OVERVIEW OF 2007 E-DEFENSE BLIND ANALYSIS CONTEST RESULTS

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ABSTRACT :

A blind analysis contest has been conducted in conjunction with the full-scale total collapse test of a four-story moment frame in September 2007 at the E-Defense shake-table facility. The purpose of the contest is to stimulate development of computational methods and efficient modeling techniques for collapse analysis. In this report, statistical data are presented for the types and parameter values employed by the participants of the contest, and the key factors to accurate estimation of collapse behavior are investigated.

KEYWORDS: Blind analysis contest, Collapse analysis, Seismic response, Steel frame

1. OVERVIEW OF THE CONTEST

A blind analysis contest has been conducted in conjunction with the collapse test of the full-scale four-story steel building frame in September 2007 at the E-Defense shake-table facility. See Suita et al. (2007) and Tada et al. (2007) for the details of the four-story building frame. The brief report of the test results can be found in Suita et al. (2008). The overview of the series of the tests of steel building frames is presented in Kasai et al. (2007).

The contest has been carried out by two working groups under the supervision of the executive committee. The “Analysis Method and Verification WG” did tasks including announcement, distribution of data, answering questions, and judgment. The “Building Collapse Simulation WG” produced the experimental data for the collapse of the four-story building.

The purpose of the blind analysis contest is to stimulate development of computational methods and efficient modeling techniques for steel frames for prediction of seismic responses and collapse behavior. The final goal is to improve seismic performance of steel frames through numerical simulation.

The main difficulties of the contest are summarized as follows:

- The actual motion of the table is not known before the test due to the control error of the shake-table.
- The shake-table tests are conducted consecutively with increasing levels of seismic motion, and the seismic level of the subsequent test is decided according to the actual deformation and damage observed in the current test.
- The property of the concrete material is measured only a few days before the test.

Therefore, the following two-step process has been adopted for the contest:

- The contest has two parts: *pre-test analysis* based on anticipated seismic motions, and *post-test analysis* using the actual table acceleration.
- The building model and the analysis procedure for the *post-test analysis* must be identical to those for the *pre-test analysis* except the property of concrete material and input accelerations.

The contest is categorized by the types of analysis methods and participants. Analysis methods are classified to 3D-analysis and 2D-analysis. Each category has two winners: one from researchers including students, and another from practicing engineers. Therefore, a total of four winners were expected to be selected; however, we had five winners, because the two best scores of the 3-D analysis by researchers were same.

Although the purpose of the contest is the development of techniques for collapse analysis, it is very difficult to predict the total collapse behavior by the currently available simulation techniques. Furthermore, the total collapse is prevented in the test by placing the retaining walls so as to avoid any damage to the shaking table. Hence, the responses to be predicted are determined as

- Analysis results should be submitted for the *incipient-collapse level*, the seismic level immediately prior to the *collapse level* at which collapse of the building occurs.
- The analysis should be performed continuously from the seismic level at which the first plastification occurs up to the collapse level, by serially combining the corresponding table motions.
- Only the time at collapse is to be predicted for the *collapse level*.

2. METHOD OF JUDGMENT

The data to be submitted for judgment are specified as

- For *incipient-collapse level*:
  Maximum values of relative displacement from base, absolute acceleration and overturning moment at each floor; maximum values of story shear, story drift angle; maximum engineering strain at a specified point (center of the column in 1st story) in an elastic region; and residual story drift at each story (the story drift at the end of the specified duration of the seismic motion).
- For *collapse level*:
  Time, measured from the beginning of the collapse-level motion, at which the drift angle of any story in X- or Y-direction reaches 0.13 rad.

The judgment process is summarized as follows:

(a) Compare the RMS errors for each response quantity, which is computed from

$$E_i = \sqrt{\sum_j (F_{i,j} - F^*_{i,j})^2} \tag{1}$$

$F_{i,j}$: analysis result of ith response quantity at jth floor/story.

$F^*_{i,j}$: test result of ith response quantity at jth floor/story.

E_i : RMS error of ith response quantity

It is possible to normalize $F_{i,j} - F^*_{i,j}$ by $F^*_{i,j}$ before summation. However, in this case the errors of the small responses are magnified. Therefore, we did not make normalization in this contest.

(b) The basic point b_i for ith response quantity is 8 for the minimum error, 5 for the second, 3 for the third, and 1 for the fourth. The total point P is computed from

$$P = \sum_{i=1}^{n} w_i b_i \tag{2}$$

w_i : weight for ith response quantity

n: number of response quantities

The team/individual with maximum total point will be the winner for each category. The weight w_i was announced to be 1.0 for all response quantities by the committee before the submission of pre-test analysis results.

(c) The judgment is carried out completely anonymously. Judges will only know the participant submission name only via the ID-number.

(d) In each category, up to and including the third place winners are announced and the names of all the participants are asked to disclose their names and affiliations.

3. RESULTS OF THE CONTEST

The numbers of submission are as follows:

· Total: 47 (3D: 30, 2D: 17)
  – Researchers: 30 (3D: 18, 2D: 12)
  – Practicing engineers: 17 (3D: 12, 2D: 5)

The numbers of types of softwares adopted in each category are shown in Table 1, where, "commercial" means any commercially available software package, "research" means free software that may possibly be used for commercial purpose, and "personal" means in-house program developed for own use.

Table 1 Numbers of types of softwares and analysis models adopted in each category.

		3-dimensional analysis		2-dimensional analysis	
		Researcher	Engineer	Researcher	Engineer
Types of softwares	Commercial	6	8	3	1
	Research	9	2	8	1
	Personal	2	2	1	3
	Unknown	1	0	0	0
Model of beams and column	Line	5	2	2	3
	Line+hinge	3	6	4	2
	Line+fiber	5	0	5	0
	Line+hinge+fiber	2	0	1	0
	Shell	0	3	0	0
	Lumped mass	1	0	0	0
	Others	1	1	0	0
	Unknown	1	0	0	0

The numbers of methods of modeling of beams and columns are also listed in Table 1. "Line" indicates the conventional beam-column line element. "Line+hinge+fiber" means that fiber elements are used for beams, and plastic hinges are used for columns. "Others" include "applied element method" and "discrete element method." Note that the plastic deformation at each member end can be effectively simulated without using plastic hinge or fiber element, if each member is divided into an appropriate number of beam-column elements, e.g. 10 elements, considering plastic deformation.

4. STATISTICAL INVESTIGATION OF RESULTS

We next carry out statistical investigation of the RMS values defined by Eq. (1) for the responses in Y-direction, for which the responses are computed by both of 2D- and 3D-analyses. To prevent obviously wrong data from affecting the statistical values of the results, the exceptional data are extracted using the standard techniques of clustering called K-means; i.e., the RMS errors of all the participants are divided to two clusters for each response quantity, and the data in the cluster with larger errors are removed. In the following, the data mining tool called WEKA Ver. 3.5.8 (Witten and Frank, 2000) is used for clustering and classification of the data. The number of exceptional data in each response is listed in Table 2. After removing those data, the values of mean, maximum, minimum and standard deviation of each response are computed as shown in Table 2.

Table 2 Number of exceptional data, and the values of mean, maximum, minimum and standard deviation of the RMS value of each response in Y-direction (RD: relative displacement, AA: absolute acceleration, OM: overturning moment, SS: story shear, IDA: interstory drift angle, RIDA: residual interstory drift angle, CS: column strain, CT: collapse time).

	RD (mm)	AA ($\times 10^3$ mm/s^2)	OM ($\times 10^7$ kN mm)	SS ($\times 10^3$ kN)	IDA ($\times 10^{-2}$ rad.)	RIDA ($\times 10^{-2}$ rad.)	CS ($\times 10^{-3}$)	CT (sec.)
Number of exceptional data	6	5	6	1	7	3	3	19
Mean	103.1	3.20	0.483	0.562	1.36	1.21	0.891	5.57
Std. dev.	92.8	1.57	0.264	0.364	1.09	1.87	2.03	0.770
Max.	303.4	8.02	1.23	1.91	4.39	9.15	13.0	3.25
Min.	97.9	0.857	0.110	0.0537	0.192	0.118	0.0460	0.0100

Table 3 Mean, maximum, minimum and standard deviation of the RMS errors of the maximum interstory drift angles and shear forces in Y-direction by 2D- and 3D-analyses.

	3D- analysis		2D-analysis	
	Drift angle ($\times 10^{-2}$ rad.)	Shear force ($\times 10^3$ kN)	Drift angle ($\times 10^{-2}$ rad.)	Shear force ($\times 10^3$kN)
Mean	1.54	0.520	1.04	0.641
Maximum	4.39	1.91	2.87	1.44
Minimum	0.306	0.0537	0.192	0.183
Std. Dev.	1.253	0.351	0.667	0.397

Table 3 shows the mean, maximum, minimum and standard deviation of the RMS errors of the maximum interstory drift angle and shear force in Y-direction among the participants in 2D- and 3D-analyses. As is seen, 3D-analysis has better performance in shear force; however, 2D-analysis is better in drift angle. Note that the obviously wrong results have also been omitted in the same manner as Table 2.

In order to compare the RMS errors of different responses by 2D- and 3D-analyses in the same performance measure, the RMS errors are normalized as

$$\mathrm{NormRMS}(i,j) = [\mathrm{RMS}(i,j) - \mathrm{Mean}(j)] / \mathrm{StdDev}(j)$$

where RMS(i,j) and NormRMS(i,j) are the original and normalized RMS errors of group i for the jth response, respectively, and Mean(j) and StdDev(j) are the mean value and the standard deviation of the RMS error of jth response. RMS(i,j) is then summed up over j to obtain the total score of group i, which has smaller (negative) value for a group with better performance.

Three exceptional data have been extracted for the total score, and they are replaced by the maximum value of the remaining data. The values of (mean, std. dev., max., min.) are (8.358, 14.43, 47.50, –5.383). For 2D-analysis, those values are (8.702, 13.38, 47.50, –5.041), while (8.164, 15.21, 47.50, –5.383) for 3D-analysis. Among 10 best groups in the total score, the ranks 1, 2, 4, 5, 6, 7 and 8 are 3D-analysis, and 2, 9 and 10 are 2D-analysis. Therefore, a slight advantage of 3D-analysis is observed over 2D-analysis.

Table 4 Values and selection of key factors adopted in the groups in each category.

		3D-analysis		2D-analysis	
		Researcher	Engineer	Researcher	Engineer
CPU time	Less than 1 min.	2	3	2	2
	Between 1 min. and 30 min.	7	4	8	1
	Over 30 min.	8	4	2	1
	N/A	1	1	0	1
Use of material and member test results	Use member test.	6	5	7	3
	Use material test.	4	2	2	0
	Do not use.	5	4	3	0
	N/A	3	1	0	2
Consider composite beam.	Yes.	7	7	10	4
	No.	1	0	0	0
	N/A	10	5	2	1
Rigid-floor assumption	Yes.	4	4	1	2
	No.	0	1	1	0
	N/A	14	7	10	3
Damping type	Rayleigh	9	5	8	3
	Stiffness-proportional	2	2	0	0
	Other	0	0	1	0
	N/A	7	5	3	2
Damping ratio	Less than 0.02	1	1	2	0
	0.02	8	8	6	3
	Larger than 0.02	3	2	4	2
	N/A	6	3	0	0
Consider geometrical nonlinearity	Yes	3	7	5	3
	No	2	1	1	1
	N/A	13	4	6	1
Method of integration	Newmark-β	12	6	8	3
	Other	2	1	0	1
	N/A	4	5	4	1
Time step Δt (sec.) for integration	$\Delta t \leq 0.001$	1	4	1	1
	$0.001 < \Delta t \leq 0.01$	3	4	2	1
	$0.01 < \Delta t \leq 0.02$	1	0	1	0
	$0.02 < \Delta t$	0	1	0	0
	N/A	14	3	8	3

The parameters for analysis and selection of key factors that affect the analysis results of the groups in each category are summarized in Table 4, where N/A means that the details are not available from the submitted documents. Obviously, CPU time for 3D-analysis is generally larger than that of 2D-analysis. However, the relation between CPU time and accuracy of the results cannot be discussed, because the details of the type of CPU, size of memory, etc., were not available.

To investigate the key factors on the accuracy of the results, the groups are classified to four ranks based on the total score S, where the k-means method has been used. As a results, the ranks are defined as

Rank 1: $S \leq 17$; Rank 2: $17 < S \leq 38$
Rank 3: $38 < S \leq 43$; Rank 4: $43 < S$

where Rank 1 is the best among the four ranks, and the numbers of groups in Ranks 1-4 are 17, 21, 5 and 4, respectively.

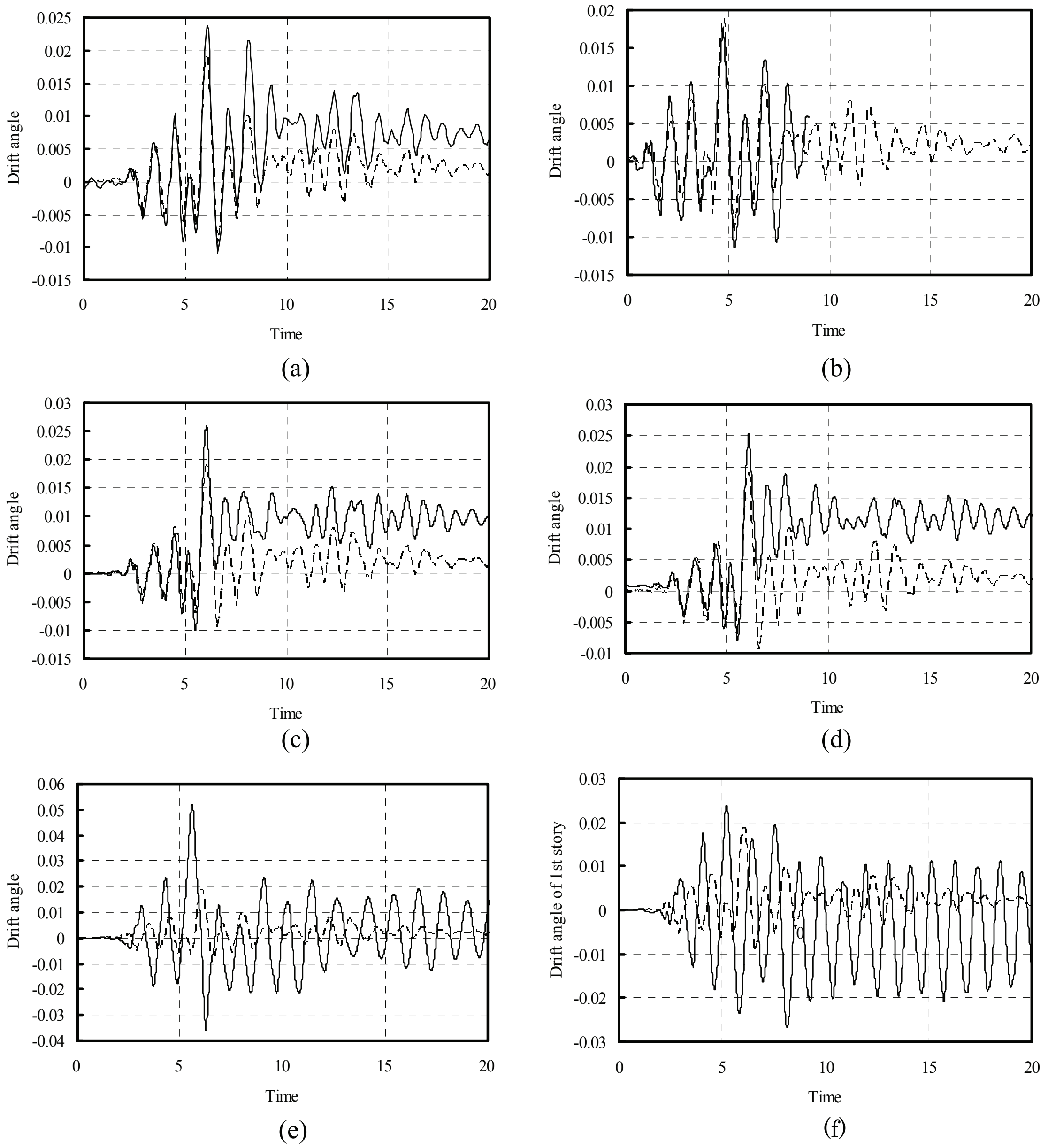

Figure 1 Time histories of interstory-drift angles in Y-direction of the 1st story; solid line: numerical result, dotted line: experimental result.

The method J48 in WEKA is used for finding dependencies of the accuracy of the results on the parameter values. Although the data mining techniques are generally used for discovering the rules or knowledge from the data of huge size, we can use data mining tools to find the hints or clues of dependencies. The following relations have been found:

1. Among 29 groups that used the material/member test results, 14 are classified as Rank 1; while 3 out of 12 are classified as Rank 1 if test results are not used.
2. Among 10 groups that used the material/member test results, Rayleigh damping, and research-purpose program, 9 are classified as Rank 1.
3. Among 11 groups that assigned damping ratio larger than 0.02, 6 are classified as Rank 1.
4. Among 25 groups that assigned damping ratio equal to 0.02, 13 are classified as Rank 2.
5. Among 4 groups that assigned damping ratio less than 0.02, 2 are classified as Rank 1.
6. Among 18 groups that considered geometrical nonlinearity, 10 are classified as Rank 1. Conversely, among 17 groups in Rank 1, 10 considered geometrical nonlinearity.

Figure 1 shows the time histories of interstory-drift angles in Y-direction of the 1st story, where the solid line is the numerical result and the dotted line is the experimental result. The plots (a), (b), (c) and (d) are the high-ranking results that have moderately good accuracy, although the residual drift angle seems to be very difficult to predict. However, the numerical results are significantly different from the experimental results for the low-ranking results in (e) and (f). Although it is very difficult to point out the major cause of this low accuracy, the result of member test has not been incorporated in modeling of composite beam action in (e) and (f).

From the results above and additional investigation of the results, the following important points are observed from the contest results:

1. As pointed out above, it is important to use material/member test results to obtain accurate results. However, in the usual design process, material/member test is not carried out before the construction of each frame; which means that accurate responses cannot be obtained in the design process using the nominal values of the material properties. Therefore, it is important to accurately incorporate variability of material parameters in the design code.
2. Rayleigh damping leads to more accurate estimation than the stiffness-proportional damping. It is important that the damping ratio should be more than 0.02 to incorporate the damping effect by nonstructural components. However, an appropriate value of the damping ratio is unknown.
3. Geometrical nonlinearity should be considered, in any form, for accurate prediction of collapse behavior.
4. Computational cost and accuracy are not correlated. It is amazing that one of the winners of 2D-analysis used lumped-mass model for dynamic analysis, although the tri-linear hysteresis model is obtained from static pushover analysis of frame model.
5. Although it is important to consider the composite beam effect, the amplification factor employed by each participant varies from 1.25 to 2.0, which means that there is no established theoretical basis for computing the amplification factor. In order to prevent the process like a random guess, more theoretical, numerical and experimental studied are encouraged.
6. The response quantities representing displacements (relative displacement, interstory drift angle) and forces (absolute acceleration, overturning moment, story shear), respectively, are obviously correlated. Therefore, the number of response quantities with similar properties and preferably the weight coefficients for the evaluation of the total point should be carefully

determined in the future event of blind analysis contest.

5. CONCLUSIONS

The framework of two-step submission procedure of the blind analysis contest has been presented, and the statistic investigation has been carried out for the contest results. The key factors that have strong effect on the accuracy of the numerical results are explored with the aid of a data mining tool.

It has been shown that no clear advantage of 3D-analysis over 2D-analysis, or vice versa, can be observed from the results of the participants of the contest. However, the use of material and/or member test results and the appropriate assignment of damping coefficient may be very important for obtaining accurate results.

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