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METHOD OF DETERMINATION OF SEISMIC DESIGN PARAMETERS BASED ON RELIABILITY

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ABSTRACT

The seismic design provisions in most building codes were developed based on performance of structures during past earthquakes, thus design parameters are generally determined based on judgement and experience. In view of the large uncertainties associated with the loadings and resistance, the design parameters need to be calibrated based on adequate safety and performance under future earthquakes. In this paper, such a method of calibration is presented. It is based on minimization of the difference between actual and target (minimum) reliabilities against serviceability and ultimate limit states in terms of interstory drift limits. To expedite the solution process, the response surface method (RSM) with a central composite design is used. The design parameters considered are load factors and interstory drift limits. The methodology proposed is demonstrated by study of low to mid–rise Special Moment Resisting Steel Frames (SMRSF) (from 2 to 12 stories) designed according to the 1992 US NEHRP provisions in the Los Angeles area. A Latin Hyper Cube sampling method is used to select building configurations and dimensions which represent the steel building population. Parametric studies are carried out to show the dependence of the design load factors and drift limits on the target reliabilities for both serviceability and ultimate limit states. The computational advantage and the accuracy of the proposed method are also demonstrated. The proposed method is therefore an useful tool for calibration of design parameters in current code procedures to achieve bi–level, reliability–based performance goals.

KEYWORDS

design parameters; reliabilities; SMRSF; interstory drifts; minimization; response surface method.

INTRODUCTION

Designing a structure to achieve the performance objectives adopted in current seismic design provisions is complicated by the uncertainties involved in the design process since there are large uncertainties in predicting the intensity as well as the spatial and temporal characteristics of future earthquakes. Also, there are uncertainties associated with the limited ability of analytical models to properly describe the response of structures. In addition, structural capacity can not be determined precisely because of the variation in material strength, workmanship, etc. Since earthquake loading, structural response, and structural capacity are probabilistic in nature, the performance of a structure is also probabilistic in nature and thus the performance is somewhat uncertain. This uncertainty should be reflected in the design and code procedures.

Probability–based (reliability–based) methods can be used to account for the uncertainties in the seismic design process. Direct use of probabilistic methods may not be suitable for routine designs since it requires detailed reliability analyses and statistical modeling of loads and structural resistance. This is too computationally intensive. However, these methods can be used to calibrate code parameters and to develop reliability–based design procedures.

In this study, a method is presented by which code (design) parameters relevant to seismic design of structures can be calibrated using probabilistic methods. In general, the design parameters can be load factors, allowable drift limits, importance factor, response modification factor, etc. The design parameters are calibrated for various values of the target limit state probabilities using the response surface method (RSM) based on a central composite design to expedite the minimization solution procedure. Limit states represent the various state of undesirable behavior of structures such as yielding, buckling, instability, severe displacement, etc. The calibration is achieved by minimizing an objective function which measures the difference between "target" and "actual" probabilities of reaching various limit state conditions. The seismic load factor, and allowable story drift limits in the NEHRP recommended provisions are selected as the design parameters to be calibrated since these parameters are dominant factors as far as the reliability of the building is concerned.

CALIBRATION OF DESIGN PARAMETERS

According to Eq.(3.1) in the NEHRP recommended provisions (BSSC, 1991), the LRFD design equation is :

$$\phi R \geq \gamma_D D + \gamma_L L \pm \gamma_E E + \gamma_S S \tag{1}$$

Since structures are assumed to be located in L.A. in this study, the value of A_V is 0.4 (Table 1.4.1.1 in the NEHRP provisions). The value of γ_D is 1.3 (=1.1+0.5x0.4). According to the NEHRP recommended provisions, snow load can be neglected if the design snow load is less than 30 pounds per square foot. Since the structures are assumed to be located in L.A., snow load is not considered. Since the live load factor (γ_L) is equal to 1.0 in the NEHRP provisions, the load format shown in Eq.(1) is can be expressed as :

$$\phi R \geq 1.3D + 1.0L \pm \gamma_E E \tag{2}$$

The allowable drift limit (Δ_a) is especially important in the design of moment resisting frames in a high seismic zone. According to the NEHRP recommended provisions (Table 3.8), the allowable drift limit is expressed as a fraction of the story height (h_{sx}). The fraction varies depending on the seismic hazard exposure group and type of structure.

STEPS TO CALIBRATE DESIGN PARAMETERS

The complete process of determining design parameters using RSM can be broken into several steps as follows :
1) Select target limit state probabilities, 2) Select representative structures, 3) Determine the configuration of input variables (combinations of design parameters) according to central composite design, 4) For each combination of design parameters, design the representative structures according to appropriate code procedures and provisions, 5) Evaluate the limit state probabilities of representative structures, 6) Calculate the value of the objective function for each combination of design parameters, 7) Based on the calculated values of the objective function, establish the 2nd order polynomial representing the objective function. The polynomial should be a function of the design parameters, and 8) Find the design parameters which minimize the fitted 2nd order polynomial (fitted 2nd order objective function).

OBJECTIVE FUNCTION

As mentioned earlier, the objective function measures the difference between actual and target probabilities for all limit states and all types of structures under consideration for a certain combination of design parameters (input variables). Seismic load factor (γ_E) and allowable drift limit (Δ_a) are the input variables of the response (objective function) to be used in the Response Surface Method. In this study following objective function is used (Wen,1993) :

$$\Omega(\gamma_E, \Delta_a) = \sum_{s=1}^{m} \sum_{l=1}^{n} \omega_{sl} \frac{\left(P_{sl}(\gamma_E, \Delta_a) - P_l^*\right)^2}{P_l^*} \tag{3}$$

where $\Omega(\gamma_E,\Delta_a)$ is the objective function which depends on the input variables γ_E and Δa, l refers to a limit state, s refers to the type of structure, P_l^* is the target limit state probability for each limit state "l", P_{sl} is the actual probability of the structure type "s" for limit state "l," and ω_{sl} is a weighting factor assigned to each combination of limit state and type of structure. The squared terms in above equation is the penalty for the deviation from a target value. Since the penalties are expressed proportional to limit state probability, and one can assign the weighting factors in proportion to the consequence of exceeding a limit state, the objective function (summation of the product of the penalties and weights over all possible limit states (l) and structure types (s)) can be interpreted as the total deviation of the "expected consequence."

SELECTION OF COMBINATIONS FOR INPUT VARIABLES (γ_E, Δ_a)

A central composite design (Box and Wilson, 1951) is used to determine the combinations of γ_E and Δ_a to be used in the analysis. The central composite design consist of 2^k factorial points, n_c center points, and 2k axial points. The center point is normally chosen based on the experience of the experimenter with the problem at hand. In this investigation, it corresponds the values of the parameters recommended in current codes. Factorial points are located at equal distance from the center point. If σ represents the distance from the center point to one of the factorial points, then the axial points are located on the axes of the parameter space at a distance α times the component of σ along that axis (See Fig. 1). The center points make it possible to measure the pure error in the system response. Unlike usual experimental design problems, there is no pure error in this study, therefore, only one center point is necessary. The axial points allow the design to fit higher order surfaces without the efforts required in 3^k factorial design. Since there are 2 input variables, γ_E and Δ_a, 9 pairs of (γ_E, Δ_a) are required according to a central composite design ($2^2 + 2x2 + 1$). The values given in the NEHRP recommended provisions for γ_E and Δ_a are used as the center point. The seismic load factor in the NEHRP recommended provisions is 1.0. The allowable drift limit is $0.015h_{sx}$. The factorial points and axial points are determined based on consideration of the range of values of γ_E and Δ_a within which the minimum of the objective function is expected to occur (Fig. 1). The load formats corresponding to each set in Fig. 1 are shown in Table 1.

REPRESENTATIVE STRUCTURES

SMRSF structures ranging from 1 to 12 stories are considered. The design variables considered in the design of the structures are shown in Table 2. The ranges of the design variables are selected based on current practice. In order to design the representative structures, representative values of the design variables need to be selected. The selected values are also shown in Table 2.

Considering all possible combinations of the representative values of design variables in Table 2 is not appropriate for practical purposes due to the significant cost and computational effort involved. Hence, a judicious selection procedure of input variables is required. The latin hypercube sampling technique (Iman and Conover, 1980) is used for this purpose. Hwang (1987) demonstrated that the latin hypercube sampling technique is a systematic and efficient technique for random sampling.

Six different combination vectors of design variables (one vector per representative structure) are established by the latin hypercube technique. These combinations are shown in Table 2. Since there are 9 different pairs of (γ_E, Δ_a) to be considered for each representative structure, fifty–four structures (6 structures x 9 load factor pairs per structure) are designed according to the NEHRP provisions and AISC LRFD manual.

EVALUATION OF THE LIMIT STATE PROBABILITIES

The limit state probabilities, $P_{sl}(\gamma_L, \gamma_E)$, are calculated considering the uncertainties in both the earthquake excitation and the live load. Monte–Carlo simulation is used to determine the conditional probabilities of exceeding drift limit thresholds given the occurrence of an earthquake. The conditional probabilities are determined based on the results of dynamic response analyses which are carried out using the Equivalent Nonlinear System (ENS) procedure described in Han and Wen (1994). Twenty simulated characteristic earthquakes and fifty simulated non–characteristic earthquakes are considered. For each dynamic analysis, a simulated value of the random live load is generated using the statistical information given in the reference by Corotis(1983). Combining the conditional probabilities based on the procedure proposed by Han and Wen(1994), $P_{sl}(\gamma_E,\Delta_a)$, which represents exceedence probabilities over an assumed design life of the structure are determined.

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CALIBRATION OF SEISMIC LOAD FACTOR AND ALLOWABLE DRIFT LIMIT

Response Surface Method (RSM) is used to perform the process for calibrating the design parameters. The value of the objective function (Eq.(3)) is calculated for each pair of seismic load factor (γ_E) and allowable drift limit (Δ_a) shown in Fig. 1 and for each target limit state probability. Then, a "best–fit" second order polynomial is determined by the least square method to represent the objective function which is shown below :

$$\Omega = \beta_0 + \beta_1\gamma_E + \beta_2\Delta_a + \beta_{11}\gamma_E^2 + \beta_{22}\Delta_a^2 + \beta_{12}\gamma_E\Delta_a \qquad (4)$$

where β_i is the the constant coefficients determined by a least square method. The design factors γ_E and Δ_a are determined by minimization of the second order polynomials which can be easily done.

RESULTS

The lifetime (50 years) limit state probabilities are shown in Table 3. The target limit state probabilities for the time window 1994–2044 for the serviceability limit state are selected as 0.25, 0.30, 0.35, 0.40, and 0.45. The target probabilities for the ultimate limit state are chosen at 0.035, 0.040, 0.045, 0.050, 0.055, 0.060, 0.065, and 0.070.

Four different sets of weights for serviceability and ultimate limit state are considered; the weight ratios (serviceability : ultimate) are 1:2, 1:5, 1:10, and 1:15. The set of weights for 2, 3, 4, 5, 6, and 12 story SMRSFs is assumed to be 20, 14, 6, 4, 3, and 1 , respectively. The rationale for weights for representative structures is based on the ATC report by Rojahn and Sharpe (1985). It is based on the total floor area associated with low–rise, medium–rise, and high–rise buildings as a measure of importance. They report that 80 % of the total floor area of buildings in California is associated with low–rise buildings and the remaining 20 % is associated with medium–rise buildings. (The floor area associated with high–rise building is negligible.) For this study, to assign a weight to each structure type, 2 and 3 story SMRSFs are classified as low rise buildings and 4, 5, 6, and 12 story SMRSFs are classified as medium rise buildings. Intuitively, weights should increase gradually as the number of stories decreases. For this reason, a weight function is proposed which is dependent on the number of stories. As mentioned earlier, the ratio of the floor area of low–rise buildings to that of medium rise buildings is 4 to 1 (80% : 20% =4 : 1). Since a two–story building is in the middle of the low–rise building category, assume its weight is 4. Similarly, a weight of 1 is assumed for a building with 5.5 stories. (Even though 5.5 is not a realistic value for the number of stories, this value is in the middle of the range of stories in the medium–rise building category ((4+5+6+7)/4). Using these two data points and assuming that the weight varies exponentially with the number of stories, the weight function becomes

$$\omega_s = 8.83\exp(-0.3959 * N_s) \qquad (5)$$

where ω_s is weight assigned to a building with N_s stories. Table 4 shows the corresponding normalized weights for the representative structures considered herein. The differences between actual and predicted values can be estimated using average residual. In this study, the average residual is defined as follows :

$$E(e_i) = \frac{1}{n_c}\sum_{i=1}^{n_c} \frac{\sqrt{\dfrac{\sum_{j=1}^{n_s}(\Omega_{pij}-\Omega_{aij})^2}{n_s-1}}}{E(\Omega_{ai})} \cdot 100\ (\%) \qquad (6)$$

where e_i denotes the residual for each pairs of target probabilities shown in Table 5. i is the number of the pairs of target probabilities in Table 5 ($i=1,...,n_c$) and j is the number of the sets of design parameters shown in Fig. 1. ($j=1,...,n_s$ where n_s is 9). Ω_{aij} and Ω_{pij} represent the actual and predicted values of the objective function at design parameter set j for a given target probability set i. E(.) denotes the average value. $E(\Omega_{ai})$ denotes the mean of the actual values of the objective function for nine sets of design parameters given target probability set i. The average residual can be estimated using Eq.(6), which is 2.92 %. Therefore, the second order polynomial approximation of the objective function using the RSM is valid. Table 5 show the "calibrated" values of γ_E and Δ_a which minimize the objective function for a given set of target limit state probabilities.

The results generally show that the higher target limit state probabilities lead to a higher allowable drift limit ratio and a lower seismic load factor as expected. Figure 2 presents the plot of γ_E and Δ_a/h_{sx} vs. target serviceability limit state probability (P_s^*) for P_u^* =0.06. These figures show the trend of dependence of γ_E on the target P_s^*. They also show the sensitivity of the seismic load factor to a change in target serviceability limit state probability (P_s^*) as the relative weight on the serviceability limit state increases. It is seen that the allowable drift ratio (Δ_a/h_{sx}) generally increases with target exceedence probability; also, the allowable drift ratio becomes more sensitive to change in P_s^* as the weight of the serviceability limit state is increased.

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Figure 3 shows γ_E and Δ_a/h_{sx} vs. target ultimate limit state probability (P_u^*) for P_s^* =0.35. These figures show the trend of dependence of seismic load factor and allowable drift ratio on the target ultimate limit state probability. It is seen that these two design parameters also become more sensitive to change in P_U^* as the weight of the ultimate limit state is increased.

CONCLUSION

The following conclusions can be drawn based on the results of this study :

(1) The RSM with central composite design is an efficient method in minimizing the objective function. Furthermore, it is not required to repeat the cycle of design, response and reliability analysis (as in a nonlinear programming solution procedure) when the target limit state probability is changed.

(2) Limit state probabilities for high–rise structures (>7 stories) which are designed according to the NEHRP recommend provisions and AISC LRFD manual are lower than those for low–rise (1 to 3 stories) and medium–rise structures (4 to 7 stories) designed according to the same provisions and manual. This implies that the design procedures in the NEHRP recommended provisions and AISC LRFD manual are more conservative when applied to high–rise structures. This observation is reasonable since the failure of a high–rise structure can lead to more serious consequences than that of a low–rise or medium–rise structure.

(3) It is found that the allowable story drift ratio of the structures have a more significant effect than the seismic load factor on the reliability of serviceability limit state as well as ultimate state. For the seismic load factor of 1.0 and the allowable drift ratio of 0.015 recommended in the NEHRP provisions, the implied target limit state probabilities for serviceability and ultimate limit states are also 0.38 and 0.060 for 50 years respectively, which correspond to annual risks of 0.0076 and 0.0012. These implied risks correspond to the risk levels associated with buildings designed according to building code (according to the studies by Hays, 1985).

(4) Load factors for seismic load and live load, and allowable story drift ratio can be calibrated based on target probabilities for serviceability and ultimate limit states. Therefore, the procedure provides a rational method for selecting these design parameters. As expected, the relative weights assigned to the limit states have an influence on the design parameters. Therefore, the weights need to be assigned in a rational manner, e.g., according to the seriousness (expected cost) of the consequence of the limit states.

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Table 1. Central Composite Design Combinations for Load Case and Allowable Drift Limit

Set No.	Load Case	Allowable Drift Limit (Δ_a)	Set No.	Load Case	Allowable Drift Limit (Δ_a)
1	1.3D + 1.0L + 1.0E	0.015 h_{sx}	6	1.3D + 1.0L + 1.7E	0.015 h_{sx}
2	1.3D + 1.0L + 1.5E	0.018 h_{sx}	7	1.3D + 1.0L + 1.0E	0.020 h_{sx}
3	1.3D + 1.0L + 0.5E	0.018 h_{sx}	8	1.3D + 1.0L + 0.3E	0.015 h_{sx}
4	1.3D + 1.0L + 0.5E	0.012 h_{sx}	9	1.3D + 1.0L + 1.0 E	0.010 h_{sx}
5	1.3D + 1.0L + 1.5E	0.012 h_{sx}	5	1.3D + 1.0L + 1.5E	

Table 2. Design Variables and Combinations of Representative Values of Design Variables Based on Latin Hypercube Sampling

N	Design Variables	Range	Representative Values	Fr 1	Fr 2	Fr 3	Fr 4	Fr 5	Fr 6
1	N. of Stories	1−15	2,3,4,5,6,12	12	6	3	4	2	5
2	Story Height −1st − others	14−18 11−15	15,17 (1st story) 12,14 (others)	12 15	14 17	12 15	14 17	14 17	12 15
3	N. of Bays(N−S)	2−5	3,4	4	3	3	4	3	4
4	N. of Bays(E−W)	2−5	5	5	5	5	5	5	5
5	Span Length	20−35	25,30	25	25	30	30	30	25
6	DL(floor)	90−100	95,100	100	95	100	95	95	100
7	DL(top)	75−85	80,85	80	85	85	80	85	80
8	LL(floor)	40−55	45,50	50	45	45	50	45	50
9	LL(top)	12−20	16	16	16	16	16	16	16

Note : for design variable 2, a(b) denotes story height b for 1st story and story height(foot) a for other stories DL: dead load (psf), LL: live load (psf) , Fr:Frame

Table 3. Limit State Probabilities for 2 Story SMRSF

No. of Story	Limit State	Set no.1	Set no.2	Set no.3	Set no.4	Set no.5	Set no.6	Set no.7	Set no.8	Set no.9
2 story	0.5%h_{sx}	0.3996	0.4146	0.4732	0.2546	0.2322	0.3237	0.5229	0.4392	0.2323
	1.5%h_{sx}	0.0655	0.0682	0.0717	0.0431	0.0405	0.0545	0.0764	0.0704	0.0388
3 story	0.5%h_{sx}	0.4186	0.4578	0.5015	0.2893	0.2661	0.3695	0.4865	0.4760	0.2031
	1.5%h_{sx}	0.0638	0.0688	0.0716	0.0500	0.0488	0.0560	0.0764	0.0730	0.0339
4 story	0.5%h_{sx}	0.3012	0.3128	0.4140	0.2323	0.2247	0.2585	0.4332	0.3315	0.1666
	1.5%h_{sx}	0.0432	0.0442	0.0584	0.0382	0.0357	0.0392	0.0621	0.0463	0.0273
5 story	0.5%h_{sx}	0.3527	0.3612	0.4263	0.2337	0.2044	0.2718	0.4346	0.3712	0.1864
	1.5%h_{sx}	0.0456	0.0470	0.0593	0.0364	0.0334	0.0406	0.0612	0.0495	0.0332
9 story	0.5%h_{sx}	0.2967	0.3449	0.3665	0.2288	0.2158	0.2890	0.4120	0.3106	0.1651
	1.5%h_{sx}	0.0470	0.0548	0.0567	0.0319	0.0313	0.0413	0.0646	0.0500	0.0278
12story	0.5%h_{sx}	0.2216	0.2626	0.3001	0.1939	0.1917	0.1991	0.2848	0.2217	0.1407
	1.5%h_{sx}	0.0346	0.0356	0.0375	0.0318	0.0334	0.0367	0.0367	0.0346	0.0245

Table 4. Weights

No. of Stories	2	3	4	5	6	12
Weight	20	14	6	4	3	1

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Table 5. Seismic Load Factor (γ_E) and Allowable Drift Limit (Δ_a) for Various Target Limit State Probabilities

Ratio of Weights for 2, 3, 4, 5, 6, and 12 Story SMRSFs=20:14:6:4:3:1

Ratio of Weights for Serviceability and Ultimate Limit States(ω_s:ω_u) = 1:2							
P_s^*	0.25	0.30	0.35	0.40	0.45	0.50	0.35
P_u^*	0.060	0.060	0.060	0.060	0.060	0.060	0.040
γ_E	*	1.40	1.21	1.02	0.85	0.75	1.34
Δ_a/h_{sx}	*	0.014	0.015	0.016	0.017	0.018	0.014
P_s^*	0.35	0.35	0.35	0.35	0.35	0.35	0.35
P_u^*	0.045	0.050	0.055	0.060	0.065	0.070	0.075
γ_E	1.30	1.26	1.23	1.21	1.19	1.17	1.15
Δ_a/h_{sx}	0.014	0.015	0.015	0.015	0.016	0.016	0.016
ω_s:ω_u= 1:5							
P_s^*	0.25	0.30	0.35	0.40	0.45	0.50	0.35
P_u^*	0.060	0.060	0.060	0.060	0.060	0.060	0.040
γ_E	1.48	1.36	1.18	1.02	0.88	0.76	1.42
Δ_a/h_{sx}	0.013	0.014	0.015	0.016	0.017	0.018	0.013
P_s^*	0.35	0.35	0.35	0.35	0.35	0.35	0.35
P_u^*	0.045	0.050	0.055	0.060	0.065	0.070	0.075
γ_E	1.36	1.30	1.24	1.18	1.13	1.09	1.05
Δ_a/h_{sx}	0.014	0.015	0.015	0.015	0.016	0.016	0.017
ω_s:ω_u = 1:10							
P_s^*	0.25	0.30	0.35	0.40	0.45	0.50	0.35
P_u^*	0.060	0.060	0.060	0.060	0.060	0.060	0.040
γ_E	1.46	1.30	1.15	1.01	0.91	0.82	1.44
Δ_a/h_{sx}	0.014	0.015	0.016	0.017	0.017	0.018	0.011
P_s^*	0.35	0.35	0.35	0.35	0.35	0.35	0.35
P_u^*	0.045	0.050	0.055	0.060	0.065	0.070	0.075
γ_E	1.43	1.33	1.23	1.15	1.07	0.99	0.93
Δ_a/h_{sx}	0.013	0.014	0.015	0.015	0.016	0.016	0.017
ω_s:ω_u= 1:15							
P_s^*	0.25	0.30	0.35	0.40	0.45	0.50	0.35
P_u^*	0.060	0.060	0.060	0.060	0.060	0.060	0.040
γ_E	1.41	1.25	1.12	1.01	0.92	0.85	*
Δ_a/h_{sx}	0.014	0.015	0.016	0.017	0.017	0.017	*
P_s^*	0.35	0.35	0.35	0.35	0.35	0.35	0.35
P_u^*	0.045	0.050	0.055	0.060	0.065	0.070	0.075
γ_E	1.47	1.36	1.25	1.12	1.02	0.93	0.86
Δ_a/h_{sx}	0.013	0.014	0.015	0.015	0.016	0.017	0.018

Note : P_s^* = target limit state probability for serviceability (0.5%h_{sx})
P_u^* = target limit state probability for ultimate failure (1.5%h_{sx})
* denote that design parameters can not be determined.

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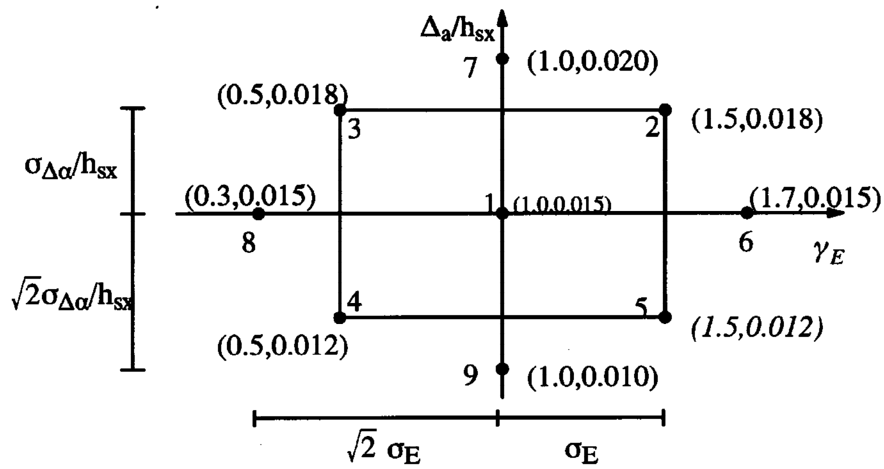

Fig. 1. Configuration of Central Composite Design for γ_E and Δ_a/h_{sx}

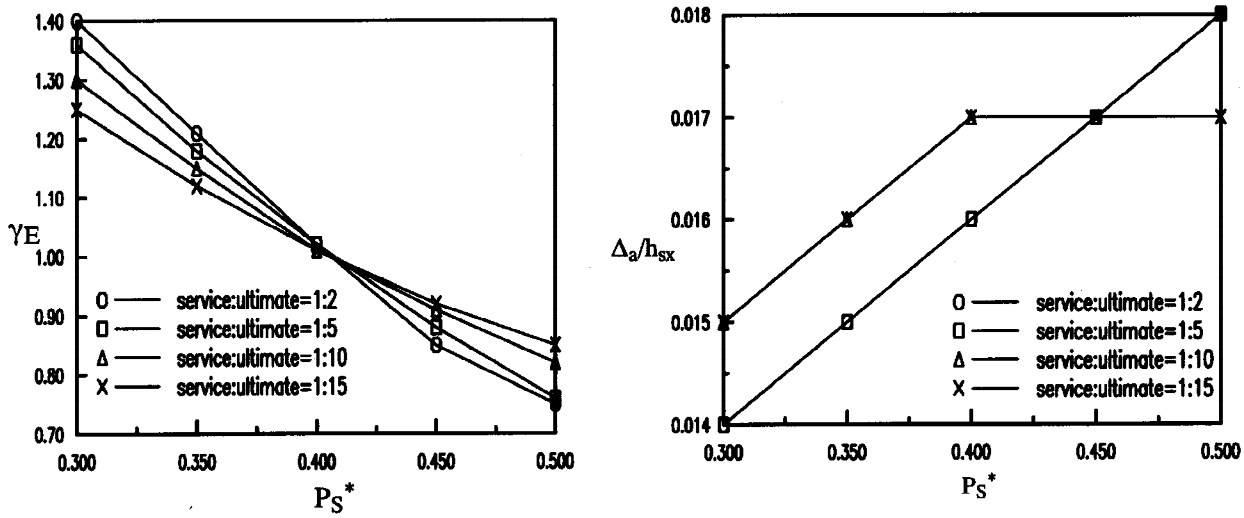

Fig. 2. Sensitivity of γ_E and Δ_a/h_{sx} to P_S^* ($P_U^* = 0.06$)

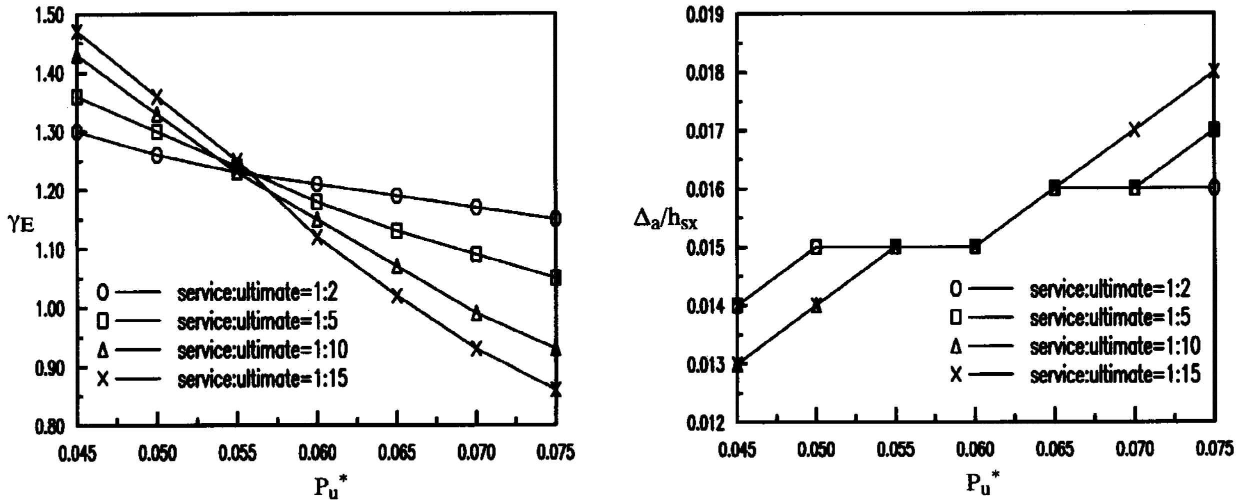

Fig. 3. Sensitivity of γ_E and Δ_a/h_{sx} to P_u^* ($P_s^* = 0.35$)