Comparison and Calculation of Architecture Structures Against Continuous Collapse of Various Countries

Xiaowei Li [a], Fan Yi [b], Ji Li [c], Maoyi Qiu [d]

School of Civil Engineering and Architecture, Southwest Petroleum University, Chengdu 610500, China

[a]444328411@qq.com, [b]370132696@qq.com, [c]739092710@qq.com, [d]491133761@qq.com

Abstract

This paper mainly introduces structural measures and design method of the anti progressive collapse design of Europe and the United States and other countries and regions, one of the keys is the comparison of several common anti progressive collapse design methods from national norms , and the advantages and disadvantages of comprehensive comparison of various design methods and suitable scope. The purpose is to provide reference for the design of the steel structure of high-rise building in China. There are some Common methods for the design of the buildings to resist progressive collapse design,such as concept design method,drawing method,removal method and key component method etc.. From the comparison of the results, during the design,we should be based on the use of building, the importance and the number of layers to classify the structure, the design method for anti progressive collapse of different structure should take different levels of design , at the same time,we should also deal with distinction from existing buildings and new buildings .

Keywords

steel structure;progressive collapse; standard contrast; analysis.

1. Introduction

In our country, the concept of progressive collapse of structures : structural progressive collapse is that the structural damage caused by accidental load then bring more structural component damage due to structural failure, eventually leading to a greater range of the collapse damage relative to the initial local failure. American Civil Engineering Association (the American Society of Civil Engineers, ASCE) in ASCE7-10[1], the definition of structural progressive collapse: Under occasional loading, structure has local damage, which is carried out along the component and triggered a chain reaction, eventually led to the collapse of the whole structure or cause collapse of a large range of structure with the initial local failure. The British standard (Building Regulation)[2]is defined as the progressive collapse: in the case of accidental events, the building should not have a disproportionate share with initial damage.

We know the design of progressive collapse of structures involves three key words from the definition of progressive collapse: accidental loading, local failure and propagation, structural collapse or failure of the whole structure .And the coping strategies are event control method, local reinforcement method, multiple load path method and reserve load method, which is to take measures to control the occurrence of accidental events. If we cannot control the occurrence or determine its size, it is need to choose local component which is easy to suffer from failure to strengthen the strength and the design of deformation .If the local damage of component is inevitable, it is need to verifies that the residual structure has the ability to "over" the local damage component, that is, the internal force redistribution.

The accidental load caused by structural collapse damage generally includes fire, earthquake, explosion and shock, etc. The earthquake load from them acting on the whole structure, which is to make the structure appear a horizontal damage. And the explosion and fire load is usually bring

structural local damage, so that a single bearing component of structure appear failure in a short period, and thus cause the overall damage of structure.

When the successive collapse occurs, which general will cause very serious loss of life and property. Therefore, from the beginning of the 60's in twentieth Century, scholars at home and abroad have carried on the research to the structural progressive collapse. Europe, the United States, Britain and Japan and other countries have issued the corresponding design principles, methods and special specifications[1,2,7-21].In the history, the specification of the progressive collapse were formulated and revised appear three times, The first is Ronan Point apartments gas explosion event, which is mainly conventional specification is introduced into the resistance progressive collapse design content and specified in this specification: "structure should not occurred with the initial damage disproportionate collapse under accidental load", meanwhile, three design methods also are proposed, which includes tensile strength method, removal method and key component method. The second occurred in 1995 ,the U.S. federal government building in the federal government of the Murrah attacks .the European standard[11]mainly refers to the standard of the United Kingdom, coming up with a safety level about building with a new classification, and make different design requirements with building of different levels. The third time was happen in 2001, New York world trade building aircraft impact event. America's structural design specification to further strengthen the anti-progressive collapse design content, the Department of Defense (DoD) and the General Services Administration (GSA) were published specifically designed to prevent structure progressive collapse design rules[13,14].

In recent years, a large number of studies were carried out on the advantage and disadvantage of the design methods with the development of national standard on the structure to resist progressive collapse, but most of the research is on reinforced concrete structure not the steel structure .In this paper, the design ideas and methods for the design is the high rise building steel structure, the United Kingdom, Europe, the United States and Japan are introduced, and a proposal for the progressive collapse of China's national conditions.

2. The basic requirements for progressive collapse design

In our specification of structure anti progressive collapse design, it take a basic requirement: "safety level which is a high rise building structure should meet the design requirements of the progressive collapse, when there are special requirements, it can be used to design the demolition of the component method of continuous collapse[3]."In the UK specification, the design of structure anti progressive collapse design basic requirement: "in addition to the three conventional design method (tensile strength design, component spanning capacity design and key component design), but also to ensure that the structure is no obvious weak, and each floor should can withstand the equivalent to 1.5% of the floor of the self-weight load level [2]". In the European code, require: "the structure must have sufficient strength to resist unexpected or unpredictable load [2]".The specification in the progressive collapse resistance design is divided into two aspects, one is based on specific accidents, the other is independent from the accident, the purpose of this design is to control the local damage which caused by the accident load. In the United States of America, there is no direct way to resist the progressive collapse of the design, but it contains measures to achieve the structural ductility and integrity of the required measures. In the specification, the reinforced component and component connecting structure should be to ensure effective components between Rachel connections, improve the integrity of the structure, including: reinforced of the bearing should be continuous, the location and requirements of Reinforcement bar, reinforced end hooks requirements. The structure should be used for the vertical, horizontal and vertical pull of the structure along the perimeter of the building, and the tensile strength of the structure is specified in detail.

From the specification of the anti-progressive collapse design, we can know all countries in the design of structures to resist progressive collapse have basically the same thoughts: "improve the overall stability of the structure, to which make the structure can not cause the collapse of structure as a whole". Each country gives a specific preventive measure or mandatory requirement to comply with

the design. In our country, the structure is divided into different levels to achieve the construction of different anti progressive collapse design, table 1 is the standard of building progressive collapse criteria for the classification from Europe and UFC.

Table 1 European standard and UFC standard building resist progressive collapse

Safety level	European standard		UFC standard	
	Classification	Design method	Classification	Design method
Minimum fortification	Agricultural architecture	No special design	Including agriculture, temporary, storage facilities	No special design
Low fortification	4 floors and the following residential, office buildings, hotels, etc.; A school	Horizontal pull junction design	Other	Pull the knot force method and the method of local reinforcement or removal of member
Intermediate fortification	5 to 15 layers of residential, office buildings, hotels, etc.; The following 15 schools, more than 3 hospitals	Horizontal and vertical pull and knot design; Removal of component method	More than 250 people, including residential, School	removal of component method; Local reinforcement method
Advanced security	Other	Risk assessment of the system is required, and any conventional and unconventional loads can be considered.	Key facilities, such as hospitals, military facilities	Pull force method, removal of component method; Local reinforcement method

3. Progressive collapse design method

In the specification of the structure of anti-progressive collapse from various countries, which is mainly reflected in the design of the structure, the commonly used structures against progressive collapse method has conceptual design method, pull the knot method, remove the component method and key component method etc.

3.1 Concept design method

Conceptual design is a qualitative design method, which improves the structural integrity, continuity, redundancy and ductility by reasonable structural layout and structural measures, which require structural component or connections have certain tensile strength, so as to make structure "bundling, and improve the integrity of the structure. In our country, the specific provisions of the concept design of progressive collapse are also given:(1)we should take necessary structural measures to strengthen the structure of the whole.(2) the structure of the main body is suitable to adopt the multi - span rules.(3)the structural components should have appropriate ductility, in order to avoid shear failure, crush failure, anchorage failure, and the failure of the joint prior to the member.(4) structural members should have a certain reverse bearing capacity. (5)column should not be too large span frame.(6) the transformation structure should have the overall multiple transfer of the gravity load way.(7) reinforced concrete structure beam and column should be rigid beam, roof, bottom reinforcement on the bearing should be continuous through tension according to requirements. (8)

Steel frame beam and column are appropriate to be connected. (9) Between the independent foundations should adopt the pull beam connection.

3.2 Knot method

The pull - knot method is connected through the existing components and connections, which can provide the overall stability of structure and load transfer path. Some people will be classified as a quantitative concept design. The concept and function of the JGJ3-2010 in the description of article 3.12.1 in the description of the article is a simple description, but there is no specific provisions. This method requires us to draw the size and direction of the pulling force, and the size of the structural elements that are required by the specification (e.g. Table 2).

Table 2 all kinds of standard tensile force limits

Standard	Horizontal tension force		Vertical tension force
	Vertical or horizontal	Surrounding	
BS5950-1	0.5（1.4D+1.6L）sl1 or 75KN	0.25（1.4D+1.6L）sl1 or 75KN	Maximum value of the vertical tension force of the column or wall is equal to the maximum value of the 2/3 of any one of the layers
EN1991-1-7	0.8（D+L）sl1 or 75KN	0.4（D+L）sl1 or 75KN	Maximum value of a column or wall should be assumed to be equal to the maximum of the vertical tension force
UFC	3（1.2D+0.5L）l1	6（1.2D+0.5L）l1+3（1.2D）l1	Tension in the column is not less than the load bearing of the upper story（1.2D+0.5L）
GSA	—	—	—

The pull knot types can be divided into four according to the position and function of the pull knot, internal pull knot, peripheral pull knot, the pull of the wall and the vertical pull knot［4］.For all kinds of pull knot, the force path is continuous and direct, and the tensile strength is checked. In general, the tensile strength of the requirements are not the same due to structural material is different. A example from Rachel, in the United Kingdom, there are some differences in the internal tensile strength of concrete structures and steel structures. In addition, the internal tensile strength of concrete structures is related to the structure layer and the length of the steel structure.

3.3 Removal method

Dismantling the structure of one or several bearing component (columns, walls) are selected to remove, and the remaining structures are analyzed to determine the extent of initial damage and the ability to resist progressive collapse.

Our country to regulate the continuous collapse of the demolition of the component method has specific provisions.

(1) The main components of the structure,(the bottom column, the conversion truss and the other important components)are removed one by one.

(2) The internal force and deformation of the remaining structures can be analyzed by the elastic static analysis method.

(3) The bearing capacity of the remaining structural members shall comply with the requirements of the following:

$$R_d \geq \beta S_d \quad (1)$$

Which: S_d —Effect design value of the remaining structural members can be calculated according to the provisions of article 3.12.4 of this specification.

R_d —Design value of the bearing capacity of the remaining structural members can be calculated according to the provisions of article 3.12.5 of this code.

β —Effect reduction factor. Take 0.67 of the central level component, and take 1 of the other components.

Design value of the effect of the load combination can be determined by the formula of the structural anti - continuous design:

$$S_d = \eta_d \left(S_{GK} + \sum \varphi_{qi} S_{Qik} \right) + \psi_w S_{wk} \quad (2)$$

Which: S_{GK} —Effect of permanent load standard value.

S_{Qik} —Effect of the standard value of the vertical variable load on the i.

S_{wk} —Effect of wind load standard value.

φ_{qi} —Quasi permanent value coefficient of variable load.

ψ_w —Wind load combination coefficient, take 0.2.

η_d —Dynamic magnification factor of vertical load. When the structure is directly connected with the vertical component of the vertical member, the other components are taken for 1. Calculation of bearing capacity of member section, concrete strength desirable standard value. Steel strength, flexural strength checking, it is desirable that the standard value of 1.25 times, shear bearing capacity calculation of desirable standard value.

In summary, the removal of the component method can be based on the consideration of the nonlinear and dynamic effects, which can be used for linear static analysis, nonlinear static analysis, linear dynamic analysis, nonlinear dynamic analysis. These four methods are simple to complex, simple to implement, fast calculation, but not accurate. At the same time, it is often used more conservative load combination. Therefore, it has a conservative calculation results. Complexity of the method is more accurate, but it is time-consuming, and it is difficult to test the results. In this regard, some scholars put forward a kind of gradual analysis step（progressive analysis procedure）[15].Which in turn adopted from the simple linear elastic static analysis to the complicated nonlinear dynamic analysis, step by step calculation precision and calculation of each stage results were established on the results of a phase based, relatively easy to test.

3.4 Key component method

When a member cannot meet the design requirements of the structural collapse resistance design, the design value of an additional 80KN/m^2 lateral load on the surface of the member is required to meet the following formula:

$$R_d \geq S_d \quad (3)$$

$$S_d = S_{Gk} + 0.6 S_{Qk} + S_{Ad} \quad (4)$$

Which: R_d —Design value of the bearing capacity of the member can be used in accordance with the regulations of article 3.8.1.

S_d —Effect design value of action combination.

S_{Gk} —Effect of permanent load standard value.

S_{Qk} —Live load standard effect.

S_{Ad} —Effect of lateral accidental action design value.

Structure cannot fulfill the anti-progressive collapse design requirements when remove a component, which means the member is very important, which can be referred to as a key structural component it should have a higher requirement and hope that the work state of the linear elasticity. At this point, in the surface of the component additional a provisions load, the overall structure were calculated, and review the structure to meet the design load bearing capacity requirements. In formula (3), the live load use the frequency, and the approximate frequency coefficient is 0.6.

Table 3 Summary of different specifications

		BS	UFC	GSA
Accidental load		Consider determining the accidental load	ReferenceUFC4-010-01	Consider determining the accidental load
Judge		Building Classification	Building Classification	Pre judgment
Vertical load		D+(0.5 or 0.3)L	1.2D+0.5L	D+0.25L
Tension force	Level	0.8w1sl1 or 75KN（Internal） 0.4w1sl1 or 75KN（Surrounding）	3（1.2D+0.5L）l1(Internal) 6（1.2D+0.5L）l1+3（1.2D）l1(Surrounding)	—
	Vertical	Maximum value of a column or wall should be assumed to be equal to the maximum of the vertical tension force	Tension within the column is not less than the upper floor load borne by the column	—
Removal member		Remove each column	Side column: column, the most close to the short edge and point in a column. Column:corner column, long side and short side near the midpoint of the column	Side column: corner column, the most close to the short edge and point in the column. Column: corner column
Analytical method		—	Linear static analysis, nonlinear static analysis, nonlinear dynamic analysis	10 the following rule building can be used in linear analysis, and the nonlinear analysis is adopted for the 10 or more irregular buildings
Dynamic effect		—	Power amplification coefficient is 0.2	According to the structure and the form of component, the power amplification factor is defined
Failure criterion	Structure	Floor area 15% and 100m2 (70m2) are small, not more than the removal of the column on the next layer	Floor slab	Near cross area or 170m2
	Component	—	Deformation control: linear, strength criterion, considering the M coefficient. Force control: strength criterion	Linear: DCR. nonlinearity: ductility and rotation

4. Standard contrast

Currently, conceptual design and tie force method is used to make a indirect design by various countries, and removing component method and local strengthening method is used to make a direct design, the comparison of codes to resist progressive collapse design methods is as follows in Table 3 shows.

5. Enlightenment

China on the structural progressive collapse of the research carried out relatively late,, we began some preliminary work with the collapse of the World Trade Center incident in 2001, China national standards《engineering structure reliability is unified standard for reliability design》[6] firstly to explicitly pointed out that the structure anti progressive collapse requirements: " when an accident of explosion, impact happen, the structure can keep overall stability of the need, no failure of components. "In the current,《code for seismic design of buildings》[3] section 3.5.2 the in paragraph 2 stipulated: "we should avoid failure of the whole structure and the bearing capacity of the load bearing capacity by avoiding the failure local components", As to how to meet this requirement, the specification of the provisions of the specification does not give a specific design criteria. China's newly launched the《code for design of concrete structures》section 3.6 firstly to take anti progressive collapse design principle to write into the national standards, to which increased for anti-progressive collapse design requirements of concrete structure, which only gives the structure anti progressive collapse design objectives and related concept design principles, although acts as a guide to the design personnel, but did not give details of quantitative design method, poor operation for the true. The 《concrete structures of tall building technical specification》 section 3.12 proposed on resisting progressive collapse of the conceptual design and detailed design method, but the stipulation is too simple to be effectively applied to practical engineering. Therefore, China needs to draw some design methods anti progressive collapse of the structure. In Table 3, the design of the progressive collapse resistance design of the foreign codes has a revelation for the design of the progressive collapse of the Chinese structure.

(1)According to the use, importance and the number of layers to classify the structure, the design method of the progressive collapse of different structures is adopted. For the lower level security structure (general structure), it is necessary to carry out the concept design by means of structural measures and pull force method.

(2) The design of the progressive collapse is required for the difference between a new structures and has been built to distinguish. For the newly built structure, it can be used to evaluate the structure of the progressive collapse resistance by using the pull force method and the removal method.

(3) At present, the design method of the standard of the foreign standards is not perfect, and the tensile strength formula is lack of theoretical verification. But based on the engineering background of foreign material parameters, reliability, the design method and engineering with China are different, so its application in the engineering structure in China cannot meet the progressive collapse resistance requirements. Therefore, it is necessary to analyze the basic principle and the problem of the design method of the foreign codes, and to consider the relationship between the tensile strength and the ductility of the member (and node).

(4) Removal component method is suitable for the analysis of continuous collapse of structures under blast and impact loads, but it is not suitable for fire damage. At present, the method of removing the component method is mainly for the frame structure, and the applicability of other structural forms (large span structure) is further studied. Remove the component method is to consider the instantaneous removal of the column, but it is not consider the effect of component failure time and the residual bearing capacity on the dynamic effects and internal force redistribution, the analysis results are too conservative.

(5) Foreign common analysis method is static analysis and dynamic analysis, the static analysis by dynamic coefficient method considering dynamic effect, and the codes generally take 2.0 in foreign, and the removal of all the upper adjacent columns, the power amplification factor is too conservative combined with China's actual project, should determine the power amplification factor and applied position for China's national conditions.

(6) Because of the emphasis on the structural integrity and continuity, the seismic design and the design of the continuous progressive collapse, therefore, there is a complementary relationship between the concept design and construction measures. Currently, this relationship has not been clearly pointed out, in view of the Chinese standard of seismic design method is more mature, the design method of anti-continuity collapse can learn from seismic design, but should pay attention to the difference between the two: a. By different forces, the former is mainly subjected to horizontal seismic action, and the latter is mainly subjected to vertical loads. b. The role of the floor is different, the former can be regarded as a rigid floor, which is a thin film effect. c. collapse mechanism is different, the former is under the collapse, meanwhile, the latter is the weight of the internal force redistribution and collapse.

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