parties.

4.2 Performance objectives

In industrial construction, the definition of seismic performance objectives should project specific; as it is not possible to cover all governing factors with code provisions. Hence, in addition to generic seismic performance specifications in PBSD codes; project specific seismic design criteria shall be prepared, binding for all parties in the project.

In industrial construction, particularly in production facilities, downtime after an earthquake can be very costly. Hence, as both cause (earthquake) and effect (system behavior) are driven statistical parameters, the confidence level to reach the required seismic performance as an additive criterion should be established and contractually agreed.

In industrial construction, the authors propose to discern between the following seismic performance objectives:

4.2.1 Basic Objectives for Post-Operation Based Earthquake State (B P-OBE)

To fulfill the basic post-OBE objectives, the seismic design shall ensure in particular that:

- The facility can be immediately and safe shut-down.
- The control systems critical for enabling the safe shut-down remain operational during and after the OBE.
- Any damage to buildings, structures, non-structural components and equipments of the facility is limited such that it can be repaired sufficiently quickly to resume operation within an agreed period (typically 5 to 30 days depending on Owner requirements).
- All buildings continue permanently to provide adequate weather protection to prevent environmental damage of the facility.
- An adequate factor of safety is maintained against the collapse of any buildings, structures, non-structural components and. The potential costs of repair and/or replacement are minimized.

These requirements exceed traditional code level design objectives.

4.2.2 Enhanced Objectives for Post-Operation Based Earthquake State (E P-OBE)

To fulfill the enhanced post-OBE objectives, the seismic design shall ensure in addition to the basic objectives that:

- The entire facility remains fully operational after being subjected to the OBE.
- All buildings, structures, non-structural components and equipment shall not require any repair and/or replacement after being subjected to the OBE.

These requirements exceed traditional code level design objectives.

4.2.3 Basic Objectives for Post-Maximum Credible Earthquake State (B P-MCE):

To fulfill the basic post-MCE objectives, the seismic design shall ensure in particular that:

- The collapse of the primary structural systems is avoided.
- The partial collapse of the primary structural systems, or parts of them, is avoided to the extent that there is no danger to human life and to life safety systems.
- The damage of the non-structural systems required for the safe and timely evacuation of buildings and structures is avoided.

These requirements fulfill traditional code level design objectives.

4.3 Link between structural response and performance objective

In PBSD codes, performance objectives and related limitations to structural materials and systems, to horizontal and vertical irregularity, to drift, to stress, to plastic hinge rotation angles and to methods of analysis are given. The background of these limitations is not given; they seem to be arbitrarily chosen.

In industrial construction, the performance objectives related to features that can be proved by structural design are mainly fulfilled by:

- Limiting seismic acceleration of the equipment at all specific locations, where susceptible equipment is mounted.
- Limiting the seismic deformations of the structure/building at all specific locations where equipment and/or non-structural components is attached.

These limits are project specific, and may substantially differ. Hence, for industrial construction, it would be more practicable, that:

- PBSD requirements are limited to either Basic or Enhanced type (as described in Section 4.2).
- PBSD codes for in particular industrial constructions should be developed.
- Such codes should be generic, procedural codes; describing a systematic approach both to determining requirements and providing solution concepts.
- Following the guidance of such codes, it should be mandatory for each industrial construction project to develop a project specific “seismic design manual”, that regulate for all involved parties the post-seismic performance to be achieved resp. the limits to seismic criteria to be fulfilled.

5 INVESTIGATED SEISMIC CODES

5.1 Turkish codes

The most hazardous earthquakes of the 20th century in Turkey occurred in 1999. The first one was the Kocaeli -Gölcük earthquake with M= 7.8 in August 1999 and the second one was the Düzce earthquake with M=7.5 in November 1999. A great number of buildings were damaged during these earthquakes. Hence, the Turkish seismic code from 1998 was revised 2007 (Specification for Structures to be built in Disaster Areas, 2007), amended with a chapter about seismic assessment and rehabilitation of existing buildings (Soyluk, A. and Harmankaya, Z. Y., 2012). The post-seismic behavior for new-build buildings and rehabilitation of existing structures that can be achieved by application of this code is described as follows:

- For earthquakes with light intensity, structural and non-structural parts of the building should remain undamaged.
- For earthquakes with medium intensity, damage to structural and non-structural parts of the building should be limited and repairable.
- For earthquakes with severe intensity, life safety should be achieved and non-repairable damage to structural parts should be limited.
- The design earthquake, defined as mandatory acc. to this seismic code, has a recurrence interval of 475 years and probability of exceedence of 10% in 50 years, valid for a building importance factor of 1.
- With the application of the building importance factor, varying between 1 and 1,5; indirectly a differentiation in the post-seismic performance to be achieved is made.

However, the Turkish Seismic Code for Coastal and Harbor Constructions, Railway, Airport Constructions (Turkish Seismic Code, 2008) is a truly PBSD code:

- Earthquake intensities are categorized (3 seismic intensities are defined).
- The structures are categorized with respect to their importance, their use and their seismic performance required (4 categories of structures are defined).
- The seismic performance to be achieved is categorized (4 seismic performance categories are defined).
- The design earthquakes, defined as mandatory acc. to this seismic code, have a recurrence interval of 72, 475 and 2475 years resp. a probability of exceedence of 50%, 10% and 2% in 50 years.

5.2 Chilean codes

In Chile, a specific seismic code for industrial construction (NCh 2369, 2005) is available, that refers to different types of industrial construction, equipment and their respective anchorage. The design response spectra of this code was estimated by John A. Blume (Blume, 1963) from the observed performance of steel chimneys and process towers during the Chilean mega earthquakes of May 21, 1960 and May 22, 1960 with M = 9.5, being the strongest earthquakes world-wide ever recorded.

The post-seismic behavior for new building and structures that can be achieved by application of this code considers interruptions no longer than a couple of weeks to do inspections and repair works. Hence, this code considers Operational Performance level, specifying lower response modification factors (R-value) compared to the Chilean Seismic Code NCh 433.Of1996 (NCh 433, 1996) that considers Life Safe Performance level. The main characteristic of this code is its calibration with the mega earthquake of May 22, 1960 and such, explains the excellent performance of industrial facilities designed with this code during the Chilean earthquake Maule 2010 with M = 8.8, being the sixth largest earthquake ever recorded (Zareian et al. , 2012).

6 CONCLUSIONS

Damage to industrial construction due to earthquakes has severe consequences. Both the direct economic loss due to damage to the facility and the indirect economic loss due to facility downtime may ruin the investment after an earthquake.

In industrial construction, the structural works costs are only a small portion (10-15%) of the overall investment. Hence, the additional costs to achieve a better seismic performance are very small, compared to the overall investment.

The main challenge in daily engineering practice remains in the identification of the project specific seismic performance criteria; and their reliable proof. Seismic design criteria in current PBSD codes may not be applicable to industrial construction due to the variety of functions and their requirements. In this respect, procedural seismic codes, describing the way of determination of the seismic performance, but leaving the criteria for post-seismic operability to be defined specifically for each project, are preferable.

REFERENCES

ASCE 7-05 (2006). Minimum Design Loads for Buildings and other Structures; American Society of Civil Engineers.

EPRI Historical Earthquake Damage to Power Plants (2005). Electric Power Research Institute California, USA.

IEEE 693 (2005). Recommended Practice for Seismic Design of Substations; IEEE Power Engineering Society.

NCh 2396 (2005). Earthquake Resistant Design of Industrial Structures and Facilities; Instituto Nacional de Normalizacion Chile.

Specification for Structures to be Built in Disaster Areas (2007). Ministry of Public Works and Settlement, Government of Republic of Turkey.

Soyluk, A. and Harmankaya, Z. Y. (2012). The History of Development in Turkish Seismic Design Codes. International Journal of Civil & Environmental Engineering IJCEE-IJENS. **Vol. 12, No. 01**: pp. 25-29.

Turkish Seismic Code for Coastal and Harbor Constructions, Railway, Airport Constructions (2008). Official Gazette No. 26617 and 27092.

Recommended Lateral Force Requirements and Commentary (1999). Structural Engineers Association of California, (SEAOC Blue Book).

Blume, John A. (1963). A Structural-Dynamic Analysis of Steel Plant Structures Subjected to the May 1960 Chilean Earthquakes. *Bulletin of the Seismological Society of America*. **Vol. 53, No. 2**: pp. 439-480.

NCh 433 (1996). Seismic Design of Buildings; Instituto Nacional de Normalizacion Chile.

Zareian, F., C. Aguirre, J. Beltran, E.Cruz, R. Herrera, R. Leon, A. Millan and A. Verdugo (2012). Reconnaissance Report of Chilean Industrial Facilities Affected by the 2010 Chile Offshore Bío-Bío Earthquake. *Earthquake Spectra*. **Vol. 28. Number S1**: pp. S513-S532.