Committee Report: JCI-TC204A

Technical Committee Report on Non-linear Modeling for Performance-based Seismic Design of Concrete Structure

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Abstract

Non-linear time history seismic response analysis is one of the most great progress of earthquake engineering for quantifying seismic performance of various concrete structures in a rational, robust and reliable manner. In practice, it is sometimes used to increase the flexibility of structural planning and ensure high seismic performance. However, there are many to be left in practice to the selection of structural modeling parameters by structural engineers, and there is a risk of arbitrary selection of the modeling parameters. To assist structural engineers to fulfill the responsibilities of accountability, and this technique to be accepted and obtain the trust of our society, standardization and documenting openly in public with transparency are indispensable. This report summarizes the committee report of JCI-TC204A: Technical Committee on Non-linear Modeling for Performance-based Seismic Design of Concrete Structure, which focuses on the state of the practice of the modeling of nonlinear time-history seismic response analysis used in seismic design of concrete structures in Japan.

Keywords: Seismic response analysis, Performance evaluation, Seismic design, Non-linearity, Modeling parameters, Seismic regulation

1. Introduction

Non-linear time history seismic (NLTH) response analysis have been used in seismic design of tall buildings in Japan since as early as 1960s. But it has not experienced critical upgrade yet. So recently there is a big gap in seismic design practice using HLTH analysis in the United States which has made significant advance in 2010s. In Japan, the application of NLTH analysis for building structure have been enclosed within parties, there are little open discussion across the structural engineers who belongs to engineering firms or general contractors who utilize them in their practice, and there are few detailed standards or guidelines documented publicly available on how NLTH nonlinear seismic response analyses are applied to design in practice. In addition, there has been little discussion between the concrete engineers of building and civil-infra structural engineers.

NLTH analysis, if used properly, is an essential part of seismic design for quantifying seismic performance in a rational, robust, and reliable manner. It also increases the flexibility of floor planning and facade and gives extra seismic performance. However, the selection of structural modeling parameters is responsible to structural engineers, there is a risk to the engineers that arises from arbitrary selection of modeling parameters. To fulfill the responsibilities of structural engineers to be accountable to the client and the society, as well as this technology is worth being trusted by our society, standardization and documentation available and opened to public with transparency are indispensable.

Based on the basic belief stated above, the committee surveyed publication in Japan and the US and summarized the status on the application of NLTH analysis to seismic design practice in Japan for improvement of our seismic design methodology and to contribute to international cooperation. The committee members wish this report to be used to identify the issues, and find to-do in the future to discuss improvement measures. This report is not intended to be a technical manual nor guidelines for unexperienced structural engineers to learn NLTH analysis but is to be served as a white paper for experienced structural engineers in Japan to draw big picture on how reliable the seismic safety of concrete structures in Japan is secured by current seismic design incorporated with NLTH analysis. The committee members are listed in Table 1, who contributed to this report.

Table 1 Committee Members

Chair	Hitoshi Shiohara, The University of Tokyo
Secretaries	Syuichi Fujikura, Utsunomiya University
	Toshikazu Kabeyasawa, Tokyo Metropolitan University
	Koichi Kusunoki, The University of Tokyo
	Tomohiro Miki, Kobe University
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	Kazuhiro Kawaguchi, JIP Techno Science Corporation
	Tsutomu Komuro, Taisei Corporation
	Fumio Kusuhara, Nagoya Institute of Technology
	Nobuyuki Nabeshima, Chodai Co. Ltd.
	Yasushi Sanada, Osaka University
	Masanori Tani, Kyoto University
	Atsushi Yamaya, Tokyo Electric Power Services Co. Ltd.

2. Responsibility of Structural Engineers in Seismic Design

In Japan, among natural disasters, bracing to earthquakes and storms is quite important. Prediction of earthquake is impossible, so earthquake-resistant design of structure is feasible way to only to reduce disaster. To continue the socio-economic activities immediately after the earthquake and to build a sustainable society that makes effective use of resources, taking measures to avoid the collapse and damage of the structure is necessary. The responsibility of the structural engineer is large because the seismic performance given to the structure is determined by the structural engineers. It is natural that one of the major purposes of the structural design codes to define the scope of the role, and responsibility of the structural engineers who are responsible to a construction project.

2.1 Objective of structural design standards

Each building and civil infrastructure is constructed as a unique one, and there is no single part that is the same each other. The strength cannot be assessed from its appearance once after it is completed. Various structural design standards and guidelines have provisions for structural design and construction management regarding the design load, type of structure and construction materials, and clarify the responsibilities that structural engineers take in the project.

For buildings, the national and local governments legally enforce on the minimum requirements to ensure the safety and property of the owner and the residents of the building and protect them from deficiency of the building. Therefore, laws also stipulate on the structural design standard.

2.2 Seismic design format in design standards

Seismic design standards and provisions usually allows some damage to structures by design seismic load. The reason for this is that earthquakes are an extremely rare phenomenon, and it is impossible to predict when, where how large, and what kind of shaking earthquakes will occur in the future. It is logically impossible to establish seismic design standards aimed so that structures would never be damaged by an earthquake. Therefore, seismic design standards or provisions adopt the description of the state in which the structure is damaged by the design earthquake.

The current seismic design standards format is usually by giving specifications required for design (not the minimum performance) where, 1) specification on the level of earthquake shaking and 2) specification on allowable damage to the structure. They are always given as a combination of 1) and 2). Recently, many seismic design standards set multiple combination for the seismic design, such for frequent earthquake level and for very rare earthquake level. Seismic design standards for practical design also should specify analytical method validated which ordinary educated structural engineers can apply it to reasonably estimate the behavior of structures. Therefore, the level of damage that can be tolerated has been set at a level well before the structure collapses. As a result, there seems to be some safety margin. However, quantification of surplus capacity is difficult, and they differ depending on the structural type, structural material, and seismic design standard.

The specifications in seismic design standards for allowable damage differ depending on the structural type and construction material. In the Great Hanshin-Awaji Earthquake of 1995, some buildings, such as pilotis buildings, were severely damaged at a relatively high rate. On the other hand, most of box wall reinforced concrete buildings escaped from any damage. In this way, under the current seismic design standards, there is a considerable difference in the margin of seismic performance depending on the type and construction material of the structure. The difference is not clearly quantified, and the public are not necessarily aware of it.

2.3 Transparency of structural technology and responsibility of structural engineers

Even if the seismic standards are not perfect, the seismic design standards are necessary, so that structural engineers could respond to social mandates and fulfilling their responsibilities. This is because society thinks that structural engineers fulfill their responsibilities by the facts that the structural engineers follow seismic design standards. Therefore, the seismic design standards must be based the consensus of society. Structural engineers are also required to make structural drawing and structural design documents to ensure transparency so that it could be verified by a third party that the contents of the design conform to the seismic design standards if necessary.

Structural design is a task to determine and specify all the construction materials, shapes, dimensions, etc. of the structure, and all decisions are to be made by each individual engineer. In making those decisions, each individual engineer is sometimes in a state of conflict of interest between the position of maximizing the interests of the customer and society, and the position of maximizing the interests of the individual engineer and his employer. Structural engineers are required to be accountable to explain that interests of the customer and the society are of the priority.

3. Development of Structural Analysis Method for Seismic Design

At the old age when linear structural analysis and allowable stress is specified to be used in structural design standards, essential modeling parameters are the mechanical properties such as the shape and dimensions of the member and the Young's modulus of the material used and their variations. Therefore, the structural design standards stipulated how to determine the allowable stress corresponding to the level of load and the damage tolerated, but they did not stipulate on the modeling method used in the structural analysis. Linear structural analysis is based on theories and is considered scientifically clear enough. The application method of structural analysis is well established and written in textbooks, and it was considered that there was no room for arbitrariness of structural engineers. Therefore, it was considered unnecessary to specify the method in the structural design standards. However, as advanced analysis methods emerge as the times go by, the idea became obsolete.

3.1 Application of numerical method to solve equation of motion

In the beginning of the 20th century, a rational method was not established for setting the magnitude of an earthquake for seismic design. So, the seismic coefficient method, a procedure using a static equivalent lateral force empirically determined, was used combined with allowable stress in the first seismic design code in Japan.

In the mid 20th century, it became widely accepted that the structural response during an earthquake is affected by the resonance of the structure under the seismic motion excitation on the structure.

Then an analytical method (seismic response analysis) has been proposed for estimating seismic response of a simplified structural model, such as horizontal displacement and acceleration by numerical method to solve the equation of motion with a digital computer. If this method is to be applied to seismic design, it is necessary to simplify extremely complicated structural system with a simple vibration system due to the limitations of computers at that time. In addition, nonlinear seismic response analysis that considers material nonlinearity due to yielding of steel and cracks in concrete requires various assumptions in the process of replacing with a simple vibration system model. It was too difficult for individual designers to make rational selection of modeling parameters and fulfill their accountability in practical design.

3.2 Non-linear time history seismic response analysis

As approaching to the end of the 20th century, various analytical methods were developed to estimate the structural behavior including the collapse under gravity and large earthquake excitation incorporated with member models of the failure.

More advanced future of the model was developed that can predict the effects of destabilization and large deformations due to cyclic loading. Various model for restoring force characteristic accounting the decrease in yield strength of members and materials were also proposed. In such models, the relationship between force and deformation is no longer proportional. Such structural analysis is called nonlinear structural analysis. NLTH seismic response analysis is one of the analytical methods that estimates the time history of seismic response by combining this with an equation of motion. The development of such a method began in the 1970s. Experimental and analytical research have been carried. At first, it started with a simplistic seismic response analysis method for mass vibration systems, and gradually extended to a method of modeling of a three-dimensional frame consisting of members, and a method using a finite element. However, it became realistic to be used in structural design only in the 21st century when the performance of computers was significantly improved and became widespread to the society.

3.3 Responsibility of structural engineers who use new technologies for seismic design

Unlike linear structural analysis, the parameters required for modeling nonlinear seismic analysis are much more diverse. As new research proposed novel models one after another, structural engineers have more options to adopt various modeling, and it has become possible for engineers to sneak in the arbitrariness in selected parameters. Therefore, when NLTH seismic response analysis is used for seismic design, the structural engineers should take the responsibility of setting arbitrary parameters when determining whether modeling is appropriate, and there is a great risk of responsibility to the structural designer. To reduce the risk of structural engineers, it is necessary to set a standard for setting modeling parameters, clarify rules to be followed, and protect structural engineers from conflicting interest pressures.

In the latter half of the 20th century, knowledge was insufficient and lacking formulate to stipulate in structural design standards. There were very few engineers who could apply this advanced procedure, so there were no such seismic design standards anywhere in the world. The only exception to this is Japan, which has been applied to seismic design of high-rise buildings where the adequacy of seismic design is individually authorized after the design review by academia and structural engineering experts for each building. After the design review, Minister of Construction admit the building is exemplified from the requirements of some part of the structural provisions in Building Standard Law. So seismic design practice using NLTH analysis started before a seismic standard was established, where a peer review by a technical expert was incorporated into law system. To say in the other words, third-party technical evaluators and a structural design engineer cooperate to fulfill the accountability to the society on the validation of modeling that the structural engineer should have done.

4. Benefit of Time History Seismic Response Analysis in Seismic Design

Structural engineers want to estimate how the members in a structure behave during an actual earthquake and how they collapse as the damage proceeds. Considering the process leading to collapse, instability due to gravity after the damage to the structure stress redistribution occurs in the members in the statically indeterminate structure as increasing the external force increases. The modeling for accurately quantifying the redistributing and concentration of deformation due to a strength degradation of members is necessary. In summary, (1) redistributed stress due to a softening, (2) concentration of deformation in a part, where rigidity is decreased, and (3) increase in stress in a part where rigidity is maintained. Furthermore, (4) location and magnitude of the inertial are faithfully reproduced in dynamic analysis, so that the stress generated in each part and its distribution are reproduced.

To achieve these goals, the constitutive relationship should be modeled reflecting reality, including non-linear constitutive law, the mechanical properties of the material in dimensions and three-dimensional shape, and the behavior of the joints between members. It is also necessary that the boundary conditions are set appropriate and that the position and magnitude of the external force are reproduced faithfully.

Seismic design based on static seismic force generally used in practice, is sometimes called specification-based seismic design. The design seismic force is usually incorporated with behavior coefficients, which adjust the linearly elastic response acceleration response to account for non-linear dynamic response behavior. The correction coefficients are provided in seismic standards by the structural type, i.e., frame system, wall system and irregularity, structural materials, structural detailing, three-dimensional effects, interaction of foundation superstructure, etc. It is necessary for the seismic design standards to be incorporated with those coefficients and reflect according to the structural plan and structural type of each building. However, to properly providing these design coeffcients in general seismic standards, it is necessary to determine classification of structural plan, structural type and scope of application in seismic codes. Furthermore, there are many simplifications and assumptions involved in determining the specific coefficient values, so it is not easy to specify which correction coefficient should be applied. Moreover, it is extremely difficult to confirm the consensus on something that both academics and practitioners can agree.

If the NLTH seismic response analysis is applied to each individual structure in the project, the NLTH seismic response analysis that considers all members as they are used for the analysis of individual buildings including irregularity issue. By verifying individual members, it is equivalent to verify seismic performance in consideration of the characteristics of each structure more rationally and appropriately than the specification-based seismic design.

Therefore, it helps increasing the flexibility in structural planning and improving the quality of design, rather than applying the seismic design standards of the specification-based seismic design. In addition, in recent research and development, it has become feasible in some cases to apply a model that reproduces the behavior leading to collapse by applying NLTH seismic response analysis under extremely large earthquake motions. It will also be feasible to incorporate verification of the reserve capacity after large earthquake motions.

However, to use these methods in practice and reflect them in the design, it takes more time to prepare the data and more time to analyze than that of conventional specification-based seismic design. There is also the demerit that the risk of design mistakes increases due to human errors. There is also the issue of how to fulfill accountability to explain the validity of each modeling to the client and the society.

5. Challenge in Applying Nonlinear Time History Seismic Response Analysis

There are limits and scopes when applying NLTH seismic response analysis to the practice of seismic design. It should also be noted that the common sense that has been taken for granted in conventional seismic design with specification based seismic may not be used. To apply NLTH analysis, there are the following points that must be known for results of seismic response analysis to be properly reflected to seismic design.

5.1 What can be done with linear analysis may be irrelevant to nonlinear analysis

The principle of superposition used in linear analysis does not hold in nonlinear analysis. It is usually irrelevant to superimpose the response values to get response in biaxial direction, in the frequency domain, e.g., under vertical load and the response analysis under horizontal load. For this reason, it is ideal for NLTH seismic response analysis should be on model of a three-dimensional structure and seismic response should be examine by simultaneously applied two horizontal and vertical seismic motions. If superposition is used within the range of conditions such as the response in one direction is within the range of linear response or the degree of plasticization is negligible, and the superposition is approximately established, the scope and validity of the superposition should be done carefully, and the relevance should be fully verified and explained separately.

5.2 Uncertainty of non-linear seismic response should be carefully handled

When the seismic force is static and constant external force distribution is used, the response is deterministically determined, but the amount of plastic deformation in member is not evaluated because plastic deformation is sensitive to the rigidity after yielding and the setting of the yield strength degradation. It is difficult, and there is a high risk that it will be dangerous to use the response value from the static analysis as it is in the design.

In the time history response analysis in which the seismic force is given as changing inertial force, the effect of cyclic loading due to the dynamically changing external force is considered, and in the multi-degree-of-freedom system, the dynamically changing shape of external force distribution is considered. But, waveform of base motion is once given, the amount of plastic deformation that occurs in the yielding member are deterministically determined.

If the maximum acceleration response spectra of the input seismic motions are the same, the maximum responses of the linear time histories will match. However, the NLTH responses do not always match, and the greater the degree of plasticization, the greater the variation of maximum response. Furthermore, the maximum response differs depending on the waveform of the selected input seismic motion. Therefore, reflecting the uncertainty of NLTH response in the seismic design is necessary to incorporate into the design by using as many different input seismic motions as possible to evaluate the demand to structure from the time history response.

5.3 Modeling has not been sufficiently validated to some type of phenomenon at present

The attenuation of the vibration and the interaction between the ground and the structure in the nonlinear response are generally considered to have the effect on reducing the maximum seismic response and the model are sometimes incorporated in the model of NLTH seismic response analysis. However, it is difficult to verify the validity of these models.

According to the observation, the response diminishes as time pass by, so it is certain that damping mechanism exists. But the causes of damping include by material itself and damping due to soil-structure interaction. It is difficult to separate contribution in measurements. In addition, the damping characteristics are different between those at small amplitude and those at large amplitude, and it is rare to obtain observation during large earthquakes. Therefore, we will continue to use damping models based on response observation records during earthquakes of structures. Further verification is also required. The response displacement and residual deformation differ depending on the setting of boundary conditions such as the presence or absence of rotation in the foundation, the vertical rigidity of the pile, and the partial subsidence of the foundation. In some cases, corrected input seismic waveform is used to consider the interaction between the structure and the ground. In this case, the response of the structure changes depending on how the boundary conditions and damping of the superstructure are set.

In this way, the validity of modeling has not been verified by experiments and observations at present, but they are accepted in practice. It is necessary to establish a rule for the handling in the seismic design standards.

5.4 Non-linear analysis model has limitations in validation

Even with the current updated knowledge, there is a limit to model the behavior of complex structures to grasp correctly the phenomenon for all seismic inputs. Not only the linear range but also the mechanism of destabilization the structure needs to be modeled for the collapse of the structure. Damage (deformation amount) of a part is sensitively affected by changes in the variation of the stiffness of members with respect to bending and shearing force / axial force in the process leading up to that. However, usually model is simplified, and it is impossible to correctly reproduce all the phenomena caused under the combination of multi-axial stresses. Therefore, it is necessary not only to determine the range in which the phenomenon can be modeled correctly but also to confirm stress and deformation is within the applicable range of modeling correctly after response is calculated.

Particular attention should be paid when a simplified model is used to reduce the degrees of freedom of three-dimensional structures and estimate the response. Detailed information on the responses by such simplified model is always lost, and it is inconvenient to confirm that the range of the response is within the range the model works fine.

When reinforced concrete members are modelled, deformation due to slipping out of reinforcing bars, deformation due to shear cracks, and concentration and dispersion of strain due to strain hardening have a great impact on the relationship between stress and strain in reinforced concrete members and joints. For models that directly represent these phenomena, such as finite element analysis for structural modeling, it is necessary to verify the validity of those micro models through experiments on member and subassembledge. In some cases, it is more reliable to directly give the strength and rigidity numerically in the macro model of each member. Thus, in nonlinear structural analysis, it is necessary to use a verified model, because micro model is not necessary highly reliable. However, in some cases, a reasonable design can be achieved by limiting the shape and material of the structure to be applied in consideration of the limit of the applicable range such as application in a range where the degree of plasticization is small. It is rules of thumb that the model of the reinforced concrete structure should be macro-verified by experiments on the relationship between stress and deformation by test on member of subassembledge.

Since the amount of calculation is enormous in the NLTH, the response of the member is predicted by the combination of nonlinear dynamic model with reduced number of DOF to evaluate the shape of horizontal force distribution then the static analysis by the model at the structural member level by applying the static horizontal force. However, those procedure is empirically accepted, there is no theoretical support for the validity of such simplification. Therefore, when using the simplified models, consideration of the limit of the applicable range, such as applying it within the range where the degree of plasticization is relatively small.

Even when trying to reproduce the same phenomenon, the response amount as the design criterion is not the same depending on the modeling method. The same criteria cannot be used when the macro response of each member is used as the design criterion and when the micro response of the constituent material unit is used as the criterion. In this way, the criteria for seismic design in practice need to be adjusted so that safety does not deteriorate by defining it as a set with the method of modeling the structure. For example, in the shear wall model, the response values are obtained with different physical quantities depending on whether the fiber model or the three-column model is used, and the design criteria should not be the same. Furthermore, it is necessary to consider the interaction of response values in the criteria of seismic design, such as the interaction between the displacement of the vertical member that loses the axial force holding capacity and the rigidity in the axial direction due to the increase in horizontal displacement and the rapid decrease in yield strength. If the axial strength reduction caused by shear failure is not considered in the model, the seismic response estimates are unreliable after the strength reduction due to shear failure of some members of the structure occurs.

When it is difficult to use good model such complicated behavior, it is necessary to determine the range of shape, dimensions, and reinforcement arrangement so that the response is reliably predicted by the model in the design of the members of the structure. For that purpose, the scope of application important and structural engineers should carefully follow this type of information.

5.5 Measures to avoid human error are to be carefully planned to cope with enormous amount of input and output data

The nonlinear dynamic analysis model usually uses overwhelming amount of information required for modeling. The amount of information obtained from the analysis is also large. The engineer's arbitrariness may be included in the modeling and interpretation of the results. Verification by a third party tends to be more difficult than conventional design procedure. Some counter measure should be taken by the engineers when NLTHSA is applied.

5.6 Responsibility of structural engineers adopting nonlinear time history seismic response analysis in seismic design

As stated above, structural engineers select from various models for the NLTH seismic response analysis. Many assumptions are made in design judgment by the individual engineer.

Considering the importance of judgement on these modeling parameters and design decisions have significant impacts on the seismic safety, structural engineers have responsibility on the validity of the assumptions selected. The structural engineer is also responsible to the validity of the analytical program for response analysis.

As the structural designer bear a great responsibility a method to avoid those risk is necessary. For that purpose, the modeling policy, the applicable design model, the design criteria corresponding to each, and the way of explaining the validity of the design to be shown by the structural engineer and the way the information is disclosed are specified in the structural design codes. Those codes need social consensus by the general public and consumers too.

In today's Japanese society, it is necessary to know what wisdom has been provided for structural engineers and whether they are responding to these issues related to application of non-linear time history seismic response analysis to seismic design in practice.

6. State-of-the-practice on Seismic Design using Non-linear Time History Analysis

In Japan, the method of NLTH seismic response analysis has already been applied to seismic design since 1980 for concrete building projects and various types of concrete structures. Building Standard Law admit the use of NLTH analysis in any building upon special permission of the Minister of Land, Infrastructure, Transportation and Tourism, but does not provide detailed technical requirements sufficiently for structural engineers for selection of design ground motion, modeling and design criteria. To enforcing the provision, selection criteria of seismic motion, validity of modeling, the selection of the type of design criteria, and the confirmation of validity are left to a peer reviewer of the structural design and many judgments are left to them.

Although the responsibilities of the peer reviewers are extremely high, the scope and scope of their responsibilities have not been clarified, and it is solely left to the self-improvement and ethics of the peer reviewer.

There is not a design codes for structural engineers to know how they can fulfill their responsibilities. While the concrete design know-how used for NLTH seismic response analysis exists in closed sectors, among the group of structural engineers belonging to structural engineering firm or contractors. Confidentiality is imposed on the peer reviewer, and the content of design evaluations is not open to the public and lacks in transparency of the design procedure. From the consumer's point of view, they are almost hidden. As a result, even if there is an inherent issue in the design method, it is difficult to be noticed by the others. Even if new research findings are made, it is not known to outsiders whether they are being fed back correctly to their practice and disclosure or related information is not obligatory.

The Ministry of Land, Infrastructure, Transport and Tourism recently issued individual administrative guidance on seismic ground motion for long-period ground motion, but generally the content regarding individual response methods is closed. This is in contrast to the fact that performance-based seismic design using NLTH seismic response analysis in the United States is widely open to the society of structural engineers based on published technical documents such as ASCE/SEI 7[1)], TBI document[2)] and LATBSDC document[3)].

7. Summary of the Committee Report

The state of practice on NLTH seismic response analysis in the seismic design of buildings and civil infra structures in Japan are surveyed keeping in mind the comparison with the current practice in the United States. Table 2 shows the table of content of the committee report. Summary of the report are described below.

§1.1 Introduction

Section 1.1 describes the background, purpose of this committee report and the structure of the report.

§1.2 Structures to be applied and seismic performance

The target performances and modeling methods used for NLTH seismic response analysis and the applicable structures are classified and organized.

For civil infrastructure, such as road bridges and railway structures, performance shall be verified on 1) the ready-to-use performance of maintaining the function after the earthquake, 2) the reparability performance after the earthquake, and 3) the performance of collapse prevention of the entire structural system due to the earthquake. Seismic design that uses the results of NLTH seismic response analysis to estimate the response is being accepted for wide range of structures. There are no particular restrictions on the types and types of structures that can be applied.

For building structures, the time history response analysis method stipulated in the Building Standards Low and Enforcement Orders can be applied to all buildings, but if the height exceeds 60 meters, the time history response analysis method is mandated. The time history response analysis method is an alternative method of allowable stress calculation by equivalent static seismic force and possessed horizontal strength calculation, and NLTH seismic response

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analysis using a shear spring model of a contracted mass system is mainly used. There is a rule to confirm the maximum value of story drift ratio. When the shear spring model of the contracted mass system is used as a basis, the reliability of the method for reasonably estimating the response of irregular structures and partially collapsed structures becomes a problem and is not usually accepted and virtually out of scope of this procedure.

§1.3 Design criteria system

The criteria specified to define the limit state in the seismic design criteria, the criteria tested by methods other than NLTH seismic response analysis, and the application method are organized in this section.

In civil-infra structures, elastic analysis and seismic load as variational load is used to check on the usability of component. Nonlinear time history seismic response analysis of the structure is used to check the safety and recoverability of the structure and members for the seismic motion treated as an accidental action, and the degree of damage is checked for the multi-level seismic motion Unlike building structures, the types of structures and the elements used for modeling are various, and it is difficult to determine uniform criteria for that purpose, so verification limit values are set for each type of individual structure.

In building structures, a NLTH seismic response analysis on mass-shear spring system is used for a level of seismic motion rarely experienced during the service period of the building, and the maximum story drift required to be 1/100 or less. Trilinear shear spring are used for the mass shear spring system. By the seismic response analysis of the same system, the maximum horizontal acceleration distribution of multiple seismic motions is calculated then statically incremental loading analysis by equivalent horizontal seismic force defined by the product of acceleration and mass points. To validate the member-level design, statically incremental loading analysis is performed to confirm that the collapse mechanism is beam yielding type, and that the attained maximum ductility factor of the member does not exceed 2.0. The members not yielding are designed to prevent from premature brittle fracture. In other words, the idea is to use the NLTH seismic response analysis of the shear spring model of the DOF condensation mass system to obtain the equivalent horizontal seismic force for design considering the higher-order mode.

§1.4 Ground motion and seismic design criteria for structural system

The criteria and guidelines for the selection of input ground motions used for the NLTH seismic response analysis are classified and organized in this section. It explains 1) Definition and method of setting seismic motion level, 2) method of artificial ground motion by scenario earthquakes, 3) artificial ground motions time history synthesized to match the acceleration response spectrum at engineering bedrock and modified considering the effects of surface ground amplification. The rules regarding the number of ground motion used for seismic response analysis and the ground model in calculating the effects of surface ground amplification are also classified and organized.

§1.5 Modeling of mass and other load combination

Issues on how distributed mass are to be considered as the inertial force in the NLTH seismic response analysis, how to consider influence of vertical force and motion, what can be neglected, the degree of fineness required for modeling according to the type of structure, boundary conditions of structural model, how to consider the external force other than seismic force and how to combine with seismic force, stipulated in the standards and guidelines used in practice are classified and organized in this section mainly for civil infra-structures. The action other than inertial force, the seismic soil pressure is not considered in the NLTH seismic response analysis and is checked by static seismic force, and the seismic hydrodynamic pressure is considered by adding mass to the substructure of the bridge. NLTH seismic response analysis is performed in consideration of mass. When considering liquefaction in dynamic analysis, the additional weight is considered in addition to the weight of the substructure of the liquefaction layer. Tsunami loads are usually superimposed assuming that the equivalent hydrostatic pressure exerts a horizontal force.

§1.6 Common principles in structural modeling

Common principles in structural modeling such as (1) element division of the structure in the NLTH seismic response analysis used in the practice of structural design, (2) combination of responses in three directions, (3) basic idea how to regulate collapse mechanism and (4) how to give the stiffness and strength of the elements in this section. It classifies and organize the principles in practices in modeling to consider boundary conditions, attenuation, material stiffness, and geometric stiffness.

§1.7 Procedure with a mass-spring model and DOF condensation

A procedure with mass-spring model and DOF condensation usually consists of NLTH seismic response of mass spring model, and the auxiliary non-linear static structural analyses. This procedure has been applied to building structures. The scope and the way to reflect the result of the analyses to member design stipulated in codes and guidelines are classified and organized in this section. In particular, how the maximum response of the NLTH analysis of the spring mass system are reflected to the required plastic deformation of the member, the method of constructing the mass-spring model, the method of setting the stiffness of and strength of the shear spring connecting the mass, and the practice of modeling the ground are described. Furthermore, modeling of irregular structures, estimation of two-way seismic motion input, by combination and modeling for multi-point input with phase difference are mentioned. If there is no rational method to reflect one of these in the design of the structural frame based on the seismic response of the mass model and auxiliary frame analysis, it may limit the scope of this procedure based on the judgement of peer review of the structural design.

§1.8 Procedure with 3D frame model

A procedure of NLTH response analysis with three dimensional (3D) frame element model is usually applied to road bridges and similar civil infra-structure as well as buildings. The criteria and guidelines regarding them, the scope of application, and the customary practice are classified and organized in this section. The method of analyzing structures and the method of reflecting the response in the design of members is explained.

§1.9 Procedure of FEA with 3D solid element

A procedure of NLTH seismic analysis with 3D finite element analysis (FEM) with solid elements are adopted in the Concrete Standard Specification [Design] (2017) issued by Japan Society of Civil Engineer. Their target of the standard is auxiliary civil-infra structures of nuclear power plant. The standard specifies the method of performance verification of reinforced concrete structures using nonlinear finite element analysis. It describes the method of modeling the materials and nonlinear finite element analysis.

§1.10 Initial stiffness and effective stiffness of structural member

The modeling method and equations to calculate initial stiffness and effective stiffness of structural member such as columns, beams, and shear walls from the nominal shape, dimensions and the mechanical properties of the materials, used for static nonlinear structural analysis stipulated in the standards and guidelines for seismic design in Japan are classified and organized.

§1.11 Seismic response uncertainty

Uncertainty and sensitivity in nonlinear seismic response exists to the variation of ground motion, combination of two-way seismic motion, influence of the phase difference of seismic motion due to the effect of the size of the foundation mechanical property of material, precision of design equations, type of modeling and so on. Some of them are reflected in seismic provisions in design codes and guidelines and the others are not. This section tries to classify and organizes how consideration for the risks caused by seismic design using NLTH seismic response analysis and how they are stipulated in the codes, guidelines for seismic design, and compare the design practices in Japan and the US.

§1.12 Deformation-controlled action

Modeling and design criteria for deformation-controlled action, member strength and ductility those are allowed to yield plastic deformation used in Japan are classified and organized in this section. Method to evaluate the flexural strength and ultimate cord rotation of columns, beams, and shear wall under bending moment from the nominal data on the shape and dimensions of the members and the mechanical properties of the materials stipulated in the codes and guidelines for seismic design in practice in Japan are calculated. Hysteresis models used for representing the characteristics of the force and displacement relation of members under cyclic loading used for NLTH seismic response analysis are also mentioned. The modeling and criteria related to the effects of beams with slabs are also mentioned in detail.

§1.13 Force-controlled action

Modeling and design criteria in the design of force-controlled action, to prevent from undesirable behavior such as shear failure and axial failure is classified and organized in this section. Method to evaluate the shear strength and safety factors considering the uncertainty of the response in seismic codes and guidelines and design practices used in practice in Japan are surveyed. Furthermore, the calculation formulas for specific member strengths stipulated in the standards and guidelines for seismic design in Japan are classified and organized.

§1.14 Peer review

The content of seismic design using NLTH seismic response analysis is too sophisticate and enormous to confirm the appropriateness and reliability from design document and design drawing like those of conventional seismic design. So, there is a significant risk to structural engineers and building officials in case there is some deficiency is found. Therefore, the process of structural design is documented, and the process of confirming the validity of the design is incorporated into the design by examination by peer review by structural design expert. In this report, criteria, standards, and guidelines regarding the implementation method of this peer review of structural design are classified and explained. The qualifications, composition, examination method, implementation period, requirements of the executing agency, liability of review panel in Japanese practice are also mentioned.

§1.15 Analytical software

When NLTH seismic response analysis is carried out by structural engineers, they use analytical software package for analysis. They are usually a black box. To be accountable for the validity of the design, it is necessary that the decision-making process of the structural engineer can be traced to show that the software was operated and applied properly. This section, the method of conducting verification analysis of the program, the method to evaluate the analysis results, the way to report the result and to preserve the data, are discussed based on the design codes and the literature survey.

§2.1 DAISHINKEN Guidelines

Daishinken Guideline[4)] is a seismic design guideline document proposed for seismic design for tall buildings bracing for near-field earthquake extreme shaking level larger than that of the code specification in Japan. The document was published by the "Study Group on Architectural Design Seismic Ground Motion and Design Methods for Earthquakes Directly Under Osaka Prefecture" in 2015. It is intended for buildings for which seismic safety is examined by NLTH response analysis, and against near-field earthquakes that may affect the Osaka prefecture area. This section introduces the essence of the guidelines.

§2.2 Guidelines on seismic design of nuclear power plant auxiliary structures

This section introduces a document of guidelines "Nuclear Power Plant Outdoor Important Civil Engineering Structure Seismic Performance Verification Guidelines / Manual (2005) [5) 6) 7)]." It briefly describes some detail of the modeling concrete structural element with FEM solid element in the seismic design using NLTH seismic response analysis.

§2.3 Introduction to Performance-based seismic design in the United States

In this section, design procedure and modeling of RC building structure expected to be used in performance-based seismic design in the United States are introduced referring to the recent NEHRP document[8) 9) 10)] briefly.

§ 2.4 Scope and function of non-linear seismic response commercial package in the US

This section introduces Perform3D, a structural analysis program commonly used in the United States which performs NLTH response analysis on general structures including buildings. The scope and functions of the software are described, and a example of the design using Perform3D is shown.

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