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学位論文題名

Seismic Demand Spectra Considering Cumulative Damage and Site Conditions

（累積損傷と地盤条件を考慮した必要耐震性能スペクトル）

学位論文内容の要旨

Present design philosophy and seismic codes allow structures to be designed with lateral strength lower than that required for it to remain elastic in the event of a severe earthquake. The design strength can usually be obtained by applying response modification factor or strength reduction factor to reduce elastic strength demand to design level. This factor whose makeup and value vary among many countries may consist of factors such as those related to the inelastic behavior of the structure, overstrength and damping. Many researchers however have expressed concern on the adequacy of the strength reduction factors contained in seismic codes due to the lack of transparency and technical basis in the assignment of its values. Strength reduction factor due to inelastic behavior of structure have been extensively studied and formulated in terms of limiting the maximum ductility demand. However, due to the fact that buildings have design strength much lower than the elastic strength level, they are expected to sustain some level of structural damage under severe earthquake excitation. Under such cyclic loading, repeated load reversals below the maximum deformation can cause fatigue or cumulative damage which in turn leads to a reduction in the ductility capacity of the structure. It therefore becomes important to consider cumulative damage in the assessment of inelastic behavior of structures designed based on current design philosophy.

The primary objective of this study is to evaluate seismic demands considering cumulative damage. The effect of site conditions, various structural properties and characteristics of the earthquake ground motions on the seismic demands are also investigated. Following is a brief summary of the chapters constituting the dissertation.

Chapter 1:General Introduction

This chapter introduces the problem which motivated the conduct of this study, followed by the statement of objectives. The chapter concludes with a brief outline of the succeeding chapters.

Chapter 2:Cumulative Damage Consideration in Seismic Design

In this chapter, current simplified design procedure based on strength and use of response modification factor is reviewed and its adequacy examined. A literature review on the previous studies on strength demands and strength reduction factor by several researchers is also made. It is shown that maximum deformation alone cannot completely characterize damage and may lead to inadequate assessment if cumulative damage is not considered. Ways on how to improve current design method is proposed by incorporating cumulative damage in the proposed design procedure.

Chapter 3:Analytical Modeling and Earthquake Ground Motion Characterization

In this chapter, the two analytical models, the single-degree-of-freedom (SDOF) system employed in Chapter 4 and the multi-degree-of-freedom (MDOF) system used in Chapter 5, are presented. The bilinear and peak-oriented (modified Clough) models used to simulate the hysteretic behavior of steel and RC structures are described next. Cyclic deterioration in strength and stiffness based on hysteretic energy dissipation is also incorporated in the hysteretic modeling. The Park and Ang damage index used in the assessment of seismic damage is then explained. This index was chosen because it combines the damage due to maximum deformation and the cumulative damage based on dissipated hysteretic energy. Since no specific values of the hysteretic energy capacity parameter used in the cyclic deterioration model is prescribed for a given monotonic ductility capacity, a procedure for calibrating such hysteretic energy capacity parameters is developed. The calibration is based on the desired minimum ductility performance criterion and the resulting calibrated values are found to be within the range of experimental results for corresponding levels of ductility capacity and cyclic deterioration.

A suite of 60 earthquake ground motions used in the time history analysis and classified into three site categories: rock, intermediate and soft soil sites is presented together with the other relevant characteristics of the earthquake records such as magnitude, epicentral distance, duration of strong motion and predominant period of ground motion.

Chapter 4:Site-Dependent Seismic Demand Spectra for SDOF System Considering Cumulative Damage

Elastic and inelastic strength demands considering cumulative damage for the SDOF system are first evaluated. A series of 32,400 time history analyses are carried out to determine the strength demands for a combination of nine strength levels (one elastic and eight levels of inelastic demands corresponding to four ductility capacities and two limit states), two hysteretic models (bilinear and peak-oriented), 30 natural periods (T = 0.1~3.0 s) and 60 input ground motions for the three site categories (rock, intermediate and soft soil sites). Since the response of the system at soft soil sites is significantly affected by the predominant period of ground motion T_g, an additional set of 10,800 strength demands is determined for soft soil sites for 30 discrete period ratios T/T_g for a total of 43,200 data sets. The damage-based strength reduction factor R_D is then computed as the ratio of the elastic to the inelastic strength demands.

The results indicate that the mean damage-based strength demands and reduction factor R_D are influenced by the site conditions particularly in the case of soft soil sites. Regardless of the site condition, the dispersion in the strength demands increases with the natural period but is not significantly influenced by the level of ductility. In contrast, the dispersion in R_D factor is relatively stable across the range of natural periods and increases with increasing ductility. The strength demands are consistently lowest for moderate earthquake magnitudes of up to M_s = 6.1 but there appears to be no significant difference among larger magnitudes intervals ($M_s \geq 6.7$). In general, the strength demands are highest for significant duration longer than 20 s. No clear trend can be observed regarding the effect of earthquake magnitude, epicentral distance, or significant duration of motion on the R_D factor. Hence, whatever effect the above factors have on the inelastic strength demands stem from its effect on the elastic strength demand and cancels out when their ratio (equal to R_D) is computed.

The ordinates of the R_D spectra are much lower compared to the magnitude of the monotonic ductility capacity μ_u since it corresponds to lower cyclic ductility capacity μ_m. An equivalent ductility factor as a ratio of the monotonic ductility capacity may also be used in determining strength demands. This ratio depends on the monotonic ductility capacity and while it is not significantly affected by the natural period, it should be carefully evaluated for bilinear systems located in soft soil sites and where the structural period is close to the predominant period of ground motion and in the case of peak-oriented systems with short natural period. The influence of hysteretic behavior on the cumulative damage is very evident in short period structures where higher energy dissipation in peak-oriented model results to higher cumulative damage compared to the bilinear model. Regardless of soil condition, the component of damage spectra due to the maximum ductility decreases with increasing μ_u which may be attributed to the higher hysteretic energy dissipation associated with more ductile structures before it collapses.

The life safety to collapse limit state strength demand ratios for both bilinear and peak-oriented systems increases with natural period in the short period range up to point corresponding approximately to the predominant period of motion, beyond which the limit state strength ratio becomes relatively constant at around 1.2. The hysteretic behavior, site conditions and monotonic ductility capacity have negligible effect on the limits state strength ratio. Nonlinear regression analysis is finally performed to obtain simple expressions for estimating R_D factor for life safety limit state which can be conveniently used for practical application.

Chapter 5:Site-Dependent Seismic Demand Spectra for MDOF System Considering Cumulative Damage

By means of the same procedure in Chapter 4, strength demands are evaluated this time using MDOF systems with n = 2, 5, 10 and 25 stories. For bilinear steel systems with code-prescribed strength distribution and parabolic stiffness variation (Steel-I), the strength demands computed for short MDOF system (n = 2) is approximately the same as that of equivalent SDOF system with the same natural period. However, as the number of stories (natural period) increases, the MDOF system tend to have higher strength demands than the equivalent SDOF. A modification factor to account for higher mode effect is therefore computed as the ratio of MDOF to the equivalent SDOF strength demands. This factor increases with increasing natural period and inelasticity. For a given number of stories, the value of this modification factor is approximately the same for both rock and intermediate sites but lower for soft soil sites.

In the case of peak-oriented RC-I buildings, the strength demand of MDOF system having n = 2 is equal to that of equivalent SDOF system only for soft soil sites. Strength demands for both rock and intermediate sites are amplified even for n = 2 and hence MDOF modification factor needs to be applied to the SDOF elastic design strength. As with bilinear systems, the MDOF modification factor for peak-oriented system increases with increasing natural period and ductility. For the same number of story, the MDOF modification factor for peak-oriented system is lower compared to bilinear primarily because the natural period of the former model is computed assuming a RC system which is lower compared to the corresponding steel system represented by the latter hysteretic model.

Examination of the mean damage spectra of the collapsing story reveals that for the same number of stories, the cumulative damage in RC system is greater than that of steel. In general, the probability of first story collapse increases with increasing ductility capacity. The few instances of collapse in the upper stories can be attributed to higher mode effect which becomes more significant for taller buildings.

The strength demand for steel buildings with stepwise strength and stiffness distribution (Steel-II) are approximately equal to those of Steel-I buildings only in the elastic and short period range. In inelastic cases, Steel-II requires higher design strength even though most of its stories have strength higher than the corresponding stories of Steel-I buildings. The higher strength is a result of high damage concentration in stories where there is a sudden stepwise drop in strength and stiffness which consequently govern the required strength. The ratio of strength demands of Steel-II to Steel-I buildings varies depending on the soil conditions whereas no significant influence of ductility capacity can be observed.

Lastly, the strength demands of RC-II buildings whose only difference with RC-I buildings is the stepwise stiffness variation are quite comparable to the latter regardless of the number of stories, ductility capacity or site conditions. It can therefore be concluded that the lateral strength distribution has a much greater influence than stiffness variation on the damage-based strength demands for MDOF systems.

Chapter 6 - Conclusions and Recommendations

This chapter highlights the most important findings of the study. The proposed design procedure together with the design tools developed in this study can make possible the explicit consideration of cumulative damage in current simplified seismic design methods. Future studies needed to further improve our knowledge and the current state of seismic design are also recommended.

学位論文審査の要旨

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（累積損傷と地盤条件を考慮した必要耐震性能スペクトル）

現在の耐震設計の基本的な考え方では、大地震動時には構造物が塑性域に入ることを許容しており、多くの耐震規定では構造物の塑性変形性能に応じて設計用地震力を低減させる係数が採り入れられている。これまで、構造物の塑性変形性能は専ら最大変形量のみで評価されるのが一般的であり、最大変形未満の繰り返し塑性変形は考慮されていないのが現状である。しかしながら、大きな塑性変形が繰り返し生じることによる損傷の累積、及び耐力や剛性の劣化が、構造物の耐震性能に大きく影響することは明らかである。

本論文は、地震時の繰り返し変形による構造物の累積損傷や性能の劣化を考慮し、構造物の必要耐震性能を適正に把握し評価することを目的としている。また、構造物立地の地盤条件、構造物の特性、及び地震動特性が及ぼす影響についても検討を行った。

本論文は以下に示す第 1 章から第 6 章で構成されている。

第 1 章では、研究の背景や本論文の目的を示すと共に、論文の全体構成を示した。

第 2 章では、既存の耐震設計法、及び設計用地震力低減係数に関する既往の研究について述べた。また、最大変形量だけで構造物の被害を説明することは適当ではなく、累積損傷を考慮する必要性を示した。更に、現在の耐震設計法に、比較的簡易な形で累積損傷を考慮する手法を提案した。

第 3 章では、解析モデル及び入力地震動について説明した。解析モデルは、第 4 章で用いる 1 自由度系モデルと第 5 章で用いる多自由度系モデルの 2 つである。復元力特性は、bilinear モデルと peak-oriented(修正 Clough) モデルを基に、それぞれ繰り返し応答による耐力と剛性の劣化を表現できるよう修正したものを用いた。構造物の損傷 (被害レベル) 指標には Park and Ang の damage index (*DI*) を用いた。応答解析には、地盤条件により 3 つ (硬質、普通、軟弱) に分類した計 60 の地震動記録を用いた。

第 4 章では、1 自由度系モデルによる解析結果及び考察について述べた。得られた結果は以下の通りである。必要耐力は地盤条件の影響を大きく受け、とりわけ軟弱地盤で顕著である。よって、軟弱地盤において必要耐力を正確に評価するためには地盤の卓越周期を考慮しなければならない。弾性時 (損傷を許容しない) 必要耐力を塑性時 (損傷を許容する) 必要耐力で除したものが、地震力低減係数 R_D となるが、R_D も地盤条件の影響を大きく受ける。R_D スペクトルの形状は、最大変形

のみを考慮して算定された既往の低減係数 R_μ のスペクトル形状とほぼ同一であった。地震マグニチュードが大きくなるほど必要耐力が大きくなる、あるいは地震動の継続時間が長くなるほど必要耐力は大きくなる、といった傾向は見られたが、マグニチュード、震源距離及び継続時間と、R_D との間に明確な関連は認められなかった。

DI=1(崩壊) 時において累積損傷が占める割合が高かったのは、(i) bilinear モデルで軟弱地盤において構造物の固有周期が地震動の卓越周期と近い場合と、(ii) peak-oriented モデルで構造物の固有周期が短い場合であった。固有周期の短い構造物では、peak-oriented モデルの方が bilinear モデルよりも必要耐力が大きくなった。これは、bilinear モデルの周期の短い応答では履歴によるエネルギー吸収が起きにくいためと考えられる。一方、固有周期の長い構造物に対しては、peak-oriented モデルの方が bilinear モデルよりも必要耐力は小さくなった。DI=0.8 時の必要耐力と DI=1 時の必要耐力の比を見ると、bilinear モデル及び peak-oriented モデル共に、短周期域では単調増加の傾向が見られ、その後 1.2 倍程度で一定となった。

次に、回帰分析により R_D の近似曲線を導いた。これは、特に耐震設計の実務に有用であると考えられ、累積損傷や劣化を適正に評価した合理的な耐震設計が可能になるものと考えられる。

第 5 章では、2, 5, 10 及び 25 層の建物について多自由度系モデルによる検討を行った。鉄骨造では復元力特性を bilinear、RC 造では peak-oriented とした。

先ず、耐力分布を Ai 分布、剛性分布を放物線分布とした解析を行った。その結果、多自由度系により求められる必要耐力は、1 自由度系による必要耐力と比較すると、弾性時かつ固有周期が短い場合のみほぼ等しいが、固有周期が長くなるほど、また塑性変形が進行するほど、大きくなることが分かった。1 自由度の必要耐力に対する大きさの割合を同層数の鉄骨造と RC 造で比較すると、低層建物では RC 造が、高層建物では鉄骨造が大きかった。また、塑性変形が大きくなるほど、最下層での崩壊の確率が高くなった。

次に、より実建物に近いケースを想定し、耐力及び剛性分布が数層ずつ等しいとしたモデルの解析を行った。曲線分布を用いた先のモデルによる結果と比較すると、本モデルによる必要耐力の方が大きくなった。これは、耐力や剛性が急変する層にて層崩壊が起こりやすくなるためと考えられる。また、耐力分布の違いによる影響の方が、剛性分布の違いよりも大きいことが分かった。

第 6 章では、本研究で得られた結果をまとめ総括した。本研究で得られた知見及び提案した設計手法により、今後、累積損傷を考慮した耐震設計が可能となると考えられる。

これを要するに、著者は、建築構造物を対象として、弾塑性地震応答に伴う累積損傷及び地盤条件による入力地震動特性を考慮した耐震設計用応答 (強度) 低減係数についての新知見を示すとともに新たな提案をしたものであり、耐震工学及び耐震設計法の発展に対して学術上貢献するところ大なるものがある。よって著者は、北海道大学博士 (工学) の学位を授与される資格があるものと認める。