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A Review on Progressive Collapse Analysis

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Abstract*: Progressive collapse of building is initiated when one or more vertical load carrying members particularly columns are seriously damaged or collapsed during any of the abnormal event. Once a column is failed the building's gravity load transfers to the neighbouring members in the structure. If those members are not properly designed to resist and redistribute the additional load that part of the structure will fails. As a result, a substantial part of the structure may collapse, causing greater damage to the structure than the initial impact. Different approaches for evaluating progressive collapse potential and a few related works on progressive collapse analysis are discussed in this paper.
***Keywords*: Progressive Collapse; Demand Capacity Ratio; Linear Static Method; Nonlinear Static Method**

I. INTRODUCTION

Progressive collapse may be described as a situation originated from the failure of one or more structural members following an abnormal loading event. It is one of the most important types of building failures, most often leading to costly damages, multiple injuries, and possible loss of life. Factors contribute to progressive collapse of the structures includes construction errors, miscommunication, poor inspections, or design faults. The local failure occurred in the structure leads to load redistribution in the entire structure and which may results in an overall damage of the structure. The General Service Administration (GSA) of the United States define progressive collapse as "a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Hence, the total damage is disproportionate to the original cause". While a number of different definitions of progressive collapse coexist, the notion of disproportionality is common to all of them. Progressive collapse of a structure occurs when loading pattern or boundary conditions of a structure is changed and some members are loaded beyond their ultimate capacities. Once a column is damaged due to some accidental loading like; fires, vehicle impact and blast loading, the building's weight transfers to the neighbouring members in the structure. It is a process in which components of the structural system distributes the gravity load to prevent the loss of critical element like column. It is a dynamic process, usually accompanied by large deformations, in which the collapsing system continually seeks alternative load paths in order to survive. One of the important characteristics of progressive collapse is that the final damage is not proportional to the initial damage.

II. ANALYSIS

In progressive collapse, the failure of a primary load resisting member in the system leads to redistribution of force to the adjoining members. If the adjoining member cannot resist the additional load, then that member will also fails. This process continues in the structure and eventually may leads to the partial or total collapse of the structure. GSA guideline suggests alternate load path method to evaluate the resistance of the structure against progressive collapse. Based on the above scenario, there are few different approaches, through which potential for progressive collapse can be evaluated. They are Direct Design Approach and Indirect Design Approach. Direct design approach includes: 1) Alternate load path method, in which structure is designed in such a way that a new load path could be developed to bridge over a missing structural element 2) Specific local resistance method, in which the building, or parts of the building is designed to resist a specific load for providing sufficient strength. Indirect Design Approach is based on provision of minimum level of strength, element continuity and ductility. This method mainly concentrates on good plan layout, integrated tie system, ductile detailing and extra reinforcement for blast and load reversal. Thus indirect method is likely to be the primary method used to enhance the robustness of the building. GSA outlines four different analysis procedures for evaluating the progressive collapse potential of a structure: 1. Linear static procedure 2.Linear dynamic procedure 3.Nonlinear static procedure (Pushover analysis) 4 Nonlinear dynamic procedure (Time history analysis).

III. LITERATURE REVIEW

The objective of literature review is to understand the current state of knowledge on progressive collapse analysis of structures from structural engineering point of view. The literature review includes results of research on various parameters related to progressive collapse such as causes, different analysis methods, limitations of various analysis methods and mitigation methods. In this section a review of some of the literatures on progressive collapse analysis is presented in brief summarizing the work done by different scholars and researchers.

A. S. M. Marjanishvili and P.E (2004)

Explained four analysis procedures; Linear static, Linear dynamic, Nonlinear static, and Nonlinear dynamic in detail to evaluate the potential for progressive collapse. The main objective of the study was to formulate the most accurate and reliable method for analysis. For that, author presented detail review of existing design guidelines prevailing in USA along with the design phenomena. Advantages and disadvantages of each method of progressive collapse analysis were discussed in detail and the most effective method for analysis was worked out and concluded at the end of study.

B. Shalva Marjanishvili and Elizabeth Agnew (2006)

Compared four methods of progressive collapse analysis; linear static, linear dynamic, nonlinear static, and nonlinear dynamic analyses and found out the most suitable method with advantages and disadvantages. A nine storey steel moment resistant framed building was analysed using SAP 2000 software. The results shows that the dynamic analysis procedure was more accurate compared to static procedure. Author highlights that the dynamic amplification factor of 2.0 used in analyses was good estimate for static analysis procedure.

C. Hyun-Su Kim, Jinkoo Kim and Da-Woon (2009)

Developed an integrated system for progressive collapse analysis. A nonlinear analysis program OpenSees was used as a finite element solver in this integrated system. The developed integrated system includes a pre-processor and a post-processor and which can evaluate the damage level of every member and automatically construct the modified structural model for the next analysis step. The analysis results show that the collapse mechanism greatly depends on the modeling technique for failed members.

D. Steven W. Kirkpatrick, Robert MacNeill, Joseph L. Smith, Kenneth Herrle, and Mikhael Erekson (2009)

Demonstrated the direct and indirect design approaches as per revised Unified Facilities Criteria. In the revision of UFC, the effectiveness of alternate load path method, specific local resistance method and tie force method was evaluated and the study was carried out to improve these approaches. Analysis procedure and improvements made for the above methods were reported in this paper. It was observed that the resistance to progressive collapse was increased for the new approaches.

E. Digesh D. Joshi, Paresh V. Patel and Saumil J. Tank (2010)

Carried out the study on progressive collapse resistance of four storey and ten storey reinforced concrete framed structures using GSA guidelines. The linear static and nonlinear static analyses were performed using SAP2000 software. In nonlinear static analysis method vertical loads are increased in a stepwise manner. The demand capacity ratios found using linear static analysis were compared with the hinge formation obtained from nonlinear static analysis. The results revealed that hinge formation starts from the location having maximum demand capacity ratio and then formation of hinge continues through the locations having higher demand capacity ratios. This study concluded that the structures designed and detailed with an adequate level of continuity, redundancy, and ductility can develop alternative load paths following the loss of an individual member and prevent progressive collapse.

F. Ali Kazemi and Mehrdad Sasani (2011)

Conducted the study on an actual eleven storey reinforced concrete structure for evaluating the effects of beam growth in progressive collapse resistance. The initial damage scenario was created by simultaneous explosion of two beam sections and four adjacent columns, two of which were exterior columns. The structure resisted progressive collapse even after the severe initial damage. Authors also developed an analytical model of the structure to study progressive collapse resisting mechanisms and the analytical results show good agreement with the experimental data. They concluded that the main progressive collapse resisting mechanism was the flexural-axial interaction of the second floor deep beams and the vierendeel frame action of the floors above also contributed to collapse resistance.

G. Nabil A. Rahman, Ayman Elfouly and Michael Booth (2011)

Carried out a study on a 5-storey barracks building to evaluate its vulnerability to progressive collapse based on DoD criteria UFC-

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4-023-03. The building was composed of composite deck floor system and steel roof trusses supported by cold-formed steel stud load bearing walls. Two different wall section removal scenarios at the first storey of the building were considered for the analysis. The analysis was performed using a three dimensional nonlinear dynamic analysis software "Extreme Loading® for Structures". The results show the ability of the composite deck floor slabs to re-distribute the gravity loads to adjacent wall components, while some of the loads were taken by the stud walls above the slabs. The author has illustrated the role of composite deck floor-cold-formed steel stud bearing walls building system in resisting progressive collapse.

H. Huda Helmy, Hamed Salem and Sherif Mourad (2012)

Carried out progressive collapse assessment on a typical 10-storey reinforced concrete framed structure by following UFC guidelines. Different vertical members were removed and nonlinear dynamic analysis of the structure was carried out using Applied Element Method. Their study highlights that the slabs should be taken into consideration for economic design due to their significant effect on structural integrity after support removal. One of the major findings of the study is that reinforced concrete structures designed according to ACI code does not meet the UFC limits and that they a have a high potential for progressive collapse for cases of loss of either corner column or edge shear wall. Authors also proposed a modification for the ACI code to meet the UFC limits.

I. Paresh V. Patel and Digesh D. Joshi (2012)

Performed a study to evaluate progressive collapse potential of 4-storey and 10-storey asymmetrical reinforced concrete framed building. Progressive collapse potential of the buildings was evaluated by performing linear static and linear dynamic analyses by following the General Service Administration and Department of Defense guidelines. Modeling, analysis and design of the buildings were performed using the software SAP2000 for five different column removal conditions. Demand capacity ratio of beams and columns were calculated and it exceeds the allowable limit in all the cases. Also, they presented three different approaches for mitigating progressive collapse like providing bracing at floor level, moderate increase in size of beam at all storey level and major increase in size of beam at bottom storey level. Among all the three approaches, providing bracing at floor level emerges as the most economic and effective approach for reducing the risk of progressive collapse.

J. Massimiliano Ferraioli, Alberto Maria Avossa and Alberto Mandara (2014)

Investigated the progressive collapse resistance of earthquake-resistant steel moment-resisting frames subjected to column failure. Nonlinear static and nonlinear dynamic analyses were performed using SAP 2000 software. They also presented two types of vertical pushover analysis (also called pushdown analysis). The first method is that load is increased in stepwise manner to a specified level after column has been removed and in the second method gravity loads are applied to the undamaged structure before column removal to reproduce the timing of progressive collapse. The load-displacement relationships obtained from pushdown analysis was compared with the results of incremental nonlinear dynamic analysis. Authors also investigated the effect of various design variables, such as number of stories, number of bays, and level of seismic design load.

K. Harinadha Babu Raparla and Pradeep Kumar Ramancharla (2015)

Performed a study on a set of four bare frames designed as per Indian standards for understanding their collapse behaviour. All the frames were subjected to Northridge earthquake ground motion. A newly developed numerical model called Applied Element Method was considered for the analysis. Initially, the linear analysis was carried out and the results were compared with commercially available software. Later, progressive collapse analysis was performed. Authors also discussed about the collapse process of each bare frame in detail. In order to understand the complete behavior of reinforced concrete frames, it is required to study the performance from no loading condition till the complete collapse. They concluded that progressive collapse can be studied by Applied Element Method, starting from no loading condition till complete collapse.

L. Sezen (2016)

Collapse performance of nine existing multi-storey buildings located in the Ohio State University campus through field experiments and computational modeling. Masonry, reinforced concrete and steel framed buildings have been tested. Single or multiple first-storey columns were physically removed from each building during the experiments. Two and three-dimensional building models were analysed to simulate the progressive collapse response. Computational models and simulations were compared with the experimental data obtained from the field tests. The author has illustrated the robustness of existing buildings and potential contribution of structural components to collapse resistance.

M. General Service Administration (2003)

Developed the guidelines "Progressive collapse analysis and design of new federal office buildings and major modernization projects" to evaluate the potential of progressive collapse. The guidelines provide a threat independent methodology for minimizing and assessing the progressive collapse potential in new and existing reinforced concrete and steel buildings.iu4

N. Department of Defense (2009)

Of United States of America published the Unified Facilities Criteria for "Design of buildings to resist the progressive collapse". The guidelines incorporate the new knowledge related to the design of buildings to resist progressive collapse. This includes steel beam-column connection, wood structure under blast damage and collapse loading, reinforced concrete slab response to large deformations. The guidelines also explained four analysis procedures; linear static, linear dynamic, nonlinear static and nonlinear dynamic analysis for evaluating progressive collapse potential of the structures.

IV. CONCLUSIONS

Progressive collapse is caused by a series of structural element failures due to large loads that exceed the elements capacities. A range of factors that lead to progressive collapse includes accidental or deliberate impacts and explosions, design or construction errors, as well as poor maintenance. General Service Administration and the Department of Defence introducing the most comprehensive progressive collapse mitigation guidelines up to date. The design methods take two distinct forms: indirect methods and direct methods. Several guidelines provide an excellent methodology regarding the selection of analysis methods. Four most effective analysis procedures for progressive collapse analysis; linear static, linear dynamic, nonlinear static and nonlinear dyanamic analyses; were described in various literatures reviewed. The advantages and disadvantages of different analysis methods are also discussed in this paper. Engineer's main aim is to design the structure such that it causes less causality to people after accidental collapse. Researches need to be carried out and experimental programs are to be arranged so as to develop provisions to resist progressive collapse in structures.

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