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SEISMIC LOAD EFFECT DIRECTLY LINKED TO SPECIFIED COLLAPSE MECHANICSMS IN ULTIMATE LIMIT STATE DESIGN

Tsuyoshi TAKADA[1] And Takashi NAKANO[2]

SUMMARY

In the current seismic design codes in earthquake-prone countries, there is significant ambiguity associated with a relationship between collapse mechanisms and plastic energy absorption of mutli-story frames. The collapse mechanisms are based on either the simple static plastic hinge analyses or the static pushover analyses, but they do not explicitly incorporate any dynamic response behavior of multi-story frames. The plastic energy absorption can be coped with by means of an R factor which has the shortcomings that the factor can neither explicitly nor implicitly express the concept of collapse mechanisms which does control the capability of energy absorption of frames. To avoid the above ambiguity, this paper proposes new concept associated with the seismic load effect to take account both of the collapse mechanisms and of the dynamic plastic energy absorption of a frame structure. Proposed here is the new concept of seismic load effect which is directly related to a specified collapse mechanism for multi-story framed buildings with the aid of the plastic hinge theory. The basic feature of the newly proposed load effect is investigated through dynamic response analyses of frame models. This concept is expected that it can be easily extended to the ultimate limit state design.

INTRODUCTION

The limit state design concept has been proposed so far and currently this concept matches the same concept of the performance-based design (ISO 1999, SEAOC 1995). In the limit state design (LSD), design limit states are usually classified into the ultimate and serviceability limit states, and the former is closely related to load bearing capacity and ductility of buildings as a whole under extreme loading conditions rather than individual structural members, while the latter deals with functionality and inconvenience during normal use of buildings. The recent literature (Ellingwood, 1994) claims that only safety checking of individual members is not sufficient for the ultimate limit states, the whole building has to be treated as a structural system and thus the system reliability issue has to be incorporated in the design format.

In the seismic design codes which are needed in earthquake-prone countries such as Japan, US and New Zealand, there is a need that the ultimate limit state should be clearly defined, which can lead to rational and more precise performance-based seismic design. The current seismic design practice, however, shows that inelastic behaviour of buildings during strong ground shaking is taken into account approximately by means of a convenient factor called "an R factor in the US", "a behavioural factor in the Eurocode 8" or equivalently "a Ds factor in Japanese seismic design code". From the viewpoint of more precise definition of the ultimate limit state, the use of these factor possesses significant ambiguity. These factors reflecting how ductile a frame is are categorized by the type of frames and constituent materials. They originated from the static equivalence of strain energy accumulated in a linear structural system and a non-linear system (Newmark and Hall 1973), then they were redefined as a ratio of maximum responses of linear and non-linear single-degree-of-freedom (SDOF) systems with the same natural period, subjected to identical earthquake motions (Riddle and Newmark 1979), as are denoted by DL-SDOF and DN-SDOF in Fig. 1. Although the R factor empirically represents rough relationship between a linear and non-linear response behaviour, the factor is capable of estimating the plastic

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energy absorption of a system once a certain non-linear deformation limit is fixed, therefore, the concept of the R factor is highly related to plastic energy absorption in a dynamic sense.

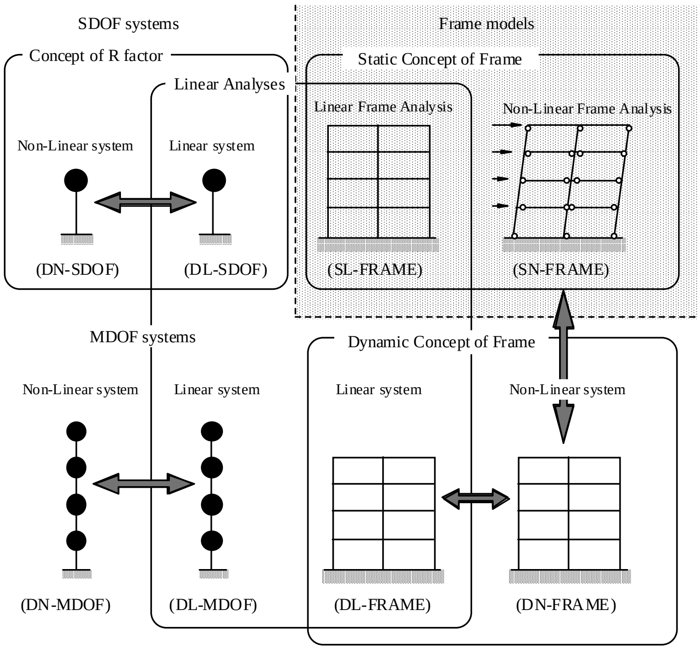


Figure 1 Classification of Analyses

Past researches on the relationship can be found, but mainly on the SDOF oscillator (Riddle and Newmark 1979, Clough and Penzien 1993). Recently Miranda and Bertero (1994) show the relationship can be characterized not only by hysteretic property of the non-linear SDOF, but also by the relative period ratio that is the ratio of the elastic natural period of the system to the dominant period of the input earthquake motions, and proposed are the R-factor spectra when a ductility criterion is selected.

On the other hands, buildings are usually modelled as multi-degree-of-freedom (MDOF) systems, as are shown by DL-MDOF and DN-MDOF in Fig. 1, and the R factor based on the results of only SDOF systems cannot be simply applied to MDOF systems. In the current practical design codes, however, the R factor is still used on the ground that ordinary buildings are often designed in such a way that every story goes into low level plastic region uniformly, and the first vibration mode tends to govern the overall behaviour of even MDOF systems.

However, multi-story buildings reveal that the structural damage tends to occur and to accumulate at one story or limited portions of buildings, as many ultimate states of middle story collapse or first story collapse were observed during the 1995 Kobe earthquake. This phenomenon was firstly pointed out by Akiyama (1986) and is nowadays known as damage concentration to multi-story buildings during strong earthquakes.

His study was done more than a decade ago and was based on an energy approach to find a spatial distribution of plastic strain energy accumulated in an MDOF system subjected to strong ground motions. The distribution was derived in terms of the deviation from an optimum distribution of yielding story shear that can make every story get uniformly plastic. However, all his findings were based on the response results of a lumped mass shear spring systems, as is indicated in Fig.1. And those findings to framed buildings may be neither straightforward nor directly relate to the control of collapse mechanisms.

The recent achievement in the field of non-linear seismic analysis in the US has been done, focusing on the new seismic design incorporating collapse mechanisms (Elwood and Wen 1995). Here, both identification of dominant collapse mechanisms by carrying out the static pushover analysis to frame models, as is shown in Fig. 1, and adoption of more ductile frames are of major concern. These studies are considered to have drawback that the phenomenon of damage concentration cannot appropriately be taken into consideration since the distribution of external force does not change in the static pushover analysis.

There have proposed been many past researches on approximation of how to treat non-linear rigid framed buildings. The literatures (Tso et al. 1993, Fajfar and Gaspersic 1996) proposed that for multi-story rigid frames, the overall behaviour of weak-beam and strong-column type frames may be approximated by non-linear SDOF systems, or the strong-beam and weak-column type frames may be modelled into an MDOF with uncoupled non-linear shear springs. However, more precise treatment of ductility capability of frames has to be done since there are various, mixed collapse mechanisms within multi-story rigid frames (Muroi and Takada 1986).

On the other hands, the plastic hinge analysis focuses partially on the system behaviour, i.e., collapse mechanisms which have been recognized to interrelate the plastic energy absorption. Higher absorption of plastic energy can only be achieved by designing more ductile collapse mechanisms, for instance, weak-beam and strong-column type collapse mechanisms. This treatment is the same as the capacity design developed in New Zealand, where all seismic input energy has to be consumed at beam ends not in columns (Pauley 1996). The concept of the collapse mechanisms, however, can only be defined in a static sense. Since the collapse mechanisms are identified under the condition that a static external force distribution is set, the concept of the collapse mechanisms can only be defined in a static sense.

Despite the past efforts mentioned in the above, there is still significant ambiguity between collapse mechanisms and plastic-energy absorption of buildings, the former can only be defined in a static concept while the latter can be empirically and approximately described in a dynamic sense. This is the objective of the present study and new seismic load effect associated with particular collapse mechanisms of framed buildings is proposed and investigated.

CONCEPT OF SEISMIC LOAD EFFECT LINKED TO COLLAPSE MECHANISMS

It is ideal for a seismic design dealing with the ultimate limit state or with the collapse states that a safety checking should be done both with the seismic load effect which has highest correlation with the structural states thus defined, and with the appropriate structural capacity. Therefore, the story drift, story ductility response may not always be sufficient. These collapse states can be considered to occur after the sufficient collapse mechanism forms and then a plastic deformation reaches a certain threshold.

Equilibrium condition related collapse mechanism based on lower bound theorem

It then follows that in order to describe the seismic load effect mostly contributing to the specified collapse mechanisms, an equilibrium condition between the external force and internal flexural moments, which is based on the lower bound theorem of plasticity, can be fully utilized as follows.

$$\mathbf{A}_i^T \mathbf{M}_p - \mathbf{B}_i^T \mathbf{P} = 0 \tag{1}$$

Where **P** is the external force vector, $\mathbf{M}_\text{p}$ is a vector representing fully plastic flexural moments of structural members, $\mathbf{A}_i$ is a coefficient vector associated with the *i*-th collapse mechanism specified, and $\mathbf{B}_i$ denotes a vector determining the external force distribution.

Definition of Seismic Load Effect Linked to Collapse Mechanism

Using the expression of Eq. (1), the seismic load effect (dynamic response) associated with the *i*-th collapse mechanism $E_i(t)$ can be defined as follows;

$$E_i(t) = \mathbf{A}_i^T \mathbf{M}(t) \tag{2}$$

Where the vector $\mathbf{M}(t)$ implies the moment response of structural members. It can be clearly observed that the response as defined above is the quantity resulting from the dynamic response analysis of a frame model, and is directly linked with the specified collapse mechanism. If one wants to be interested in the maximum response, $E_i(t)$ can be easily evaluated through a dynamic response analysis.

$$E_{i\max} = \max_{0<t<T_d}\left[E_i(t)\right] \tag{3}$$

Where T_d is a time duration which is used in a dynamic response analysis.

These seismic load effects are considered to have advantages in the following aspects: these load effects are directly linked with specified collapse mechanisms, that is not the case for the story shear force response which has been used for many years in a seismic design and analysis, and these seismic load effects can reflect directly the dynamic behaviour of a framed structure when the structure is modelled as a frame, this is not true for conventional modelling for dynamic analysis of a structure which are either an SDOF or an MDOF system. These good features of the newly proposed load effect are expected to clarify the ambiguity mentioned in the beginning, and the authors think that this new load effect can be effectively used for an ultimate limit state design, namely the performance-based seismic design.

If using both Eqs. (1) and (2), the limit state function to be used in the ultimate limit state design, which is directly related to the *i*-th collapse mechanism, can be formally written in the following, then using Eq. (3), the limit state function which can be used in a seismic design is written.

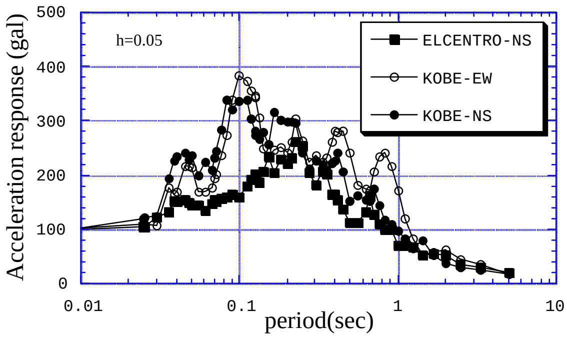
$$g_i(t) = \mathbf{A}_i^T\mathbf{M}_p - \mathbf{A}_i^T\mathbf{M}(t) = \mathbf{A}_i^T\left[\mathbf{M}_p - \mathbf{M}(t)\right] \tag{4}$$

$$g_i = \mathbf{A}_i^T\mathbf{M}_p - E_{i\max} \tag{5}$$

When the sign of g_i is negative, it means that the seismic load effect associated with the *i*-th collapse mechanism exceeds the plastic capacity of the mechanism. The expression of Eq. (5) is considered to be effectively used in an ultimate limit state design, which can precisely take account of collapse mechanisms in a dynamic sense.

BASIC FEATURES OF SEISMIC LOAD EFFECT BASED ON LINEAR RESPONSE

To grasp the basic features of the newly defined seismic load effect, here studied are those based on linear response of frame models. Since the seismic load effect E_{imax} is dependent upon the property of the earthquake ground motions, the effect of the earthquake ground motions is studied on the first hand. Past strong motion records such as the ELCENTRO NS wave, records observed at the JMA station in the Kobe 1995 earthquake, and two simulated artificial motions with different frequency contents, as are shown in Fig. 2., are used in the following analysis. All earthquake ground motions are scaled by the peak amplitude of 100 cm/sec^2.



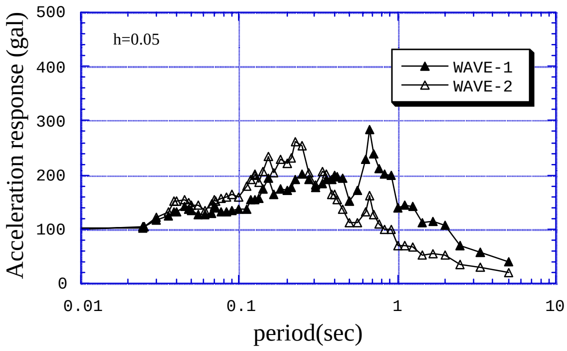


Figure 2 Response spectra used in the analysis

As a frame model, a five story-single bay frame model is used as an example. This frame has the first natural period 0.40 seconds and the second 0.13 seconds. Fifteen collapse mechanisms under consideration are the whole beam collapse mechanism denoted by (1) in Figure 3, four consecutive story collapse mechanisms by (2) and (3), three stories by (4) to (6), two stories by (7) to (10) and single story collapse (weak-column type) mechanisms by (11) to (15), all of which are illustrated in Fig. 3. So the numbering rule is that the lower number implies more weak-beam type collapse mechanisms.

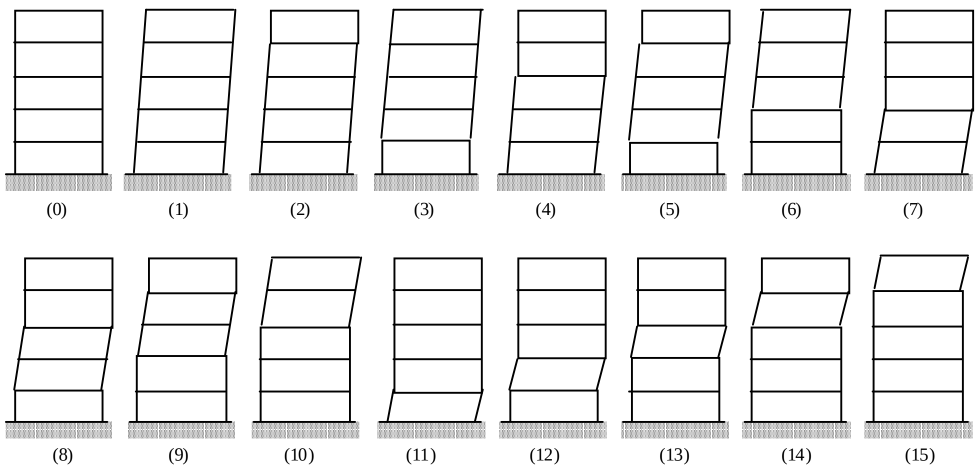


Figure 3 A frame model (0) and its selected collapse mechanisms (1-15)

Figure 4 shows how the seismic load effects E_{imax} look like, which are associated with specified collapse mechanism i of the frame model subjected to the above mentioned ground motions. It can be observed from this figure that the seismic load effects of collapse mechanisms containing more plastic hinges reveal larger response quantity, and that the seismic load effects of collapse mechanisms containing lower story collapse are greater than those of collapse mechanisms containing upper story collapses. The seismic load effects, of course, highly depend upon the input ground motions, which is fully influenced by the response behaviour of the frame. Overall tendency for each collapse mechanism, however, is similar with disregard to different input ground motions.

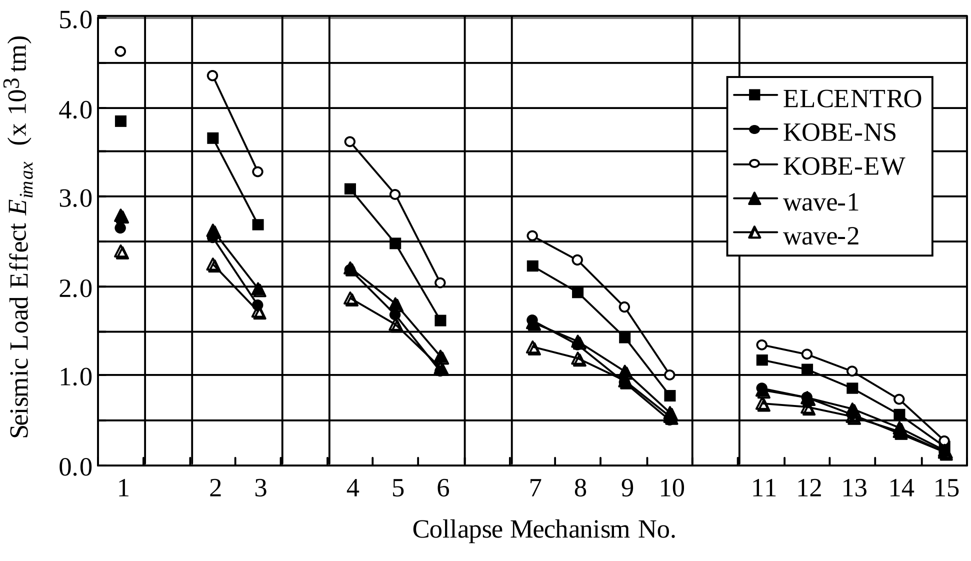


Figure 4 Seismic load effects of specified collapse mechanisms of a five-story and single bay frame

BASIC FEATURES OF SEISMIC LOAD EFFECT BASED ON NONLINEAR RESPONSE

A non-linear frame model

A two-story single bay frame model as shown in Fig. 5 (0) is used. In this figure, three possible collapse mechanisms are selected to evaluate the relevant seismic load effects. Non-linear properties of the frame are defined in terms of fully plastic moment of beams and columns and their hysteretic propoerty. To investigate the influence of dominant collapse mechanisms, the ratio of fully plastic moment of each beam to that of each column, which will be refereed to as the moment ratio, is changed as an important parameter which governs collapse mechanisms. This ratio is taken as 0.5, 1.0 and 2.0 in the following analyses. The hysteretic rule for the moment-curvature relationship at each member end is assumed to have normal bi-linear relationship. The input ground motion is the EL CENTRO NS wave.

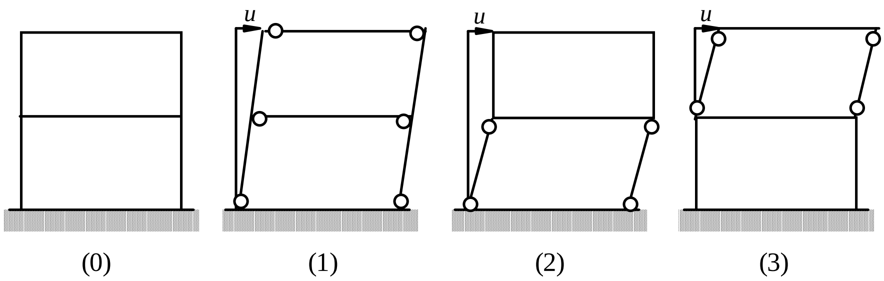
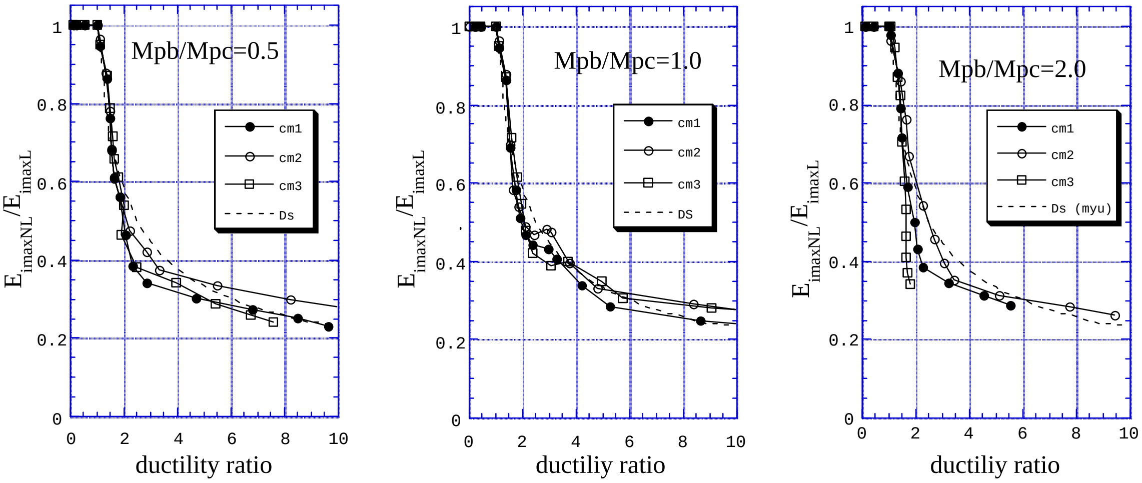


Figure 5 A two-story and single bay frame model (0) and collapse mechanisms (1-3)

Relationship between linear and non-linear seismic load effects

Like the past studies on the R factor, the results of linear and non-linear seismic load effects are investigated, as are shown in Figs. 6 (a) to (c), when the moment ratio is changed. In this figure, the displacement component corresponding to the seismic load effect E_{imax} associated with a particular collapse mechanism i is defined as shown in Fig. 5 (1) to (3). The vertical axis implies the response ratio of the maximum non-linear response to the linear response, which is similar to 1/R. In these figures, the dashed line representing the Newmark's formula, which is based on the energy equivalence of linear and non-linear systems, is also plotted. It can be seen from these figures that the Newmark's formula tends to grasp the overall behaviour of the relationship associated with specified collapse mechanisms. In the case of the plastic moment ratio of 2.0 (a strong beam and weak column type), the collapse mechanism (2) is most significant and the other collapse mechanisms are not so critical. The response ratio associated with the collapse mechanism (3) becomes very lower because the non-linear response of the second story goes beyond the elastic limit. In the case of the plastic moment ratio of 0.5 (a weak beam and strong column type), response ratios of all collapse mechanisms of this case tend to be lower than those of other cases. It can clearly suggest that this type of frame shows better performance from the view points of non-linear response.

Although these plots are quite similar to the R factor studies done in the past, the past studies never have taken account of collapse mechanisms. This is the great advantage of the newly proposed seismic load effects over the past studies which mostly concentrated on the relationship between inter-story drift and the story shear force of MDOF or SDOF systems. The seismic load effects proposed here indeed can relate the non-linear response of frames and collapse mechanisms. To obtain more general results of the fundamental behaviour of the seismic load effects for specified collapse mechanisms, wider ranges of frame models, other earthquake ground motions have to be examined as further studies.



(a) (b) (c)

Figure 6 Response ratio for specified collapse mechanisms

CONCLUSIONS AND FUTURE RESEARCH SUBJECTS

To avoid the ambiguity of the conventional seismic design method, proposed here is, instead of the lateral shear force used in most of the current seismic design codes, new concept of seismic load effect which is directly related to specified collapse mechanisms for multi-story frame buildings. Here, a frame model, instead of the conventional lumped mass-story spring model, is fully utilized to obtain linear and nonlinear dynamic response behaviour. The proposed load effects are derived from the plastic hinge theory, which can relate collapse mechanisms and nonlinear dynamic response.

It is shown in this paper that the fundamental properties of the newly defined seismic load effect contributing to the specified collapse mechanisms are investigated through linear and nonlinear response analyses of the frame model subjected to various earthquake ground motions. It is found that the new seismic load effects for specified collapse mechanisms are greatly dependent upon the earthquake ground motions characteristics. Also, these load effects can be easily extended to nonlinear response of frame models, and the response ratio, i.e., the ratio of nonlinear seismic load effect to the linear one of frames can be estimated to reduce the design effort in an ultimate limit state design or equivalently the performance-based seismic design. The authors would like to emphasize that the ambiguity as is mentioned in the beginning can be clarified much more significantly.

Some of numerical examples show the basic behaviour of the newly proposed seismic load effects for specified collapse mechanisms. To obtain more general results of the seismic load effects for specified collapse mechanisms, wider ranges of frame models, other earthquake ground motions have to be examined as further studies. Finally, the new concept of seismic load effect linked to the specified collapse mechanisms can be expected to be effectively used for the future ultimate limit state design.

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Abstract

In the current seismic design codes which are used in earthquake-prone countries such as Japan, US, New Zealand, etc. there is significant ambiguity associated with a relationship between collapse mechanisms and plastic energy absorption of mutli-story frames. The former is defined as the static concept. The collapse mechanism is based on either the simple plastic hinge analyses or the static pushover analysis, but it does not explicitly incorporate any dynamic response behavior of multi-story buildings. The latter can be defined only in a dynamic sense. The factor called R factor (equivalently, Ds factor in the Japanese code provision), which represents rough consideration of plastic energy absorption of framed structures, originates from the concept of dynamic response in which mostly, the ratio of maximum response of an SDOF and that of a nonlinear SDOF with the same elastic natural frequency and damping under the same earthquake. The concept of the factor, however, has the shortcomings that it can neither explicitly nor implicitly express the concept of collapse mechanisms which can control the capability of energy absorption of the frame. Indeed, the control of possible collapse mechanisms is the most important issue in the capacity design developed in New Zealand. This paper presents new concept associated with the seismic load effect to take account both of the collapse mechanisms and of the dynamic plastic energy absorption.

To avoid the above ambiguity of the conventional seismic design method, proposed here is, instead of the lateral shear force used in most of the current seismic design codes, new concept of seismic load effect which is directly related to specified collapse mechanisms for multi-story frame buildings. Here, a frame model, instead of the conventional lumped mass-story spring model, is fully utilized for linear and nonlinear dynamic response analyses. The proposed load effect is derived directly from the plastic hinge theory.

It is shown in this paper that the fundamental properties of the newly defined seismic load effect contributing to the specified collapse mechanisms are investigated through linear and nonlinear response analyses of the frame model subjected to various earthquake ground motions. It is found that the new seismic load effects for specified collapse mechanisms are greatly dependent upon the earthquake ground motions characteristics. Also, these load effects can be easily extended to nonlinear response of frame models and the response ratio, i.e., the ratio of nonlinear response to the linear response of frames can be estimated to reduce the design effort in an ultimate limit state design or equivalently the performance-based seismic design. The authors would like to emphasize that the ambiguity as is mentioned above can be clarified much more significantly.

Some of numerical examples show the basic behaviour of the newly proposed seismic load effects for specified collapse mechanisms. To obtain more general results of the seismic load effects for specified collapse mechanisms, wider ranges of frame models, other earthquake ground motions have to be examined as further studies. Finally, the new concept of seismic load effect linked to the specified collapse mechanisms can be expected to be effectively used for the future ultimate limit state design.

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STRUCTURAL MATERIALS, ELEMENTS AND SYSTEMS, Collapse mechanism, Dynamic behaviour, Dynamic collapse of frame, Framed buildings, Limit states design, Lower bound theorem, Plastic design, Response modification factors, Seismic design codes, Ultimate limit state, Plastic energy absorption, Preformance based design,