RELIABILITY ASSESSMENT SOFTWARE FOR EXISTING BUILDING STRUCTURES

Kai Sun[1], Xianglin Gu[2], Weiping Zhang[3], Xiaojing Yin[4], Bin Peng[5], and Qinghua Huang[6]

ABSTRACT

The development and implementation of reliability assessment procedures for existing building structures encounter many problems in practice due to few computer programs to assist this job. This paper is proposed to introduce the design concepts and system of REASES, REliability Assessment Software for Existing building Structures, and its developing significance. The whole research especially focuses on the effectiveness and efficiency of assessing an actual structure. With an easy and practical modeling, and analyzing methods in accord with the codes and current research products developed for existing structures, REASES can synthetically analyze the reliability (safety, serviceability and durability) of a structure and all of its components, give out assessment result outputs, and finally generate an assessment report automatically. Extensive modules, which extremely enrich the functions of REASES and greatly improve the suitability of this software, can simulate the whole process of the damage for a structure under earthquake action. An example of assessment shows that REASES is effective and accurate.

KEY WORDS

reliability assessment, existing building structure, simulation, seismic response, collapse analysis.

INTRODUCTION

Assessment of an existing structure may be required if there are evident signs of deterioration, change of occupancy, change of loads, or as a part of a regular monitoring program. The reliability assessment is going towards a standardized and codified way. In fact, some reliability-based code type documents have been developed for reliability assessment of existing structures (Val et al. 2002). However, the efficiency of assessment is still very low, for what the main reason is few suitable commercial software is available to assist the

1 Postgraduate Student, Dept. of Build. Engrg., Tongji Univ., Shanghai, China, sunkai2002@21cn.com
2 Prof., Dept. of Build. Engrg., Tongji University, Shanghai, China, gxiangl@online.sh.cn
3 Assoc. Prof., Dept. of Build. Engrg., Tongji University, Shanghai, China, zhwp621@online.sh.cn
4 PhD. Student, Dept. of Build. Engrg., Tongji University, Shanghai, China, darkblueyxj@hotmail.com
5 Lect., Dept. of Build. Engrg., Tongji University, Shanghai, China, pengTJ77@hotmail.com
6 PhD. Student, Dept. of Build. Engrg., Tongji University, Shanghai, China, chadyellow@126.com

ssessment.

There are significant differences between design and assessment situations (Val et al. 2002): firstly, uncertainties about the dimension and the material strength are reduced after an existing structure being inspected/tested; Secondly a conservative assessment may result in unnecessary and costly repairs or replacement, and what is more, it is rather unfair for both the disputants to receive an inaccurate assessment report in the instance that the structure is in accusation of quality, which is often happened; Finally it is quite difficult to make experiment for an existing structure with real situation. These differences have been recognized by more and more people in the field of engineering (Melchers 2001).

Basically, engineering applicable software systems on the market are classified as the design software and the analysis software. For the design software, it is usual to follow some certain design codes. As the above-mentioned differences between the assessment and design procedures, it is not suitable to induce the design software into the reliability assessment directly. For the analysis software, especially with general finite element method (FEM), no unified failure modes and assessment criteria are specified, so the assessment will depend on too much individual experience in the use of analysis software. Besides, too much time will be taken on modeling and computing for an existing structure fully based on the FEM (Nie and Ellingwood 2004).

Unfortunately, now in China almost all assessment work is done by dint of the comparison between the designing results by the design software and that in actual situations, and only some important components are analyzed by the analysis software, which is not only inconvenient in operation but also irrational in theory. Furthermore, there will be many potential safety problems under this kind of assessment, so it is necessary to develop a set of software focusing on the reliability assessment for existing building structures. REASES is hereby developed.

RELIABILITY ASSESSMENT FOR EXISTING BUILDING STRUCTURES

The reliability assessment particularly mentioned here is guided by correlative codes (ISO/CD 13822 2001, DG/TJ 08-804-2005, and so on) developed for existing structures, so that it has its regulatory authority and public conviction. Meanwhile, it should be operated carefully and be carried out as accurately as possible.

THE CONCEPT OF TARGET PERIOD OF USAGE

Target period of usage is the expected continuing period of usage determined by the period in use, history status and expected using demands of the building. Different from design reference period corresponding to the design codes, usually equals to 50 years in China, target period of usage may be 10 years, 20 years, or even 100 years. All loading nominal values and constitutive relationships of materials should be adjusted according to the target period of usage. Hence the target period of usage of an existing structure must be made clear, before the structure is assessed.

BASIC RULES OF ASSESSMENT

The reliability of existing building structures can be defined as a sign of sufficient safety, serviceability and durability. Generally speaking, a reliable structure and all of its components should be capable, during its expected service time or target period of usage, of withstanding the expected loads and environmental effects with reliability conditions (Marek et al. 1995). However, when assessment work is implemented in detail, the criteria of it vary in different countries. The following paragraphs will illustrate several principles mainly adopted by REASES.

Safety calculation formula for an existing structural member is proposed as Eq. (1) based on the bearing capacity:

$$\gamma_0\left(\gamma_{\mathrm{G}}S_{\mathrm{Gk}}+\gamma_{\mathrm{Q1}}S_{\mathrm{Q1k}}+\sum_{i=2}^{n}\gamma_{\mathrm{Qi}}\psi_{\mathrm{ci}}S_{\mathrm{Qik}}\right)\leq R\left(f,a,\cdots\right)/\gamma_{\mathrm{R}} \quad (1)$$

where, γ_0 is the importance coefficient; γ_G is the partial factor of permanent loads; γ_{Q1}, γ_{Qi} is the partial factor of live load 1 and i; S_{Gk} is the nominal value effect of dead load; S_{Q1k} is the nominal value effect of live load 1, which is greater than any other effect of live load i; S_{Qik} is the nominal value effect of live load i; ψ_{ci} is the combination coefficient of live load i; $R(\bullet)$ is the resistance function of the structural member; γ_R is the resistance partial factor of the structural member; f is the nominal value of actual material performance; a is the nominal value of actual geometrical parameter. Gu et al. (2004) suggested that $\gamma_G = 1.0$, γ_{Q1}, $\gamma_{Qi} = 1.3$ and γ_R for different members range from 1.11 to 1.82.

The serviceability for a structural member is determined based on Eq. (2)

$$S_{\mathrm{k}} \leq C \quad (2)$$

where, S_k is the unfactored structural response and C is the allowable value in the serviceability limit states. Time variable should be introduced into the durability assessment of existing structural members according to the safety and serviceability within the target period of usage (Mori 2002, Gu et al. 2005).

Structural members are evaluated with the reliability grades, which are shown in Table 1.

The reliability of the structural system should be evaluated according to the safety, serviceability and durability respectively. The principles are as follows (Gu et al. 2005):

- The reliability of the structural system should be analyzed using the stratification method, which treats the ground foundation as the bottom story of the structural system, stratifies the superstructure as natural story.
- Evaluate the reliability of the ground foundation and each story of the superstructure.

- Find out the story that owns the lowest grade of reliability and the structures above have the same reliability grade.

Table.1 Classification of Reliability for a Structural member

Grade		Criterion	Physical meaning
Safety ($R/\gamma_0\gamma_R S$)	a_u	≥1.0	No need to take measures
	b_u	≥0.95 and <1.0	Could take no measures
	c_u	≥0.90 and <0.95	Should take measures
	d_u	<0.90	Must take measures immediately
Serviceability	a_s	Through comparing items between actual conditions and corresponding specification such as displacement, cracks, corrosion and so on.	No need to take measures
	b_s		Could take no measures
	c_s		Should take measures
Durability	a_d	Through evaluating time-dependent safety and serviceability within the target period of usage.	No need to take measures
	b_d		Should take measures

ASSESSMENT REPORT

Obviously the term reliability involves many uncertainties in the assessment (Ellingwood 1996). However, from a very practical point of view, engineers may prefer to get a clear idea whether an assessed structure is safe or not and what steps should be taken on it. So though uncertainties are concerned in the analysis process as all sorts of variables, the assessment conclusions had better be presented in a deterministic way.

With the development of inspection and assessment over the two last decades, a completed format for assessment report has been concluded. The report should include: a) a general description about the assessed building; b) purpose and content of the assessment; c) results of inspection, analysis and appraisal; d) conclusions and suggestions; e) appendix.

It appears that a complete report requires a large amount of labor and time. As a convenient software system with automation, REASES can generate a reliability-based assessment report in all structural facets, which extremely facilitates the assessment work for engineers. The powerful design and drawing software have promoted the development of design processes dramatically during recent two decades, since design drawings reflecting a complete design concept can be exported directly, and so will the assessment software. As Figure 2 shows, simulation results are also included in an assessment report, which could confirm the reliability assessment of an existing structure.

DEVELOPMENT OF REASES

As assessment work is something like a kind of analysis on existing buildings following some certain codes, REASES needs to synthesize the advantages of both design and analysis software. Developed in C++ language using Open Graphics Library (OpenGL), REASES features an intuitive and powerful graphical interface coupled with complete modeling and analysis procedures, shown in Figure 1.

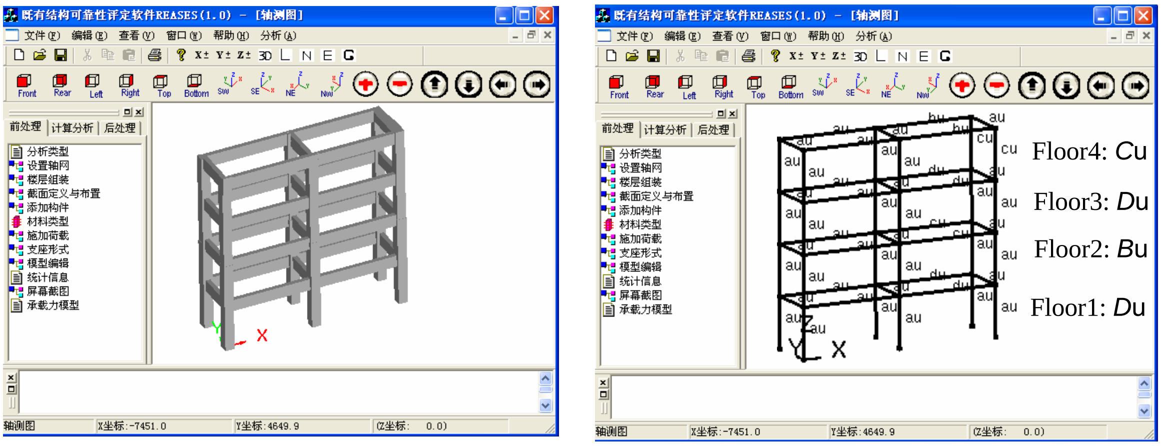


Figure 1: User Interface of REASES

SYSTEM OF REASES

REASES consists of two sets of platform systems. The main one is an assessment platform for existing structures; the other one is an experiment platform including three modules shown in Figure 2.

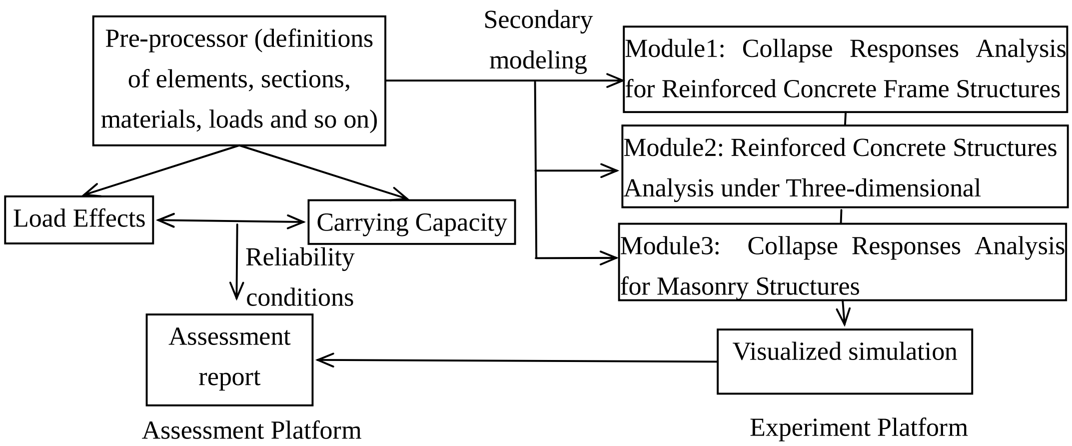
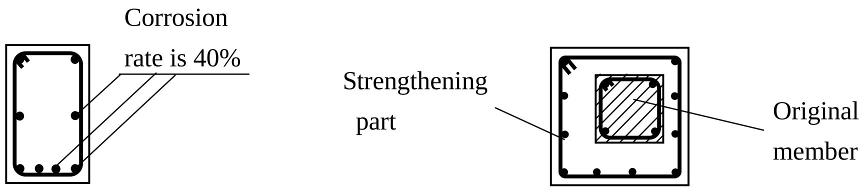


Figure 2: System of REASES

The main platform has three parts: Preprocessor, Analysis, and Postprocessor. In the preprocessor, a visualized modeling process with a full consideration about real structure conditions in accord with customs of engineering is included. A model can be established and transformed after an overall inspection on an existing structure. The model is based on the assumption that all necessary data are measured or tested, which is possible with the recently fast development of inspection techniques.

Now a reinforced concrete frame structure is taken as an example to introduce the function of REASES. Beams and columns are considered as linear elements. As one of the most characteristics in REASES, any sectional shape with any reinforcement can be defined, which means, each bar in a section can have its own property, which indeed exists in real situations (e.g. cases a) and b) shown in Figure 3). Then defined section forms could be located in any position of a beam or a column, as an element may have various sections on it, e.g. reinforcement at the ends of a beam is often different from that in the middle of it.



a) A Beam Section with Multiple Reinforcement Properties

b) A Strengthened Column Section

Figure 3: Complex Section Forms in the Assessment Analysis

Some constitutive relationships of materials involving recent research products are suggested such as those of corrosive bar and carbonized concrete, and what should be alert is that it must employ the material strength of actual measurement in material definition. Loading values refer to actual measurement and expected extreme values, which should be considered carefully. Supports and connections on an existing structure should never be taken for granted as hinged or fixed ones (Melchers 2001), so that they can be taken into account for a certain degree of degradation according to their actual states. These definitions are more flexible and various than design software given the multiplicity and complexity of real structures.

After a whole model is finished setting up, a transformed model is generated automatically and stored into a database. In this process, applied load is transferred from floor slabs and walls to the main bearing system containing beams and columns for a frame structure. Afterwards calculated models prepared for computing and analyzing are provided for the assessment system and extensive modules. For reliability assessment, load effects (S) and resistance (R) can be figured out. Finally, grades could be obtained through the comparison between R and S as above-mentioned reliability conditions.

An assessment report output with a specific format will extremely facilitate assessors using this program. The output may be viewed graphically, displayed in tabular output, sent to a printer, exported to a database file, or saved in an ASCII file. Types of output include reactions and member forces, mode shapes and participation factors, story displacements and shears, inter-story drifts and joint displacements, time history traces and so on in the aspect of loading response; and also reference values corresponding to those in loading response in the limit states; and grades of each component and the structural system.

THE MAIN ALGORITHM OF REASES

Special attention should be given to the evaluation and representation of individual loads and to the analysis of their combination referring to structural safety. In REASES, reactions and internal forces are figured out mainly with the matrix displacement method in the three-dimensional analysis. After that, they are combined with combination coefficients such as load partial factors and load combination factors by default or set by users arbitrarily (See Eq. (1)). With an automatic comparison among the responses of different kinds of loads defined by the user, the extreme load effects (*S*) of the load-carrying system are picked out.

Various resistances (*R*) corresponding to load effects are calculated according to the commendatory method in related codes (some of them are for design currently). What needs to emphasize is that *R* is influenced by *S* complicatedly, e.g. the flexural capacity of a cross-section of a concrete beam exposed to bending and axial force, interaction formulas for members under combined bending forces, and buckling (Marek 2003).Thus they have to be calculated step-by-step dynamically and compared one by one.

FUNCTIONS OF NUMERICAL SIMULATION

If it is not sure to guarantee the safety under earthquake action at an as-yet building for its unique structural form or shape, as known to all, a similar model of the building can be tested on the shaking table. Nevertheless, as an obvious fact, a whole existing structure is not able to be tested in a laboratory because it is difficult to simulate physically the damage states in the existing structure (Gu and Sun 2002). At most through a destructive or nondestructive inspection, the material properties and the damage states can be gained. Therefore, besides the analysis for earthquake action with the Response Spectrum Method as a part of load effects combination, numerical simulation is employed into a reliability assessment analysis.

When loading on the being analyzed structure is not too large, the system of computer simulation for reinforced concrete structures under three-dimensional earthquake, considering elastic-plastic effect and second-order effect based on FEM, is in operation. As the deformation increases more and more, analysis based on FEM is not so appropriate, so the system of analysis of collapse responses for reinforced concrete frame structures based on the Discrete Element Method is applied. Both of them are operated in the same computing environment, and data can be transited from each other without any barrier. They assist the main assessment platform to make with a final assessment report.

Besides, the system of analysis of collapse responses for masonry structures is dedicated in REASES with an extended-rigid-body-spring (ERBS) model (Peng et al. 2004) to simulate collapse responses of masonry structures. It is expected that still more modules may join in the experiment platform of REASES to serve for different kinds of existing structures.

SIGNIFICANCE OF REASES

REASES can extremely enhance the work efficiency of reliability assessment, ensure the assessment results are correct and rational, and also it can carry through and popularize the correlative standards and codes, play a huge role in the industry of inspection and assessment for existing buildings and have its attractive extensive research future and market value. Besides, it can provide a basis and a platform for maintaining and strengthening design.

EXAMPLE

A three-dimensional model representing an existing four-story building is examined. After 10 years in service, the structure is meant to change its usage, leading to live loads augmenting on the right span in X direction. It is necessary to decide whether the structure is reliable enough for the current load-bearing system. As wind loads do not dominate the safety for multistory buildings, they are ignored. To compare the analysis results directly, loads are applied on beams and columns, so the influence of slabs and walls is also not considered.

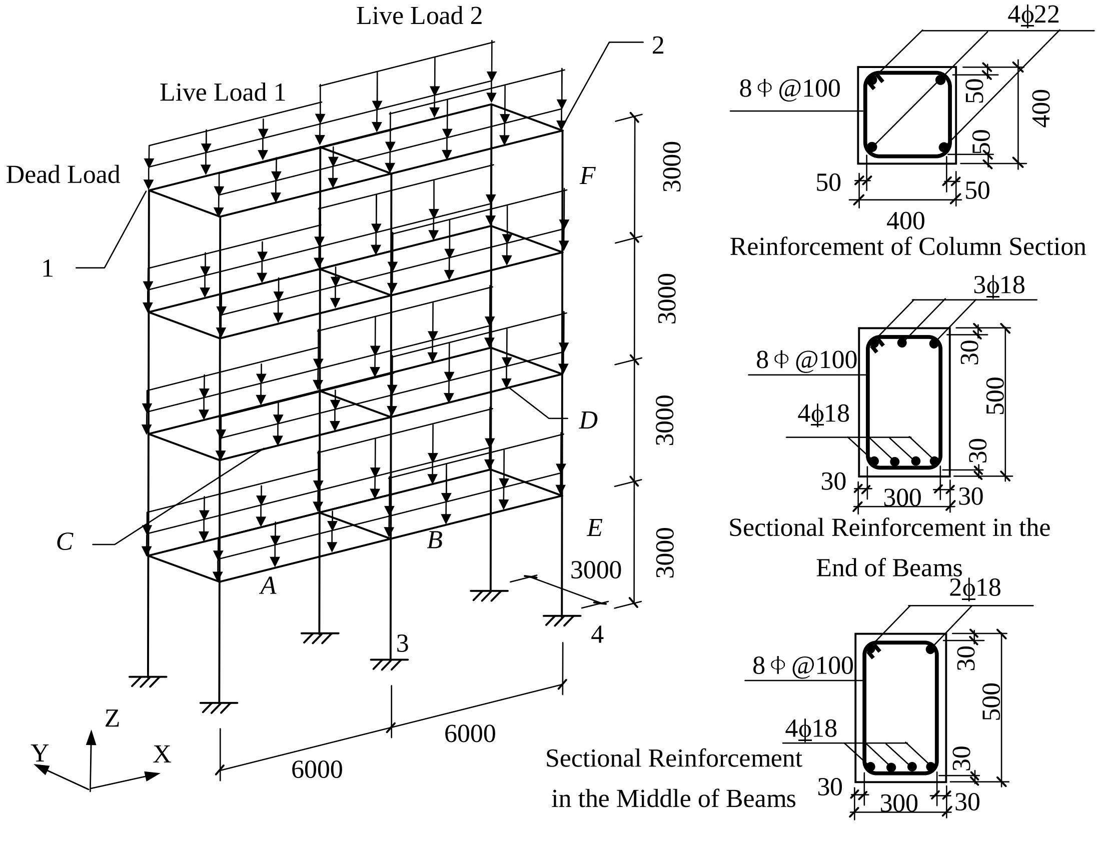


Figure 4: Computing and reinforcement drawings

According to the inspection, data on frame dimensions and reinforcements are made clear, shown in Figure 4. The live load effects by REASES are compared with that by the ANSYS, which shows good match. General information and assessment results are partly listed in Table 2, where γ_0 equals to 1.0, and γ_R is judged by REASES automatically for different failure modes.

Table 2: Information and Results of Structural Assessment

General Information							
Material Parameters		Concrete: $E_c = 2.51\times10^4$ N/mm², $f_c = 26$ N/mm², $f_t = 2.3$ N/mm², $P_{oi} = 0.2$					
		Longitudinal Steel Bar: $E_s=1.97\times10^5$ N/mm², f_s=335 N/mm², f_s'=335 N/mm²					
Applied Load		**Dead Load**		**Live Load 1**		**Live Load 2**	
Values (N/mm)		12		8		16	
Analysis Results							
Deformation of nodes		***D*x (mm)**	***D*y (mm)**	***D*z (mm)**	***R*x (rad)**	***R*y (rad)**	***R*z (rad)**
REASES	1	-1.805×10^{-1}	0	-1.736×10^{-1}	-3.219×10^{-20}	2.201×10^{-4}	2.014×10^{-19}
	2	-2.343×10^{-1}	9.994×10^{-16}	-3.531×10^{-1}	1.220×10^{-20}	-5.462×10^{-4}	1.897×10^{-19}
ANSYS	1	-1.805×10^{-1}	-2.255×10^{-16}	-1.736×10^{-1}	-7.332×10^{-21}	2.201×10^{-4}	1.776×10^{-19}
	2	-2.343×10^{-1}	1.832×10^{-15}	-3.531×10^{-1}	2.711×10^{-19}	-5.462×10^{-4}	2.033×10^{-19}
Reaction Force of Supports		***F*x (N)**	***F*y (N)**	***F*z (N)**	***M*x (N•mm)**	***M*y (N•mm)**	***M*z (N•mm)**
REASES	3	4.609×10^{3}	3.910×10^{-13}	2.933×10^{5}	-5.789×10^{-10}	4.942×10^{6}	-1.455×10^{-10}
	4	9.336×10^{3}	1.284×10^{-13}	1.894×10^{5}	-4.650×10^{-10}	9.138×10^{6}	-9.417×10^{-11}
ANSYS	3	4.609×10^{3}	1.435×10^{-13}	2.933×10^{5}	-3.984×10^{-10}	4.942×10^{6}	-7.638×10^{-10}
	4	9.336×10^{3}	1.145×10^{-12}	1.894×10^{5}	-2.635×10^{-10}	9.138×10^{6}	-2.253×10^{-11}
Reliability Assessment							
Assessment of components		**Beam *A* (N•mm)**	**Beam *B* (N•mm)**	**Beam *C* (N•mm)**	**Beam *D* (N•mm)**	**Column *E* (N•mm)**	**Column *F* (N•mm)**
Load effects		-8.170×10^{7}	-1.080×10^{8}	-7.934×10^{7}	-1.108×10^{8}	4.317×10^{7}	9.307×10^{7}
Resistance		-1.600×10^{8}	-1.121×10^{8}	-1.123×10^{8}	-1.128×10^{8}	1.471×10^{8}	9.974×10^{7}
Safety Grade ($R/\gamma_0\gamma_R S$)		a_u (1.182)	d_u (0.8525)	a_u (1.253)	c_u (0.9012)	a_u(2.988)	c_u (0.9401)
Assessment of structure		**Floor 1**		**Floor 2**	**Floor 3**		**Floor 4**
Safety grade for each floor		*D*u		*B*u	*D*u		*C*u
Safety grade for the structure		*D*u					
Conclusions	The safety grade of the structure is *D*u, and the structure needs to the strengthened.						

CONCLUSIONS

In this paper, a reliability assessment software system under the guideline of correlative codes for existing structures is introduced. The main purpose of the proposed software which has complete modeling, analyzing and exporting processes, is to enhance the efficiency and conviction of reliability assessment and reduce the intervention of individual experience. An application example shows that to do reliability assessment work with REASES is effective and fairly accurate. It is also demonstrated that REASES can provide a clear result, suggesting engineers what measures should be taken on an existing structure.

REFERENCES

DG/TJ 08-04 (2005). "Standard of Structural Inspection and Assessment for Existing Buildings." Shanghai, P.R.China (in Chinese).

Ellingwood, B.R. (1996). "Reliability-based Condition Assessment and LRFD for Existing Structures." *Structural Safety*, 18, 67-80.

Gu, X.L., and Sun, F.F. (2002). "Computer Simulation for Concrete Structures." *Press of Tongji University*, Shanghai, P.R. China (in Chinese).

Gu, X.L., Xu, Y., and Zhang, W.P. (2004). "Safety Analysis of Structural Members for Existing Buildings." *Journal of Building Structures*, 25(6), 117-122 (in Chinese).

Gu, X.L., Yin, X.J., Zhang, W.P., Chen, X.J., and Xu, Y. (2005). "Reliability Assessment of Existing Building Structures Based on Target Period of Usage." *Proceedings of 9th International Conference on Inspection, Appraisal, Repairs &Maintenance of Structures*, 247-254.

ISO/CD13822 (2001). "Bases for Design on Structures - Assessment of Existing Structures."

Marek, P., Gustar. M., and Anagnos T. (1995). "Simulation-based Reliability Assessment for Structural Engineers." *CRC Press*, Boca Raton, Florida.

Marek, P., Brozetti, J., Gustar, M. and Tikalsky P. (ed.) (2003). "Probabilistic Assessment of Structures using Monte Carlo Simulation. Background, Exercises, Software." *CRC Press*.

Melchers, R.E. (2001). "Assessment of Existing Structures —Approaches and Research Needs." *Journal of Structural Engineering*, 127(4), 406-411.

Mori, Y., and Nonaka, M. (2001). "LRFD for Assessment of Deteriorating Existing Structures." *Structural Safety*, 23, 297-313.

Nie, J.S., and Ellingwood, B.R. (2004). "Finite Element-Based Structural Reliability Assessment Using Efficient Directional Simulation." *Journal of Engineering Mechanics*, 131(3), 259-267.

Peng, B., Gu, X.L., and Qian, Y.L. (2004). "Parameter Study on Computer Simulation of Collapse Responses for Masonry Structures." *Proceedings of 13th International Brick and Block Masonry Conference*, 1177-1186.

Val, D., and Stewart, M.G. (2002). "Safety Factors for Assessment of Existing Structures." *Journal of Structural Engineering*, 128(2), 258-265.