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Overview of Performance-Based Seismic Design of Building Structures in China

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Abstract

The development history, the current situation and the future of the performance-based seismic design of building structures in China are presented in this paper. Firstly, the evolution of performance-based seismic design of building structures specified in the Chinese codes for seismic design of buildings of the edition 1974, 1978, 1989, 2001 and 2010 are introduced and compared. Secondly, in two parts, this paper details the provisions of performance-based seismic design in different Chinese codes. The first part is about the "Code for Seismic Design of Buildings" (GB50011) (edition 1989, 2001 and 2010) and "Technical Specification for Concrete Structures of Tall Building", which presents the concepts and methods of performance-based seismic design adopted in Chinese codes; The second part is about "Management Provisions for Seismic Design of Out-of-codes High-rise Building Structures" and "Guidelines for Seismic Design of Out-of-codes High-rise Building Structures", which concludes the performance-based seismic design requirements for high-rise building structures over the relevant codes in China. Finally, according to those mentioned above, this paper pointed out the imperfections of current performance-based seismic design in China and proposed the possible direction for further improvement.

Keywords: Building structures, Performance-based seismic design, Out-of-codes high-rise building structures

1. Introduction

Before 1970s, Chinese seismic design theories and methods were mainly influenced by the codes of former Soviet Union, afterwards, China began to carry out independent research on seismic design.

In 1956, the first edition of seismic intensity zoning map of China was completed; In 1957, a new seismic intensity scale of China was put forward; In 1959, the first draft code for seismic design was put forward; In 1964, the second draft code for seismic design, "Design Specifications for Buildings in Earthquake Areas (draft edition)", was put forward.

So far, 5 editions of seismic design codes has been promulgated, they are "Anti-seismic Design Code of Industrial and Civil Building (Trial)" TJ 11-74, "Anti-seismic Design Code of Industrial and Civil Building" TJ 11-78, "Specifications for anti-seismic construction design" GBJ 11-89 (implemented since 1990, partially revised in 1993), "Code for Seismic Design of Buildings" GB 50011-2001 (partially revised after the 2008 Wenchuan Earthquake) and "Code for Seismic Design of Buildings" GB 50011-2010, hereinafter respectively referred to as Code74, Code78, Code89, Code01 and Code10.

In Chinese code, fortification intensity is regarded as criterion of seismic design requirements, corresponding to basic seismic intensity. The basic seismic intensity of a certain region in China is defined as the impact of the earthquake with 10 percent probability of exceedance in 50 years, divided into 12 degrees, demarcated by maximum ground acceleration and the earthquake impact or damage extent on landform or buildings (Table 1).

Code74 and Code78 use single seismic demand level, see Table 2, taking design intensity of 7 degree and above into consideration, requesting no damage under earthquakes of fortification level, which is to control structural deformation under earthquake and to ensure adequate structural seismic bearing capacity. In the former, for general buildings, the design intensity is one degree lower than the basic seismic intensity (not when the basic seismic intensity is 7 degree); In the latter which was promulgated after the 1976 Tangshan Earthquake, the design intensity is equal to the basic seismic intensity.

In Code89, three-levels performance objectives of seismic design of buildings as "no damage under minor earthquakes, repairable under moderate earthquakes, no collapse under severe earthquakes" was proposed, which means "No damage or applicable without repair when suffered from frequent earthquake (minor earthquake), (10 percent probability of exceedance in 50 years); Applicable after normal repair when suffered from earthquake action of fortification intensity; No collapse or serious damage that can create hazard to life safety when suffered

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Table 1. Seismic Intensity Scale of China

Intensity	Senses by people on the ground	Degree of building damage		Other damages	Horizontal motion on the ground	
		Damages	Mean damage indicator		Peak acceleration m/s^2	Peak speed m/s
I	Insensible					
II	Sensible by very few still indoor people					
III	Sensible by a few still indoor people	Slight rattle of doors and windows		Slight swing of suspended objects		
IV	Sensible by most people indoors, a few people outdoors; a few wake up from sleep	Rattle of doors and windows		Obvious swing of suspended objects; vessels rattle		
V	Commonly sensible by people indoors, sensible by most people outdoors; most wake up from sleep	Noise from vibration of doors, windows, and building frames; falling of dusts, small cracks in plasters, falling of some roof tiles, bricks falling from a few roof-top chimneys		Rocking or flipping of unstable objects	0.31 (0.22-0.44)	0.03 (0.02-0.04)
VI	Most unable to stand stably, a few scared to running outdoors	Damages - Cracks in the walls, falling of roof tiles, some roof-top chimneys crack or fall apart	0 - 0.10	Cracks in river banks and soft soil; occasional burst of sand and water from saturated sand layers; cracks on some standalone chimneys	0.63 (0.45-0.89)	0.06 (0.05-0.09)
VII	Majority scared to running outdoors, sensible by bicycle riders and people in moving motor vehicles	Slight destruction - localized destruction, crack, may continue to be used with small repairs or without repair	0.11 - 0.30	Collapse of river banks; frequent burst of sand and water from saturated sand layers; many cracks in soft soils; moderate destruction of most standalone chimneys	1.25 (0.90-1.77)	0.13 (0.10-0.18)
VIII	Most swing about, difficult to walk	Moderate destruction - structural destruction occurs, continued usage requires repair	0.31 - 0.50	Cracks appear in hard dry soils; severe destruction of most standalone chimneys; tree tops break; death of people and cattle caused by building destruction	2.50 (1.78-3.53)	0.25 (0.19-0.35)
IX	Moving people fall	Severe destruction - severe structural destruction, localized collapse, difficult to repair	0.51 - 0.70	Many cracks in hard dry soils; possible cracks and dislocations in bedrock; frequent landslides and collapses; collapse of many standalone chimneys	5.00 (3.54-7.07)	0.50 (0.36-0.71)
X	Bicycle riders may fall; people in unstable state may fall away; sense of being thrown up	Most collapse	0.71 - 0.90	Cracks in bedrock and earthquake fractures; destruction of bridge arches founded in bedrock; foundation damage or collapse of most standalone chimneys	10.00 (7.08-14.14)	1.00 (0.72-1.41)
XI		Wide spread collapse	0.91 - 1.00	Earthquake fractures extend a long way; many bedrock cracks and landslides		
XII				Drastic change in landscape, mountains, and rivers		

Notes about Qualifiers: “very few” - < 10%; “few” - 10~50%; “most” - 50~70%; “majority” - 70~90%; “commonly” - > 90%.

from predicted rare earthquake (severe earthquake), (2-3 percent probability of exceedance in 50 years)".

In Code89, to realize the three-levels of performance objectives, came out "two-steps' seismic design method", detailed as following:

1st step: Using ground motion parameter (ground motion peak acceleration and characteristic period of earthquake motion response spectrum) of minor earthquake, firstly calculate the elastic relative inter-story drift to be less than the limit value, in order to satisfy the requirement of "no breaking for nonstructural component and no damage for structure" of first level; secondly combining the effect of earthquake action with effect of other loads to check the member bearing capacity, in order to satisfy the bearing capacity requirements of first level.

2nd step: Using ground motion parameter of severe earthquake, calculate the elastic-plastic relative inter-story drift to be less than the limit value, in order to satisfy the requirement of "no collapse of building structure" of third level.

Code89 is one of the first codes in which the performance-based seismic design (hereinafter referred to as PBSD) was introduced. Meanwhile, imperfection exists: 1) The requirements for "no damage under minor earthquakes" and "no collapse under severe earthquakes" were given, see Table 2, but not for the "repairable under moderate earthquakes"; 2) In member bearing capacity checking of "no damage under minor earthquakes", partial factor of earthquake action larger than 1.0 is introduced, thus the earthquake action is not exactly the same as that of minor earthquake with 10 percent probability of exceedance in 50 years.

The three-levels performance objectives employed in Code89 is continued in Code01 and Code10, furthermore, in Code10, the performance objectives are specified to structural members and nonstructural components.

2. Seismic Design Provisions of PBSD in China

2.1. Provisions in "Code for Seismic Design of Buildings" GB 50011-2010

In Code10, requirements of PBSD are specified in 3.10, titled as "Performance-Based Design of Buildings".

When PBSD is adopted in designing, the objectives shall be evaluated both technically and economically, according to fortification intensity, site condition, structure type and irregularity, functional requirements of building and ancillary facility, investment, post-earthquake loss and repair cost. Objectives of PBSD could be targeted respectively to overall structure, parts of the structure, key members, important members, secondary members, construction members and electromechanical equipment bearing.

The PBSD steps are: 1) Select the seismic ground motion level; 2) Select the performance objectives; 3) Select the performance-based design demand; The anticipated performance objectives of PBSD are listed in Table 3 to choose from.

Concrete performance-based design demands on bearing capacity, inter-story drift and seismic grade of construction measures are then specified to realize the performance objectives, as listed in Tables 4, 5 and 6.

2.2. Provisions in "Technical specification for concrete structures of tall building" (JGJ3-2010)

Titled as "Structural Performance Seismic Design", it's suggested in the 3.11 of "Technical specification for

Table 2. Seismic design requirements of building structures of China

	First Level (Minor earthquake)	Second Level (Moderate Earthquake)	Third Level (Severe earthquake)
Code74	Member Bearing capacity Checking[a]	-	-
Code78	-	Member Bearing capacity Checking	-
Code89, Code01, Code10	1) Structural Elastic Deformation Checking 2) Member Bearing capacity Checking	-	Structural Elastic-Plastic Deformation Checking

a) The design intensity in Code74 is one degree lower than the basic seismic intensity, which can be regarded as the first level in three-levels design (where the design intensity is 1.55 degree lower than the basic seismic intensity)

Table 3. Anticipated performance objectives of PBSD for buildings

Performance objectives / Seismic demand level	1	2	3	4
Frequent earthquake	Perfect	Perfect	Perfect	Perfect
Design earthquake	Perfect, In normal use	Nearly perfect, Applicable after maintenance	Minor damage, Applicable after slightly repair	Minor to moderate damage, Deformation $< 3[\Delta U_e]$
Rare earthquake	Nearly perfect, Applicable after maintenance	Minor to moderate damage, Applicable after repair	Applicable after strengthening	Serious damage, Applicable after overhaul

Note: ΔU_e: maximum elastic inter-story drift caused by standard value of frequent earthquake action.

Table 4. Performance-based design demands on bearing capacity

	Frequent earthquake	Design earthquake	Rare earthquake
Performance objective 1	Perfect Conventional design	Perfect, Review with the design value	Nearly perfect, Review with the design value adjustment
Performance objective 2	Perfect Conventional design	Nearly perfect, Review with the design value	Minor to moderate damage, Review with the limit value
Performance objective 3	Perfect Conventional design	Minor damage, Review with the standard value	Moderate damage, Limit value of bearing capacity shall remain stable, with a reduction less than 5%
Performance objective 4	Perfect Conventional design	Minor to moderate damage, Review with the limit value	Not serious damage, Limit value of bearing capacity shall mostly remain stable, with a reduction less than 10%

Table 5. Performance-based design demands on inter-story drift

	Frequent earthquake	Design earthquake	Rare earthquake
Performance 1	Perfect, Deformation shall be far less than limit value of elastic displacement	Perfect, Deformation shall be less than limit value of elastic displacement	Nearly perfect, Deformation could be slightly larger than limit value of elastic displacement
Performance 2	Perfect, Deformation shall be far less than limit value of elastic displacement	Nearly perfect, Deformation shall be slightly larger than limit value of elastic displacement	Slight plastic deformation, less than double of the limit value of elastic displacement
Performance 3	Perfect, Deformation shall be much less than limit value of elastic displacement	Minor damage, Deformation shall be less than double limit value of elastic displacement	Significant plastic deformation, less than 4 times limit value of elastic displacement
Performance 4	Perfect, Deformation shall be less than limit value of elastic displacement	Minor to moderate damage, Deformation shall be less than triple limit value of elastic displacement	Not serious damage, Deformation shall be not more than 0.9 time plastic limit value

Table 6. Performance-based design demands on seismic grade of construction measures

	Seismic grade of construction measures
Performance 1	Basic aseismic construction measures, using relevant provisions of conventional design with two degrees decreased, but not less than 6 degree and no brittle failure.
Performance 2	Low ductility construction measures, using relevant provisions of conventional design with one degree decreased, or two degrees decreased when the bearing capacity is higher than the requirement under frequent earthquake with two degrees increased, both not less than 6 degree and no brittle failure.
Performance 3	Moderate ductility construction measures, using relevant provisions of conventional design with one degree decreased when the bearing capacity is higher than the requirement under frequent earthquake with one degree increased, but not less than 6 degree.
Performance 4	High ductility construction measures, using relevant provisions of conventional design.

Note: The seismic grade is used for determining the construction measures and is defined by the density, structure type and height, divided into 4 grades.

concrete structures of tall building"(JGJ3-2010) that "the particularity of the structure scheme shall be analyzed, proper earthquake-resistant performance objectives shall be selected and adequate measures shall be adopted in structural performance-based seismic design".

Similar to Code10, the performance objective of tall buildings is divided into four gardes named A/B/C/D. In addition, the aseismic performance level is divided into 5 levels named 1/2/3/4/5, each performance objective corresponds to a group of aseismic performances under different earthquake levels, see Table 7.

In JGJ3-2010, anticipated post-earthquake performances of different members are set, see Table 8.

In addition, the design requirements for members of different seismic performance levels are given.

Table 7. Anticipated performance objective of PBSD of tall buildings

Performance Objective Performance Level Seismic demand level	A	B	C	D
Frequent earthquake	1	1	1	1
Design earthquake	1	2	3	4
Rare earthquake	2	3	4	5

Level 1 Using elastic design. Bearing capacity and deformation shall accord with general provisions; Earthquake resistant bearing capacity of structural members

Table 8. Anticipated post-earthquake performances

Seismic performance level	Macroscopic damage	Damage position			Possibility to continue using
		Key member	General vertical member	Dissipative member	
1	Perfect, no damage	No damage	No damage	No damage	Applicable without repair
2	Nearly perfect, Minor damage	No damage	No damage	Minor damage	Applicable after slight repair
3	Slight damage	Minor damage	Minor damage	Slight damage, partially moderate damage	Applicable after repair
4	Moderate damage	Slight damage	Moderate damage of certain members	Moderate damage, partially quite serious damage	Applicable after restoration or strengthening
5	Quite serious damage	Moderate damage	Quite serious damage of certain members	Quite serious damage	Needy of overhaul

Note: "Key member" refers to those the failure of which could lead to continuous failure or serious damage threatening life-safety; "General vertical member" refers to the vertical-load bearing member apart from "Key member"; "Dissipative member" includes frame beam, coupling beam of shear wall and dissipative brace.

under design intensity shall accord with expression 1(see below).

Level 2 Earthquake resistant bearing capacity of key members and general vertical members under earthquake action of design intensity or rare earthquake action shall accord with expression 1, shear capacity of dissipative members shall accord with expression 1, and the normal section bearing capacity of dissipative members shall accord with expression 2.

Level 3 Using elastic-plastic analysis. Normal section bearing capacity of key members and general vertical members under earthquake action of design intensity or predicted rare earthquake action shall accord with expression 2, normal section bearing capacity of key members of long horizontal overhang structure and large span structure shall accord with expression 3, and its shear capacity shall accord with expression 1, shear capacity of dissipative members shall accord with expression 2.

Level 4 Using elastic-plastic analysis. Normal section bearing capacity of key members under earthquake action of design intensity or predicted rare earthquake action shall accord with expression 2, normal section bearing capacity of key members of long horizontal overhang structure and large span structure shall accord with expression 3, the shear section of reinforced concrete vertical members shall accord with expression 4, and those of steel-concrete shear wall shall accord with expression 5.

Level 5 Using elastic-plastic design. Normal section bearing capacity of key members under earthquake action of design intensity or predicted rare earthquake action shall accord with expression 2, the shear section vertical members shall accord with expression 4 or 5, part of dissipative members are allowed to be quite seriously damaged.

Summarized as in Table 9, in which the "EX" means the expression of number X to be adopted in analysis.

Expressions in Table 9 are:

$$\gamma_G S_{GE}+\gamma_{Eh} S_{Ehk}+\gamma_{Ev} S_{Evk} \le R_d/\gamma_{RE} \tag{1}$$

R_d, γ_{RE}: Design value and seismic adjusting factorof bearing capacity

S_{GE}, γ_G, γ_{Eh}, γ_{Ev}: Effect of gravity load's representative value, partial factor of gravity load, partial factor of horizontal earthquake action, partial factor of bi-directional earthquake action

S_{Ehk}: Internal force in member under standard value of horizontal earthquake action

Table 9. Design provisions of structural members of different seismic performance levels

Performance level	Key member	General vertical member	Key member of long horizontal overhang structure and large span structure		Dissipative member		Shear section of vertical member	
			Normal section bearing capacity	Shear capacity	Normal section bearing capacity	Shear capacity	Reinforced concrete	Steel-concrete shear wall
1	E1	-	-	-	-	-	-	-
2	E1	E1	-	-	-	E1	-	-
3	E2	E2	E3	E1	-	E2	-	-
					Partially yield		-	-
4	E2	Partially yield	E3	E3	Mostly yield		E4	E5
5	E2	Many yield	-	-	Partially quite serious damage		E4 or E5	

S_{Evk}: Internal force in member under standard value of vertical earthquake action

$$S_{GE}+S_{Ehk}+0.4S_{Evk}\le R_k \quad (2)$$

R_k: Standard value of section bearing capacity calculated by standard value of material strength

$$S_{GE}+0.4S_{Ehk}+S_{Evk}\le R_k \quad (3)$$

$$V_{GE}+V_{Ek}\le 0.15f_{ck}bh_0 \quad (4)$$

$$(V_{GE}+V_{Ek})-(0.25f_{ak}A_a+0.5f_{spk}A_{sp})\le 0.15f_{ck}bh_0 \quad (5)$$

V_{GE}: Shear force (N) in member under standard value of gravity load
V_{Ek}: Shear force (N) in member under standard value of earthquake action
f_{ck}: Standard value of concrete axial compressive strength (N/mm^2)
f_{ak}: Standard value of section steel strength in concealed column at shear wall end (N/mm^2)
A_a: Area of section steel strength in concealed column at shear wall end (mm^2)
f_{spk}: Standard value of steel plate strength in shear wall (N/mm^2)
A_{sp}: Cross section area of steel plate in shear wall (mm^2)

3. Seismic Design Provisions of Out-of-codes High-rise Buildings

3.1. Definition of out-of-codes high-rise buildings

In China, for the high-rise buildings over the limits of relevant codes, naming out-of-codes high-rise buildings in this paper, the additional provisions of seismic design are proposed in "Management Provisions for Seismic Design of Out-of-codes High-rise Building Structures" and "Guidelines for Seismic Design of Out-of-codes High-rise Building Structures".

Out-of-codes high-rise buildings are divided into two types: building height exceeding limits and structure regularity exceeding limits. The minimum height of the height exceeding limits is listed in Table 10, the irregularity types of the regularity exceeding limits are listed in Tables 11, 12 and 13.

3.2. Seismic design requirements for out-of-codes high-rise buildings

For the out-of-codes high-rise buildings, seismic tests shall be conducted when necessary and a peer review for the seismic design scheme shall be adopted.

The additional requirements for design of out-of-codes high-rise buildings are:

1. Using two independent structure analysis softwares to proceed the seismic calculation respectively;
2. Elastic time-history analysis demanded;
3. Elastic-plastic time-history analysis demanded for buildings over 200 m; Using two independent structure analysis softwares to proceed elastic-plastic time-history analysis for buildings over 300 m;
4. Considering the elastic deformation of floor.

The enhancement on aseismic constructions of out-of-codes high-rise buildings are:

1. For members of weak location, measures shall be taken to increase the ductility grade, like strengthening the stirrup of reinforced concrete members, setting section steel in concrete members, decreasing the section width-breadth ratio of steel members, control-

Table 10. Minimum height of the height exceeding limits out-of-codes high-rise buildings (m)

Type of structure \ Design Intensity		6	7 (0.15g included)	8 (0.20g)	8 (0.30g)	9
Concrete Structure	Frame structure	60	50	40	35	24
	Frame-shear wall structure	130	120	100	80	50
	Shear wall structure	140	120	100	80	60
	Partially frame supported shear wall structure	120	100	80	50	Prohibited
	Frame-core-tube structure	150	130	100	90	70
	Tube-in-tube structure	180	150	120	100	80
	Slab column-shear wall structure	80	70	55	40	Prohibited
	Short-limb wall		100	60	60	Prohibited
	Frame-shear wall with floor disalignment		80	60	60	Not adopt
Hybrid structure	Steel frame-reinforced concrete tube	200	160	120	120	70
	Steel reinforced concrete frame-reinforced concrete tube	220	190	150	150	70
Steel Structure	Frame structure	110	110	90	70	50
	Frame-brace structure	220	220	200	180	140
	Tube and megastructure	300	300	260	240	180

Note: For structures with irregularitiesboth in plane and elevation, the minimum height shall be reduced by at least 10%

Table 11. Irregularities of out-of-codes high-rise buildings 1 (no matter the height is larger than that in Table 10 or not)

No.	Type of irregularity	Brief meaning
1	Torsion Irregularity	Torsional displacement ratio considering accidental eccentricity, larger than 1.2
	Eccentricity disposal	Eccentricity > 0.15 distance of centroids between adjacent layers > 15% side length
2	Concavity and convexity	Projection of the concavity and convexity greater than 30% of the corresponding side length
	Complex plane	Wasp-waisted or overlap at the corner
3	Diaphragm discontinuity	Effective width < 50%, opening area > 30%, staggered floor > beam height
4	Discontinuity in stiffness	Stiffness change of two adjacent layers larger than 70% or the stiffness change of three continuous layers larger than 80%
	Discontinuity in dimensions	-
5	Discontinuity of members	-
6	Discontinuity in bearing capacity	Change of shear capacity between two adjacent layers larger than 80%
7	Other irregularity	-

Note: Buildings with three of the irregularities above shall be regarded as out-of-codes buildings.

ling the axial compression ratio of columns and walls;
2. For members in transfer story, measures shall be taken to increase the ductility grade;
3. For weak location of irregular floor or long-narrow floor, floor thickness shall be increased and two-layer two-direction reinforcement shall be adopted to satisfy "no cracking under minor earthquakes and no bar buckling under moderate earthquakes";
4. For corner columns of high-rise buildings of plane irregularity, bearing capacity and ductility grade shall be increased properly

Seismic tests shall be conducted for the especially important out-of-codes buildings, particular out-of-codes buildings or the out-of-codes buildings using new material, new structure form and new aseismic technique. The tests are: Static tests and cyclic loading tests of key members and key nodes; Simulating earthquake shaking table tests of entire structure model.

4. Conclusions and suggestions

4.1. Primary Achievements

From the translation of "Codes for Buildings in Earthquake Zones" of former Soviet Union in 1955 to the publication of "Code for Seismic Design of Buildings" GB 50011-2010 in 2010 with the proposition of PBSD concept, significant achievements have been gained.

Table 12. Irregularities of out-of-codes buildings 2 (no matter the height is larger than that in Table 10 or not)

No.	Type of irregularity	Brief meaning
1	Large torsion	Torsional displacement ratio considering accidental eccentricity > 1.4
2	Small torsional rigidity	Torsional period ratio > 0.9
3	Small story stiffness	Lateral stiffness less than 50% of that of adjacent upper layer
4	High transfer	Location of transfer member of partial frame wall: over 5th floor for design intensity of 7, over 3rd floor for design intensity of 8
5	Slab transfer	Slab transfer structure for design intensity of 7-9
6	Tower offset	The distance of centroids between the towerand the enlarged bottom part is larger than 20% of the corresponding side length of enlarged bottom part.
7	Complex connection	-
8	Multi-complex	Having 3 of the complex types like story transition, enhanced story, floor disalignment, connecting body and multi-tower

Note: Buildings with one of the irregularities above shall be regarded as out-of-codes buildings.

Table 13. Particular out-of-codes high-rise buildings

No.	Type	Brief meaning
1	Particular high-rise buildings	High-rise buildings not listed in seismic design codes, specifications of concrete or steel structures of tall buildings, large public building of particular form and overlength overhang structure and connecting body structure of especially large span
2	Out-of-codes large span structures	Span of roof > 120 m, overhang length > 40 m or largest length of a side > 300 m

1. Three-levels performance objectives seismic design as "no damage under minor earthquakes, repairable under moderate earthquakes, no collapse under severe earthquakes" was proposed, with consideration for function, economy and life safety under earthquake, which is scientific;
2. Different performance objectives are allowed to be adopted for different buildings, and performance-based aseismic requirements are proposed for different members;
3. Additional performance-based aseismic requirements and judge requirements are proposed for out-of-codes high-rise buildings.

4.2. Existing problems

Meanwhile, a few problems exist requiring for further development, they are:

1. Performance-based aseismic requirements of structural bearing capacity are considered under elastic minor earthquake action, with no distinction to different ductile structures. In fact, dissipative capacity, which is closely related to ductile deformation ability, is more suitable in judging the structural aseismic capacity. For the structures of same bearing capacity, there is a positive correlation between dissipative capacity and ductile deformation ability, that is to say, for the structures with same performance-based aseismic requirement, the bearing capacity can be lower while the ductile deformability is higher;
2. Construction requirements are related to ductile deformation ability, while in the codes, the construction requirements are highly correlated to seismic fortification intensity and structure height;
3. It relies mainly on bearing capacity but not the member ductile deformation ability in defining the different seismic performance levels of members.

4.3. Improvement suggestions

1. Three-levels performance objectives of seismic design shall be adjusted and clarified as: ensuring "no damage under minor earthquakes" by checking elastic deformation, ensuring "repairable under moderate earthquakes" by checking bearing capacity while determining the earthquake action with consideration to ductile deformation ability of different structures, and determining construction requirements according to structural ductile deformability, ensuring "no collapse under severe earthquakes" by checking elastic-plastic deformation.
2. The definition for different seismic performance levels of members shall rely on ductile deformation ability aside from the bearing capacity.

5. Appendix

5.1. Basic design parameters specified in the codes of seismic design in China

In Code89, the seismic influence is characterized mainly by the seismic intensity zoning of that time, and the characteristic period was brought in to reflect the influence to the design response spectrum caused by near and distant earthquake. Since Code01, the basic design acceleration of ground motion and characteristic period were brought in, see Tables 14 and 15.

Table 14. Relationship between the intensity and basic design acceleration of ground motion

Fortification intensity	6	7	8	9
Basic design acceleration of ground motion	0.05g	0.10 (0.15)g	0.20 (0.30)g	0.40g

Note: g is the gravitational acceleration

Table 15. Characteristic period value (s)

Design earthquake group	Site-class				
	I_0	I_1	II	III	IV
1st group	0.20	0.25	0.35	0.45	0.65
2nd group	0.25	0.30	0.40	0.55	0.75
3rd group	0.30	0.35	0.45	0.65	0.90

5.2. Checking requirements of member bearing capacity in codes of seismic design in China

In Code74 and Code78, the checking shall be made using the following design expression:

$$KS_k \leq R_k$$

where:
S_k: effect of standard value of load
R_k: standard value of resistance of structural member computed with standard value of material strength
K: single safety factor, see Table16
where:

$$S_k = S_{dk} + 0.5S_{sk} + S_{lk} + S_{Ek} + 0.25S_{wk} + S_{ck}$$

S_{dk}: effect of standard value of dead load;
S_{Ek}: effect of standard value of earthquake load;
S_{sk}: effect of standard value of snow load;
S_{lk}: effect of standard value of floor live load;
S_{wk}: effect of standard value of wind load;
S_{ck}: effect of crane load

Base shear force specified in Code78 (namely the total horizontal earthquake action) is:

Table 16. Safety factor

Member	Stress Characteristic	Basic safety factor[13,14]
Concrete member	Axial tensile, bending, eccentric tensile	1, 40
	Axial tensile, eccentric compression, shear and torsion of oblique section, local compression	1, 55
	Shear wall	1.55
Hot-rolled Steel member	Eccentric compression	1.41
Cold-formed member	Eccentric compression	1.52
Masonry member	-	2.50
Timber member	-	1.89

Note: it is specified that, in checking the aseismic strength, the safety factor shall be taken as 80% of basic safety factor, not less than 1.1 when using safety factor method

Table 17. Structure factor C in Code78

Type of structure		C
Frame structure	Steel	0, 25
	Reinforced concrete	0, 30
Reinforced concrete frame with shear wall (or aseismic brace) structure		0.30-0.35
Reinforced concrete shear wall structure		0.35-0.40
Unreinforced masonry structure		0.45
Multi-Story building with internal frame, bottom full frame structure		0.45
Hinged bent	Steel column	0.30
	Reinforced concrete column	0.35
	Masonry column	0.40
High-rise flexible structure (chimney, water tower etc.)	Steel	0.35
	Reinforced concrete	0.40
	Masonry	0.50
Timber structure		0.25

$$Q_0 = C\alpha_1 W$$

where:

C: structure factor, being the reduction factor considering the ductility difference between different structural materials and systems. See Table 17

α_1: earthquake factor corresponding to basic period of structure, of which the maximum value is 0.23, 0.45, 0.90 when the design intensity is 7, 8 or 9

W: total gravity of constructions

In checking the bearing capacity, the Code89, 01 and 10 have almost the same provisions. Provisions in Code10 are showed as following.

The checking of seismic resistance of cross section shall be made using the following design expression:

$$S \le R/\gamma_{RE}$$

where:

γ_{RE}: aseismic capacity factor, see Table 18

R: design value of bearing capacity of the structural member

S: design value of the combination of inner forces, which shall be determined by the following equation:

Table 19. Partial factor of earthquake action

Earthquake action	γ_{Eh}	γ_{Ev}
Only horizontal earthquake action	1.3	0.0
Only vertical earthquake action	0.0	1.3
Both horizontal and vertical earthquake action (horizontal predominant)	1.3	0.5
Both horizontal and vertical earthquake action (vertical predominant)	0.5	1.3

$$S = \gamma_G S_{GE} + \gamma_{Eh} S_{Ehk} + \gamma_{Ev} S_{Evk} + \psi_w \gamma_w S_{wk}$$

γ_G: partial factor of gravity load, which shall be taken as 1.2 in ordinary conditions; when the effect of gravity load is favorable to the bearing capacity of the member, such factor shall not greater than 1.0

γ_{Eh}, γ_{Ev}: partial factors for horizontal and vertical earthquake action respectively, which shall be determined by Table 19

γ_w: partial factor of wind load, which shall be taken as 1.4

S_{GE}: effects for representative value of gravity load

S_{Ehk}: effects for characteristic value of earthquake action in horizontal direction

S_{Evk}: effects for characteristic value of earthquake action in vertical direction

S_{wk}: effects for characteristic value of wind load

ψ_w: factor for combination value of wind load, which shall be taken as 0.0 for ordinary structures, and taken as 0.2 for tall building structures that the wind load is control load

5.3. Seismic checking for deformation of codes of seismic design in China

Seismic checking of deformation in Code89, 01 and 10 are similar, checking elastic deformation under frequent earthquake and checking elastic-plastic deformation under rare earthquake are specified. The provisions of Code10 are showed below.

Elastic deformation checking shall be made under frequent earthquake, and the maximum elastic inter-story

Table 18. Aseismic capacity factor

Material	Structural member	Stress Characteristic	γ_{RE}
Steel	Column, beam, brace, gusset plate, bolt, weld	Strength controlled	0.75
	Column, brace	Stability controlled	0.80
Masonry	Shear wall with constructional column and core column at both the two ends	Shear	0.9
	Other shear wall	Shear	1.0
Concrete	Beam	Bending	0.75
	Column with axial compression ratio less than 0.15	Eccentric compression	0.75
	Column with axial compression ratio not less than 0.15	Eccentric compression	0.80
	Shear wall	Eccentric compression	0.85
	Other members	Shear, Eccentric tensile	0.85

drift shall comply with the following requirement:

$$\Delta u_e \leq [\theta_e]h$$

where:
Δu_e: elastic inter-story drift caused by the characteristic value of the frequent earthquake action
$[\theta_e]$: Limit value of elastic relative inter-story drift, which may be taken in accordance with Table 20
h: height of story

Elastic-plastic deformation checking shall be made for the weak stories (or locations) of the structure under rare earthquake, and shall comply with the following expression:

$$\Delta u_p \leq [\theta_p]h$$

where:
Δu_p: elastic-plastic inter-story drift
$[\theta_p]$: limit value of elastic-plastic relative inter-story drift, which may be taken in accordance with Table 21
h: height of weak story

5.4. Foundation Interaction

Influenced by the foundation interaction, the horizontal earthquake action calculated with a rigid foundation has a significant reduction, therefore, provisions as following are set in Codes:

For reinforced concrete tall buildings using box-type or a relatively rigid raft foundation or box-pile foundation for intensity 8 and 9 and with site-class III or IV, and the fundamental period of the structure is within the scope of 1.2 to 1.5 times of the characteristic period of site, if the foundation interaction is to be considered, the horizontal shear forces assumed for rigid base may be reduced, and the story drift may be calculated according to the reduced shear force. Specifically as following:

1. For structures with height-width-ratio less than 3, the reduction factor of horizontal seismic shear of each floor may be determined by following equation:

$$\psi = \left(\frac{T_1}{T_1 + \Delta T}\right)^{0.9}$$

where:
ψ: seismic shear reduction factor considering the foundation interaction;
T_1: the fundamental period of the structure, which determined by assumption of the rigid base (in s);
ΔT: the additional period after considering the foundation interaction (in s), that may be determined from Table 23.

2. For structures with height-width-ratio not less than 3, the shear force of the bottom of structure may be reduced according to point 1 of the clause, while the shear force of the top of the structure may not be reduced, and the shear force of the middle floors may be reduced according to the linear interpolation values.

5.5. Damping adopted in different editions of code

5.6. Nonstructural systems

Nonstructural components of buildings shall be primarily constructed to reduce the necessity of earthquake action calculation and seismic checking. For earthquake action calculation, the following provisions are to be respected:

Gravity of nonstructural components and electromechanical components permanently attached to structures shall be taken in consideration in earthquake action calculation.

Stiffness of membership of flexible connect can be ignored. For rigid nonstructural component implanted into the plane of lateral force resisting member, influence of its stiffness shall be taken into consideration. Generally, its earthquake resistant bearing capacity shall not be taken into consideration unless specific construction measures are adopted.

For structural members which support nonstructural components, the effect of earthquake action of the latter shall be treated as additional action[8].

5.7. Inspection Procedures

For general building structures, peer review shall be

Table 20. Limit value of elastic relative inter-story drift

Material	Type of structure	$[\theta_e]$
Reinforced concrete	Frame	1/550
	Frame-wall, slab-column-wall, frame-core-tube	1/800
	Wall, tube-in-tube	1/1000
	Frame-supported stories of structure	1/1000
Steel	Multi-story and tall structures	1/250

Table 21. Limit value of elastic-plastic relative inter-story drift

Material	Type of structure	$[\theta_p]$
Reinforced concrete	Bent of single story with reinforced concrete columns	1/30
	Frame	1/50
	Frame-wall of masonry structure with bottom-frame	1/100
	Frame-wall, slab-column-wall, frame-core-tube	1/100
	Wall, tube-in-tube	1/120
Steel	Multi-story and tall structures	1/50

Table 23. Additional period (s)

Intensity	Site-class	
	III	IV
8	0.08	0.20
9	0.10	0.25

Table 24. Damping adopted in different editions of code[15]

<table>
<tr><th></th><th>Concrete structure</th><th>Masonry structure</th><th colspan="3">Steel structure</th></tr>
<tr><td>Code74/78/89</td><td colspan="5">0.05</td></tr>
<tr><td rowspan="3">Code 01</td><td rowspan="3">0.05</td><td rowspan="3">0.05</td><td rowspan="2">Frequent earthquake</td><td>Over 12 floors</td><td>0.035</td></tr>
<tr><td>Not more than 12 floors</td><td>0.02</td></tr>
<tr><td colspan="2">Rare earthquake</td><td>0.05</td></tr>
<tr><td rowspan="4">Code 10</td><td rowspan="4">0.05</td><td rowspan="4">0.05</td><td rowspan="3">Frequent earthquake</td><td>Height 50 m</td><td>0.04</td></tr>
<tr><td>50 m < Height < 200 m</td><td>0.03</td></tr>
<tr><td>Height 200 m</td><td>0.02</td></tr>
<tr><td colspan="2">Rare earthquake</td><td>0.05</td></tr>
</table>

conducted by a qualified drawing review firm after the design is completed.

For out-of-codes high-rise buildings, peer review shall be conducted by the Expert Committee organized by local or national construction department, according to the “Management Provisions for Seismic design of Out-of-codes High-rise Building Structures”.

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