STUDY ON THE DESIGN METHODS TO RESIST PROGRESSIVE COLLAPSE FOR BUILDING STRUCTURES

Xin-Zheng Lu[1,2], Yi Li[1,2], Lie-Ping Ye[1,2], Yi-Fei Ma[1,2], and Yi Liang[1,2]
[1] *Department of Civil Engineering, Tsinghua University, Beijing 100084, P.R. China*
[2] *Key Laboratory of Structural Engineering and Vibration of China Education Ministry, Tsinghua University, Beijing 100084, P.R. China*

Abstract: Since the collapse of the Ronan Point Tower in United Kingdom in 1968, the progressive collapse resistance of building structures has attracted a global attention. Important foreign design codes have developed their specifications for building structures to resist progressive collapse, but the related research is still lack in China. This paper presents a series of researches by the Department of Civil Engineering in Tsinghua University on progressive collapse resistance of building structures. The existing design methods are briefly summarized, and two major design methods, which are alternate path (AP) method and tie force (TF) method, are proposed together with feasible procedure and carefully studied factors that are suitable for Chinese structures. The effects of each proposed methods are verified with nonlinear dynamic simulations and the additional cost due to progressive collapse resistance design is compared.
Keywords: Building structure, Progressive collapse design, Nonlinear dynamic alternate path method, Linear static alternate path method, Tie force method

1 INTRODUCTION

The progressive collapse of a building is initiated by an event that causes local damages which the structural system cannot absorb or contain, and that subsequently propagates throughout the structural system, or a major portion of it, leading to a final damage state that is disproportionate to the local damage that initiated it (Ellingwood, 2006). The progressive collapse analysis differs from routine structural analysis such as seismic design because the structure during progressive collapse has initial damages. So special design method needs to be proposed to resist progressive collapse.

Since the collapse of the Ronan Point Tower in London (1968), the progressive collapse of building structures has been studied in western countries for almost 40 years. Currently, the progressive collapse resistance design (PCRD) methods have already been specified in main foreign design codes. But the related researches are still lack in China. The current Chinese code for design of concrete structures (GB50010-2002, 2002) just has one regulation without operational details: “The structures shall have the integral stability; the local damage of structures shall not lead to collapse of wide scope”. So the PCRD methods that are suitable for Chinese structures should be developed.

2 CURRENT SPECIFICATIONS TO RESIST PROGRESSIVE COLLAPSE

2.1 Design methods

In most foreign codes, the methods for PCRD can be classified into 3 major types: Conceptual method, Tie Force (TF) method and Alternate Path (AP) method (Liang et al., 2007a).

Conceptual method is an indirect design approach. It requires the enhancement on the integrity, ductility and redundancy of structures by rationally arranging structural members and strengthening weak members and joints. But this method greatly depends on engineers' experience.

Tie force (TF) method is also an indirect design approach that enhances the continuity of the structural elements by requiring tie strength to guarantee the integrity of structures and reserved load path. It's convenient to implement because it does not need to calculate the response of the whole structure. However, as too many assumptions have been set to build up this

Table 1 Classification design of Eurocode 1 and DoD 2005 for progressive collapse resistance

<table>
<tr><td rowspan="2">Eurocode 1</td><td>Protection Level</td><td>1</td><td>2(Lower Risk)</td><td colspan="2">2(Upper Risk)</td><td>3</td></tr>
<tr><td>Design Method</td><td>Conceptual Method</td><td>Horizontal TF Method</td><td colspan="2">(1)TF Method
(2)AP Method</td><td>Risk Assessment</td></tr>
<tr><td rowspan="2">DoD 2005</td><td>Protection Level</td><td>Very Low</td><td colspan="2">Low</td><td colspan="2">Medium and High</td></tr>
<tr><td>Design Method</td><td>Horizontal TF Method</td><td colspan="2">(1)Vertical TF Method
(2)Horizontal TF Method (AP Method if failures)</td><td colspan="2">(1)TF Method
(2)AP Method
(3)Ductility Requirement</td></tr>
</table>

method, the empirical factors are needed to be carefully checked to guarantee the safety of TF method.

Alternate path (AP) method is a direct design method to guarantee that the structure is capable of bridging over a removed structural element so as to prevent the damage from exceeding beyond the limits. If there is a structural element that can not be bridged over, this element must be designed as a key element, which should have enough strength to resist possible extreme loads.

2.2 Design strategies

The reliability, complexity and workload of the three methods mentioned above obviously increases in order. And therefore, the foreign codes categorize building structures according to their protection level, as seen in Table 1, and suggest proper methods for each protection level.

3 ALTERNATE PATH METHOD

Alternate path method is the most precise design method for PCRD. Two key issues should be discussed before setting up the detailed specifications.

Complexity of collapse process

Accurate collapse simulation of structures requires powerful computational tools and skilled operators, which can not be afforded in every case. So most foreign codes suggest using nonlinear dynamic (ND) procedure, which is precise but complicated, for complex or important structures, while using linear static (LS) procedure, which is easy to implement, for regular structures. And the difference when using LS procedure to approach ND procedure is represented with dynamic magnification factor A and strength reduction factor β to consider the dynamic effect and the nonlinear behaviour of materials.

Uncertainty of initial damage

It is impossible to consider innumerable possible situations of initial damage. The common method in foreign codes to deal with this problem is that only one vertical element is removed in every collapse analysis. So this paper also follows this assumption.

3.1 Nonlinear dynamic alternate path (NDAP) method

3.1.1 Finite element model

In order to accurately simulate the collapse process, the finite element model should consider the strong geometrical nonlinearity of collapse, the strong material nonlinearity of element failure, and even the contact nonlinearity of impact. But the common finite element packages are insufficient to solve such complicated problem. So the Department of Civil Engineering in Tsinghua University developed a RC fibre model, THUFIBER, which can precisely simulate the collapse of the frames.(Liang et al., 2007b; Lu et al., 2007a; Lu et al., 2007b; Wang et al., 2007) The benchmark of THUFIEBR for collapse simulation is shown in Figure 1 and Figure 2.

3.1.2 NDAP design

A typical Chinese RC frames is analyzed by the authors with NDAP design. A typical result of NDAP design, which successfully prevents the progressive collapse of original building, is shown in Figure 3 and Figure 4, and the consumption of longitudinal bars in frame beams is shown in Table 2. Moreover, being a most precise method, NDAP design results are also used to verify the design results of other methods.

Figure 1. Collapse test of plane frame (Yi et al.,2007)

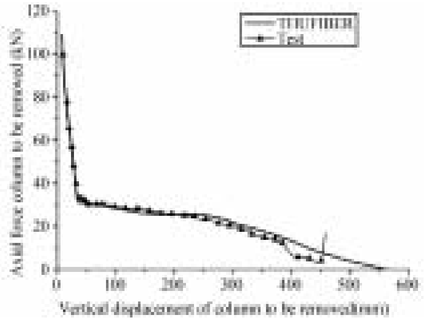


Figure 2. Comparison for the axial force and displacement of removed column: THUFIBER vs. test

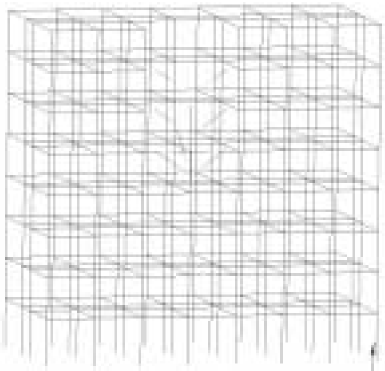


Figure 3. Structure collapse before NDAP design

3.2 Linear static alternate path (LSAP) method

Linear static analysis is a method which is familiar with structural engineers and it can be used as a simplified approach for NDAP design to reduce the complexity and the workload. So LSAP method is a balance solution between the precision and the workload which will lead to a wide application of this method. So the procedure and the factors for LSAP method are discussed in detail in this work.

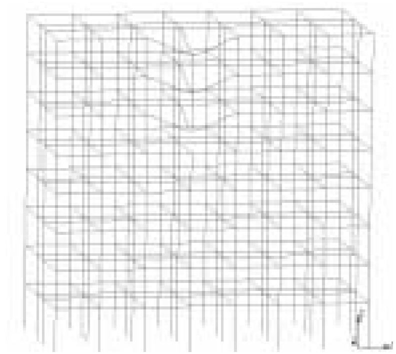


Figure 4. Structure survive after NDAP design

Table 2. Comparison for the consumption of longitudinal bars in beams of 8-storeys frame (ton)

Storey	Original	NDAP	LSAP	TF
1	5.43	5.43	5.51	5.52
2	5.36	5.36	5.40	5.43
3	4.87	4.84	4.89	4.99
4	4.26	4.26	4.36	4.27
5	3.64	3.64	3.75	3.90
6	2.91	3.09	3.18	3.52
7	2.33	2.64	2.75	3.10
8	2.00	2.27	2.36	2.81
Total	30.80	31.56	32.20	33.54

3.2.1 Design Procedure

The general design procedure for LSAP method is as follows:

(1) Remove target vertical structural elements one-by-one and conduct a LS analysis for each removing to get the static design internal force S_{static};

(2) Approximately estimate the dynamic design internal force S_{dynamic} with the dynamic amplification factor A:

$$S_{\text{dynamic}} = A \cdot S_{\text{static}} \tag{1}$$

(3) The elasto-plastic strength requirement of residual structural elements R can be calculate by

$$R \geqslant \beta \cdot S_{\text{dynamic}} \tag{2}$$

in which β is the strength reduction factor that represents the energy dissipation capacity in plastic deformation of real structures.

So from above procedure, it can be found that the two major simplifications of LSAP method, which are the static approach and the linear approach, are represented with dynamic amplification *A* factor and strengthen reduction factor β, respectively. These two factors need to be determined by comparing the difference between nonlinear dynamic results and linear elastic results.

3.2.2 Design factors

A typical Chinese 3-storeys concrete frame is analyzed with linear static analysis, linear dynamic analysis and nonlinear dynamic analysis to determine suitable values of design factors mentioned above. It is found that A=2.0 and strength reduction factor β=0.67 is rational and safe (Figure 5 and Figure 6).

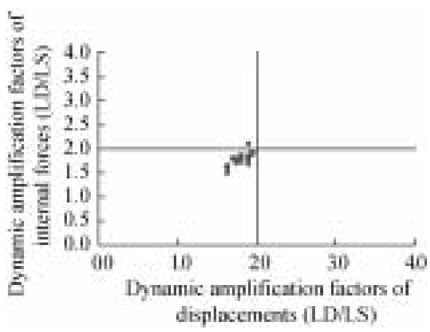


Figure 5. Dynamic amplification factors from 3- story RC frame analysis

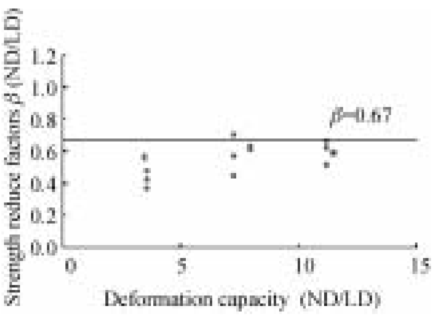
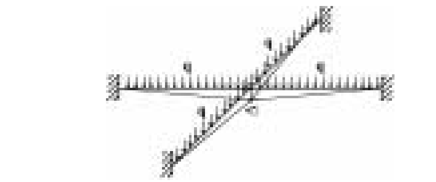


Figure 6. Strength reduce factors from 3- story RC frame analysis

The proposed procedure and factors for LSAP design is checked with the 8-storey RC frame in former chapter. The structure avoids progressive collapse, which proofs the effect of proposed LSAP method. And material cost is listed in Table 4 which shows that the proposed LSAP method is safe and very close to the precise value from NDAP design.

4 TIE FORCE METHOD

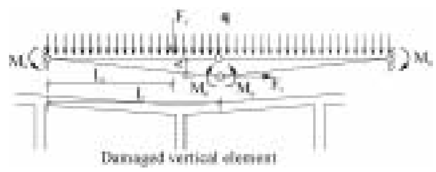
Comparing to AP method, Tie Force (TF) method does not calculate the response of the whole structure. On the contrary, it treats the whole structures as the combination of many substructures (Figure 7) and assumes that if every substructure has proper strength and enough deformation capacity, the whole structure can avoid the collapse. Besides above,



(a) interior

(b) side (c) corner

Figure 7. Substructures for TF design in different locations



q—Distributed Load F_c—Concentrated Load
L—Span Length of Beams L_i—Location of F_c
Δ—Allowable Deflection F_t—Tie Force
M_u—Moment of Plastic Hinge

Figure 8. Loads on substructures in TF design

the TF method directly analyzes the ultimate state of each substructure thus the substructure can be treated as a static determinate problem (Figure 8). So TF method is much easier than AP method but also has lower precision.

4.1 Basic assumptions

1. The tied elements bridge over a vertical structural element by two mechanisms, beam

mechanism with bending strength (Figure 9) and catenary mechanism (Figure 10) with tensile strength.

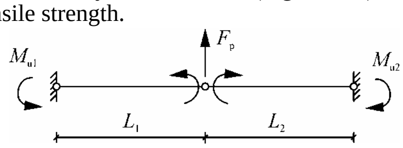


Figure 9. Computational model for beam mechanism

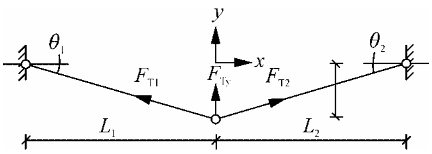


Figure 10. Computational model for catenary mechanism

2. For the beam mechanism, only bending capacity at the fixed end of the beams are considered (Figure 9).

3. The catenary mechanism of beams is considered only if the beams are continuous and pass through the joint.

4.2 Design procedure

1. Build up the substructure model as shown in Figure 7 according to their locations in the building.

2. Transform distributed loads and concentrated loads on each beam to an equivalent concentrated load *N'* at the joint, which results in an equal bending moment to the fixed end of each beam. Sum *N'* of every beam in the substructure to obtain the total equivalent concentrated load *N*.

3. *N* will be borne by the resistance of beam mechanism (Figure 9) and catenary mechanism (Figure 10).

$$N = \sum_{i=1}^{n}(F_{\text{P}}^{i} + F_{\text{Ty}}^{i}) \tag{3}$$

where: i is the serial number of beam, n is the total number of beams in the substructure, F_{P}^{i} and F_{Ty}^{i} are the resistances of i^{th} beam with beam mechanism and catenary mechanism, respectively.

4. The total resistance of beam mechanism can be calculated:

$$\sum_{i=1}^{n} F_{\text{P}}^{i} = \sum_{i=1}^{n} \frac{M_u^i}{L_i} \tag{4}$$

where: L_i is the length of i^{th} beam, M_{u}^{i} is the negative bending capacity at the fixed end of i^{th} beam.

5. If *N* can be borne by beam mechanism, the tie force does not need to be considered. Otherwise, the total vertical resistance from tie force is given by:

$$\sum_{i=1}^{n} F_{\text{Ty}}^{i} = N - \sum_{i=1}^{n} F_{\text{P}}^{i} \tag{5}$$

And if there is more than one direct in which there are beams continuously pass through the joint, the tie force in each direction can be obtained according to the bending stiffness of beams in each direction:

$$F_{\text{Ty}}^{j} = \frac{\frac{EI_j}{L_j^3}}{\sum_{j=1}^{m} \frac{EI_j}{L_j^3}} \times \sum_{i=1}^{n} F_{\text{Ty}}^{i} \tag{6}$$

where: j is the direction number, I_j is the rotational inertia of beams in j^{th} direction, F_{Ty}^{j} is the tie force of beams in j^{th} direction.

Finally, in j^{th} direction, the tie forc of beam can be obtained from the balance of horizontal tie force at the joint:

$$F_{\text{Ty}}^{j1} = \frac{L_{j2}}{L_{j1} + L_{j2}} \times F_{\text{Ty}}^{j} \tag{7}$$

$$F_{\text{Ty}}^{j2} = \frac{L_{j1}}{L_{j1} + L_{j2}} \times F_{\text{Ty}}^{j} \tag{8}$$

where: F_{Ty}^{j1} and L_{j1} are the tie force and the length of the first beam in j^{th} direction, F_{Ty}^{j2} and L_{j2} are the tie force and the length of the second beam in j^{th} direction.

4.3 Application and verification

The former 8-storey frame is redesigned by TF method proposed by this paper. There are three kinds of substructures in the structure, as seen in Figure. 7. For the interior substructures, four beams provide tie forces in both two directions because of their continuities (Figure. 7a). On the contrast, only two beams provide tie forces for the side substructures (Figure. 7b). And both interior and side substructures can provide beam mechanism and catenary mechanism to prevent collapse. However, for corner substructure (Figure. 7c), only beam mechanism can provide the collapse resistance capacity.

The 8-storeys frame after TF design satisfies the requirement of progressive collapse resistance, and consumption of longitudinal steel bars is also listed in Table 2. It can be concluded that TF method in this paper is effective.

5 CONCLUSIONS

AP method and TF method are feasible for engineering design. NDAP method is the most accurate methods but with high difficulty and complexity, so it is suitable for very important and complicated structures. On the contrary, LSAP method and TF method are easier to implement and their accuracy are guaranteed by carefully choosing the factors and computational models. Based on a series of rigorous researches, this paper suggests empirical factors, computational models and design procedures of LSAP method and TF method on progressive collapse resistance design for Chinese engineers.

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