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A Review on Progressive Collapse Designing Based on UFC Regulation

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ARTICLE INFO

Article history

Submitted: 25 September 2019

Accepted: 21 November 2019

Published Online: 31 January 2020

Keywords:

Progressive collapse
Alternative path method
Specific local resistance

ABSTRACT

Progressive collapse is a relatively rare event which happens due to unusual loading on a structure that lacks adequate continuity, ductility and indeterminacy which causes local collapse in that structure and then extends it to other structural parts. The US department of defense published UFC4-023-03 regulation regarding the building design against progressive collapse. This regulation, based on the ASCE 7-05 standard, introduces two general approaches to building design against progressive collapse, including direct design and indirect design approaches. In this study, a variety of structural design methods for progressive collapse have been investigated. Moreover, their strengths and weaknesses have been mentioned. In general, the results of this study show that design based on alternative path (AP) method is more economical than other methods. Moreover, application of AP method is much more commonly accepted by researchers and designers.

1. Introduction

Progressive collapse is a relatively rare event which is caused by an abnormal loading on a structure that is insufficiently connected, formable and indeterminate, and leads to local collapse in that structure, extending to other structural parts. In 2003, the US Department of Defense published the UFC 4-023-0-03^[1] regulation for the construction of buildings against collapse and in 2009, it presented a revised version of the mentioned regulation.

UFC 2009 regulation by referencing the ASCE 7-05 standard^[2], introduces the progressive collapse as “the expansion of an initial local collapse from an element into another element of the structure which eventually leads to the collapse of the entire structure or a large part

of it in a disproportionate way”. the ASCE 7-05 standard also states that the building must be designed in such a way that the overall system of architecture remains stable in the event of a local collapse and does not allow the collapse of a location to develop inappropriately. The ASCE 7-05 standard provides two general approaches to address progressive collapse including direct and indirect design approaches. The direct design approach includes explicit considerations regarding the building’s resistance to progressive collapse during design stages consisting of Alternate Path Method (AP) and Specific Local Resistance (SLR). In the indirect design approach, resistance to progressive collapse can be achieved implicitly through regulation of least levels of resistance, continuity and ductility.

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UFC 4-023-03 regulation provides the Tie Forces (TF) method in the indirect design approach, which is based on the design against the progressive collapse in English and European standards as well^[3-4]. In recent years, extensive research has been carried out using the above mentioned methods^[5-23]. Rahnavard et al.^[5-10] investigated the effect of side and corner column removal effect on the moment and axial reaction force. The considered two types of lateral system, two types of regular and irregular in plan for a 20-story building. Their results showed that the lateral system doesn't have remarkable effect on progressive behavior of the building. Astaneh-Asl et al.^[11] using experimental test on one floor building evaluated the simple bolted connection affecting column removal. Rahnavard and Thomas^[12-19] investigated four types of bolted and welded connection affecting fire scenario to figured out mode of failure. Sasani^[20] investigated the response of a reinforced concrete infilled-frame structure to removal of two adjacent columns. Kima and Kim^[21] studied the assessment of progressive collapse-resisting capacity of steel moment frames. Fu^[22] Investigated progressive collapse analysis of high-rise building with 3-D finite element modeling method. Rahnavard et al^[23-26] investigated the effects of plastic hinge formation and collapse consequences on different steel structures including moment frame with on buckling restrained brace and also eccentrically brace frames.

In this study, a variety of structural design methods for progressive collapse have been investigated. Moreover, their strengths and weaknesses have been mentioned. Also, using this method is much more commonly accepted by researchers and designers.

2. Investigating Design Methods Against Progressive Collapse

2.1 The Tie Force (TF) Method

In the tie force (TF) method, building is mechanically bonded together with increased continuity, ductility and alternate load transfer paths. Resisting tensile forces by which structure mainly resist progressive collapse, can be supplied through existing structural elements that are designed using conventional design methods for transmitting regulation-based loads to structures (Fig. 1).

In this method, three horizontal ties (including longitudinal, transverse, and peripheral ones) should be provided. Vertical ties are also supplied in load-bearing columns and walls (Fig. 2).

If members of a structure, such as beams, shafts and longitudinal beams and joints are capable of transferring

the forces of longitudinal, transverse and longitudinal ties to an angle of rotation of 0.2 radians, the longitudinal, transverse and peripheral ties should be supplied through the ceiling and floor system.

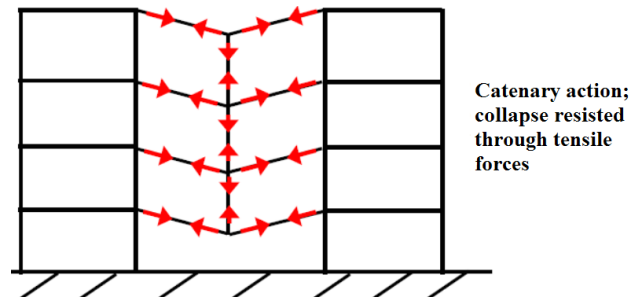


Fig.1- Resistance to collapse using chain action of structures

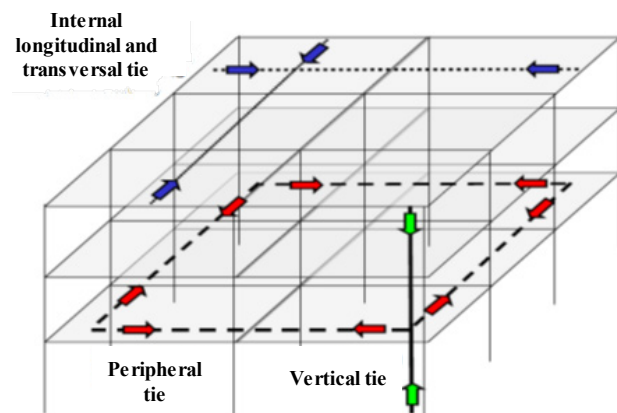


Fig. 2- Inhibition of longitudinal and transverse ties to peripheral ties

The longitudinal and transverse ties for the system of building frames and the load bearing wall should have tensile strength in both directions based on relation (1).

$$F_i = 3W_f L_1 \tag{1}$$

$$W_f = 1.2D + 0.5L \tag{2}$$

Where L_1 , D , and L are the largest distance of center to center of the columns respectively in each direction of the dead and live loads (as shown in Fig.3). Also, the peripheral ties for the system of building frame and the load bearing wall in both directions must have a tensile strength equal to relation (3).

$$F_p = 6W_f L_1 L_p + 3W_c \tag{3}$$

Where L_1 and W_c are respectively the largest distance of center to center of the columns along the building's circumference and 1.2 times the dead load along L_1 . Also L_p is equal to one in accordance with the regulation.

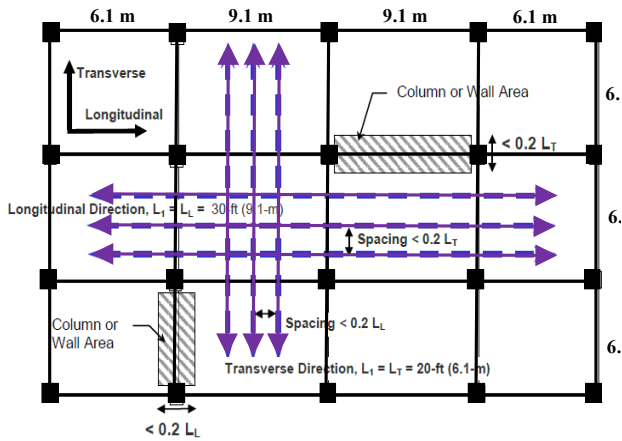


Fig.3. The way of distributing loads among components of structure

For a load-bearing wall system in one direction, the tensile strength must be equal to relation (4).

$$F_p = 6W_f L_1 L_p + 3W_c + 3W_w \quad (4)$$

Where W_w is 1/2 times the dead load along the h_w (net height of the floor). The load-bearing columns and walls are used to transmit required resistant ties. They have to be connected continuously from the ceiling to the columns and the walls of the first floor above ground level. Also, vertical ties must have tensile design strength equal to the vertical load that is obtained from the columns and the load bearing walls in each floor.

LRFD criteria for TF method

Based on the LRFD for the TF method, Design resistance of tie (ΦR_n) must be greater than or equal to the nominal tensile strength of the tie including the coefficient of resistance increase (R_u), where Φ is the coefficient of resistance reduction. The nominal tensile strength of the tie includes the coefficient of resistance increase which is obtained using relation (5).

$$R_u : \sum \gamma_i Q_i \quad (5)$$

Where γ_i and Q_i are load factor as well as effective load, respectively.

2.2. Alternative path (AP) Method

In the AP method, the designer must demonstrate that the structure can bridge from the removed pillar or wall and, as a result, does not exceed the permissible values of deformations and internal efforts. As shown in Fig. 4, in this way, the structure resists collapse through membranous flexural response.

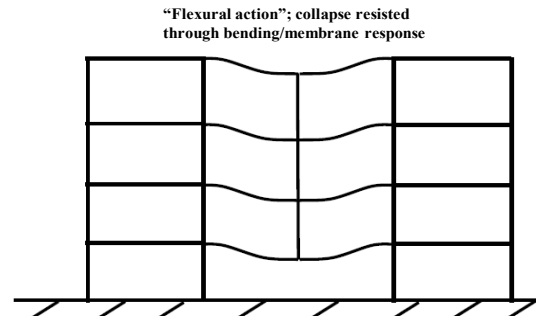


Fig.4. Flexural action: resistance to collapse through membranous flexural response

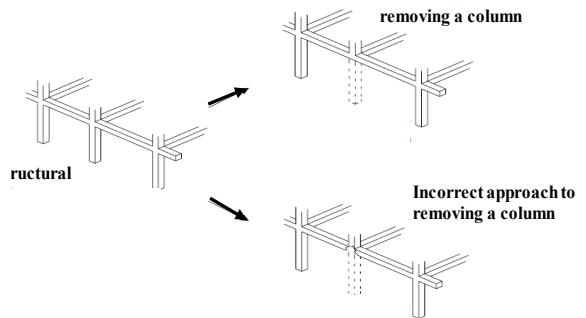


Fig.5. Correct and incorrect ways of removal of columns

As it is shown in Fig. 5, the connection and the bond between the beam and the column must also be maintained after the column has been removed, it, that is, the net height between the side constraints to be removed. According to the UFC regulation, column deletion areas for internal and side columns are based on Figures 6 and 7.

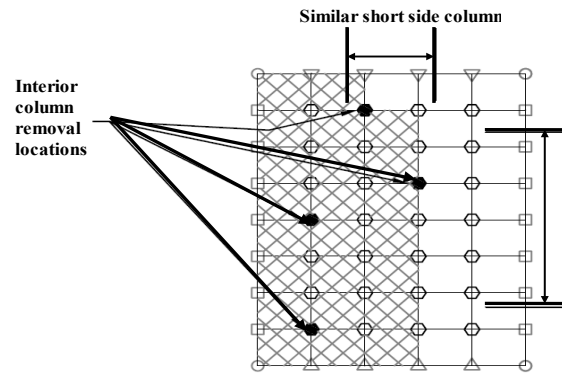


Fig.6. The removal areas of internal columns

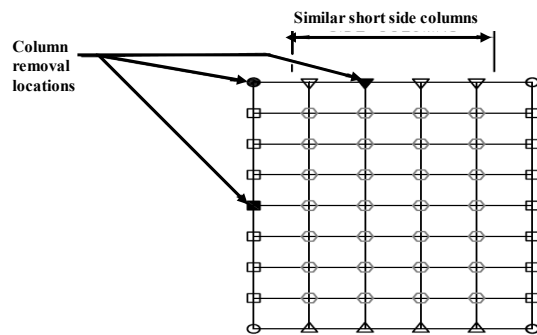


Fig.7. The removal areas of lateral columns

According to the UFC, for each plan, 4 areas are selected to remove the column at the height of the building, which include: A) The first floor B) a floor below the roof C) middle floor (right in the middle of building height) D) the upper level of the place where there is change in the sections.

Types of Analysis Methods in the AP Method:

1. Linear static: According to the UFC regulation, a linear static analysis can be used in case the following conditions are established:

- it is limited to regular buildings or states where the ratio requirement to capacity is less than 2 ($DCR < 2$).
- The construction model of the analysis should be 3-dimensional (use of the 2-D model is not allowed).
- Load states are as follows:

For increased gravity loads for roof areas above the removed component (control -location shift mode):

$$G_{LD} = \Omega_{LD} [(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S)] \quad (6)$$

For adjacent components as well as upper components above the removed member (Force control mode):

$$G_{LF} = \Omega_{LF} [(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S)] \quad (7)$$

And the lateral load is equal to:

$$L_{LAT} = 0.002 \sum P \quad (8)$$

Where G_{LD} , G_{LF} , D , L , Ω_{LD} , Ω_{LF} and $\sum P$ are respectively increased gravity load for the control - shift location mode in linear static analysis, increased gravity load for force control mode in linear static analysis, the dead load consisting of the front load, the live load including reduced live overload, incremental load factor for control- location shift mode in linear static analysis according to Table 1, incremental load factor for force control mode in linear static analysis according to Table 1 and the sum of gravity loads.

For areas far away from the location of removing member of the gravity load, it is equal to the following relation: $G = 1.2 D + (0.5L \text{ or } 0.2S)$ (9)

Table 1- Load Increase Coefficients in Linear Static Analysis

Ω_{LF}	Ω_{LD}	Type of structural system	Materials
2.0	$0.9m_{LIF} + 1.1$	The frame	Steel
2.0	$1.2m_{LIF} + 0.80$	the frame	Reinforced concrete
2.0	0.2	Load-bearing wall	
2.0	0.2	Load-bearing wall	Building materials
2.0	0.2	Load-bearing wall	Wood
2.0	0.2	Load-bearing wall	Cold rolled steel

According to the UFC regulation, each component of the structure is assigned a coefficient in which m_{LIF} is called the smallest m in the members which are directly connected to the removed member.

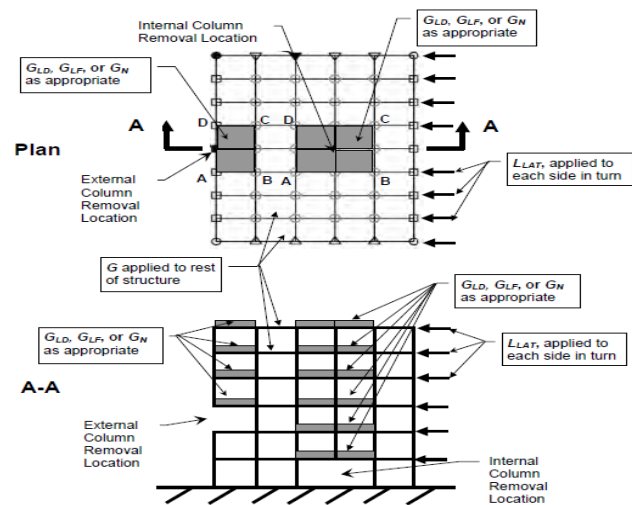


Fig. 8. The position of the loads and removed areas of the column

Admission criteria in linear static analysis for the state of control- location shift and control-force mode follow the relationships 10 and 11, respectively.

$$\Phi m Q_{CE} \geq Q_{UD} \quad (10)$$

$$\Phi m Q_{CI} \geq Q_{UF} \quad (11)$$

Where Q_{CE} , Q_{UD} , Φ , Q_{CI} and Q_{UF} are the internal efforts of the members in the control-location shift mode, the expected resistance of the members in control-location shift mode, the reduction factor of resistance based on properties of materials specified in the regulation, the lowest level of resistance of the members in the control - force and the internal efforts of the members in the control of the force, respectively.

2. Non-linear static analysis: according to the UFC regulation, a nonlinear static analysis can be used in case the following conditions are met:

- There is no limit on the ratio of demand to capacity and irregular geometry
- There is 3-dimensional analysis model.
- Reduced resistance coefficients are applied in components of control-location shift mode
- A force-location shift diagram is drawn for all components of the control-location shift mode.
- Reducing live overload is allowed.
- Load states are as follows:

In the upper areas of the removed member, the following relation is established:

$$C_N = \Omega_N [1.2D + (0.5L \text{ or } 0.2S)] \quad (12)$$

Where G_N and Ω_N are respectively increased gravity load in static nonlinear analysis and the dynamic increase

coefficient for calculating efforts of force -control and control-location shift mode based on Table 2.

Table 2. Dynamic Gain Coefficient for Static Nonlinear Analysis

Ω_N	Type of structural system	Materials
$1.08 + 0.76 / (\theta_{pra} / \theta_y + 0.83)$	the frame	Steel
$1.04 + 0.45 / (\theta_{pra} / \theta_y + 0.43)$	the frame	Reinforced concrete
2	Load-bearing wall	
2	Load-bearing wall	Building materials
2	Load-bearing wall	Wood
2	Load-bearing wall	Cold rolled steel

According to the UFC regulation, the plastic rotation angle of members is named θ_{pra} components and joints and θ_y represents the yield rotation angle of members.

For areas Away from removed member, the following relation is applied:

$$G = 1.2D + (0.5L \text{ or } 0.2S) \tag{13}$$

where G is a gravity load.

Acceptance criteria in nonlinear static analysis for the control-location mode are such that the main components and sub-components must have the expected deformation capacities larger than the deformations involved. This matter follows relation 14 for the force-control state:

$$\Phi Q_{CL} \geq Q_{UF} \tag{14}$$

Where Q_{CL} and Q_{UF} are respectively the lowest level of members' resistance as well as the internal efforts of the members in the control of force- control state.

1. Nonlinear Dynamic Analysis: According to the UFC regulation, a nonlinear dynamic analysis can be used provided that the following conditions are established:

- Model requirements are the same as static nonlinear analysis.
- Acceptance criteria are the same as static nonlinear analysis.
- applying loads start from zero using history of applying loads, and reaches the final value at least after 10 steps.
- The analysis continues until it reaches the maximum displacement or a cycle from the vertical movement of the removed member site.

2.3 SLR Method

In the special localized resistivity method (SLR), a certain level of bending and shear resistance outside the plate is created for the peripheral columns of the building (with its joints and column planes), in which the shear resistance is increased more than the cut dependent to the flexural

strength outside the column plate.

The bending strength is equal to the maximum load applied to the Load-bearing column which causes its bending fracture, i.e., three joints are created in the member, or a similar fracture occurs.

In other words, the column and its connection should not be broken in the cutting by applying the unit load for the base bending resistance because when it is reached to the shear capacity before the bending capacity, a non-formable fracture is created in the element, which leads the structure to progressive collapse.

In the 2005 version of the Structural Analysis Guide against Progressive collapse (UFC 4-023-03), the SLR method is used, in which case the key elements of the structure should be able to withstand a static pressure of 34 kN/m^2 .

In this way, key elements are designed for a certain time, such as blows caused by accidents or explosion, thereby the likelihood of initial damage is reduced. The weakness of this method is its dependency to the introduction of an attack or design load that has been modified in the 2009 version of this method.

In this version, the SLR is created at a nominal level for protection of peripheral columns which is independent of the threat and it is modified to enhanced local resistance. The LRFD criteria for the SLR method follow Equation 15:

$$\Phi R_n \geq R_u \tag{15}$$

Where ΦR_n , R_n and R_u are design resistance, nominal bending resistance including the coefficient of increase in resistance and required shear strength, respectively.

3. Conclusion

The direct design approach includes explicit considerations regarding the building's resistance to progressive collapse during design stages. In the indirect design, resistance against progressive collapse is implicitly achieved through minimum levels of strength, continuity and ductility. In the SLR, resistance against the progressive collapse is achieved through the chain performance of the floor slab system and tensile forces in the ties, whereas, according to AP method, the structure should be able to bridge above the removed column or the wall, as a result of which the internal deformations and internal efforts of the members do not exceed the permissible values. In the SLR method, a certain level of flexural and shear strength is created out of the plate for the building's peripheral pillars in such a way that the shear strength is more than the shear dependent to the increased flexural strength outside the plate column.

In general, AP related results represent more economi-

cal than other methods.

Also, using this method is much more commonly accepted by researchers and designers.

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