BEHAVIOUR OF HIGH RISE BUILDING UNDER ACCIDENTIAL LOADING

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ABSTRACT:

Accidental loads such as explosion and vehicle impact could lead to failure of one or several load-bearing members in the structures, which is likely to trigger disproportionate progressive collapse of overall structures. Prestressed concrete (PC) frame structures are usually at great risk of collapse once load-bearing members fail, because the members in PC frame structures are usually subjected to much more load than those in common reinforced concrete (RC) frame structures. The purpose of the study was to describe the process of progressive collapse and to find more methods and approaches to design the structure for preventing from this kind of failure.

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Words are inadequate to express my deep sense of gratitude to my guide Dr. D. S. Yerudkar (M.Tech co-ordinater), for consistent guidance and inspiration throughout the project work, which I am sure, will go a long in my life.

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Last but not least, I express my deep sense of gratitude to my family and friends and all those who have helped me directly or indirectly for their constant support and motivation throughout the course of this project work.

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1. INTRODUCTION

1.1 General

Structures are exposed to shock loads of different magnitude generated from low to high intensity earthquake, tsunami, water wave impacts with coastal structures, vehicle accidents with structures, missile attacks, aircraft accidents with building and blast load on buildings etc. These impacts carried huge amount of energy over short time duration therefore always responsible for severe structural damage. Therefore, impact resistance design of structures is very necessary to reduce damage of structures, to increase structural durability and to save human lives. Therefore, studies have been carried out by researchers and scientists to understand behavior of structural members under impact loading. In a study impact resistance behavior and load carrying capacity of hollow and concrete filled tubes have been determined under static and impact loading. The location of applied impact load has been varied with magnitude of axial load. Further the results obtained for both types of loading were reproduced in finite element tool ABAQUS. It was observed that hollow steel sections have experienced local buckling before it undergoes global failure mode. The use of stainless-steel sections has increased load carrying capacity and ductility of hollow and concrete filled columns as compared to carbon steel hollow sections. In another impact study, influence of amount of fiber content and external strengthening by fiber reinforced polymer (FRP) sheets on impact resistance characteristics of FRC slabs has been identified. The volume of steel content was varied between 0.5 to 1.5%. It was observed that peak impact force, energy absorption capacity and number of repeated hummers drops for failure of slab have been increased in FRP laminated slabs. On the other side the magnitude of deflection has reduced therefore external lamination of concrete members in sensile zone was suggested an effective method for retrofitting. Moreover, the strength of slabs has been increased with increase in amount of fiber content. In a different study, experimental and numerical attempt have been done to investigate load-displacement behavior, energy dissipation capacity, stiffness and damage pattern of concrete beams under monotonic static and low velocity impact loading. The type of loading applied hus significant influence on behavior of concrete beams. Therefore, the load carrying capacity, stiffness and energy absorption capacity have increased under impact loading. Furthermore, when hammer was dropped from relatively more height resulted an increase in peak deflection at the mid-span, could be a reason of increase in kinetic energy of hammer. In another impact study, influence of high-mass low-velocity impact on behavior of reinforced concrete beams and slabs has been investigated. In few tests a piece of ply has been incorporated as buffer medium to avoid direct contact between hammer and tests specimens to reduce local deformation, and for better energy transfer on relatively larger beam area. As reported, the span length of beams has significant influence on peak impact force as compared to their support conditions. Further, minimum thickness to prevent scabbing and perforation of slab has been identified using few empirical formulae available in some other literature. The damage on concrete members could be reduced by providing additional claddings on these members. In another study, behavior TRC beams have been investigated under varying rate of loading to understand their impact resistance behavior, toughness or energy absorption characteristics.

1.2 Accidental Loading

Accidental loads comprise all the loads characterised by a very low probability of occurrence and, therefore, usually disregarded in the normal design process. They may cause significant damage to the construction, resulting from a partial or complete progressive collapse, which, in consequence, may lead to casualties. Potential accidental loads that can trigger a progressive collapse include, among others, an airplane strike, a bomb explosion during a terrorist attack and a fire or a gas explosion within a confined space. A construction that is not sensitive to abnormal loads is defined as resistant to collapse. As a result of terrorist attacks the US General Services Administration (GSA) and the Department of Defence (DoD) have developed the relevant regulations, aimed at ensuring the security of people and protecting building structures from a progressive collapse. The main recommendation arising from the Accidental loads comprise all the loads characterised by a very low probability of occurrence and, therefore, usually disregarded in the normal design process. They may cause significant damage to the construction, resulting from a partial or complete progressive collapse, which, in consequence, may lead to casualties. Potential accidental Loads that can trigger a progressive collapse include, among others, an airplane strike, A bomb explosion during a terrorist attack and a fire or a gas explosion within a confined space. A construction that is not sensitive to abnormal loads is defined as resistant to collapse. As a result of terrorist attacks the US General Services Administration (GSA) and the Department of Defence (DOD) have developed the relevant regulations aimed at ensuring the security of people and protecting building structures from a progressive collapse. The main recommendation arising from the GSA and DoD regulations is the mitigation of the potential for a progressive collapse.

The potential abnormal loads that can cause the progressive collapse are categorized like that:

a. Pressure Loads

- Internal gas explosions
- Blast Wind over pressure
- Extreme values of environmental loads

b. Impact Loads

- Aircraft impact
- Vehicular collision
- Earthquake
- Overload due to occupant overuse
- Storage of hazardous material

1.3 Aim

To study the responses of prestressed building under progressive collapse for accidental loading using ABAQUS.

1.4 Objectives

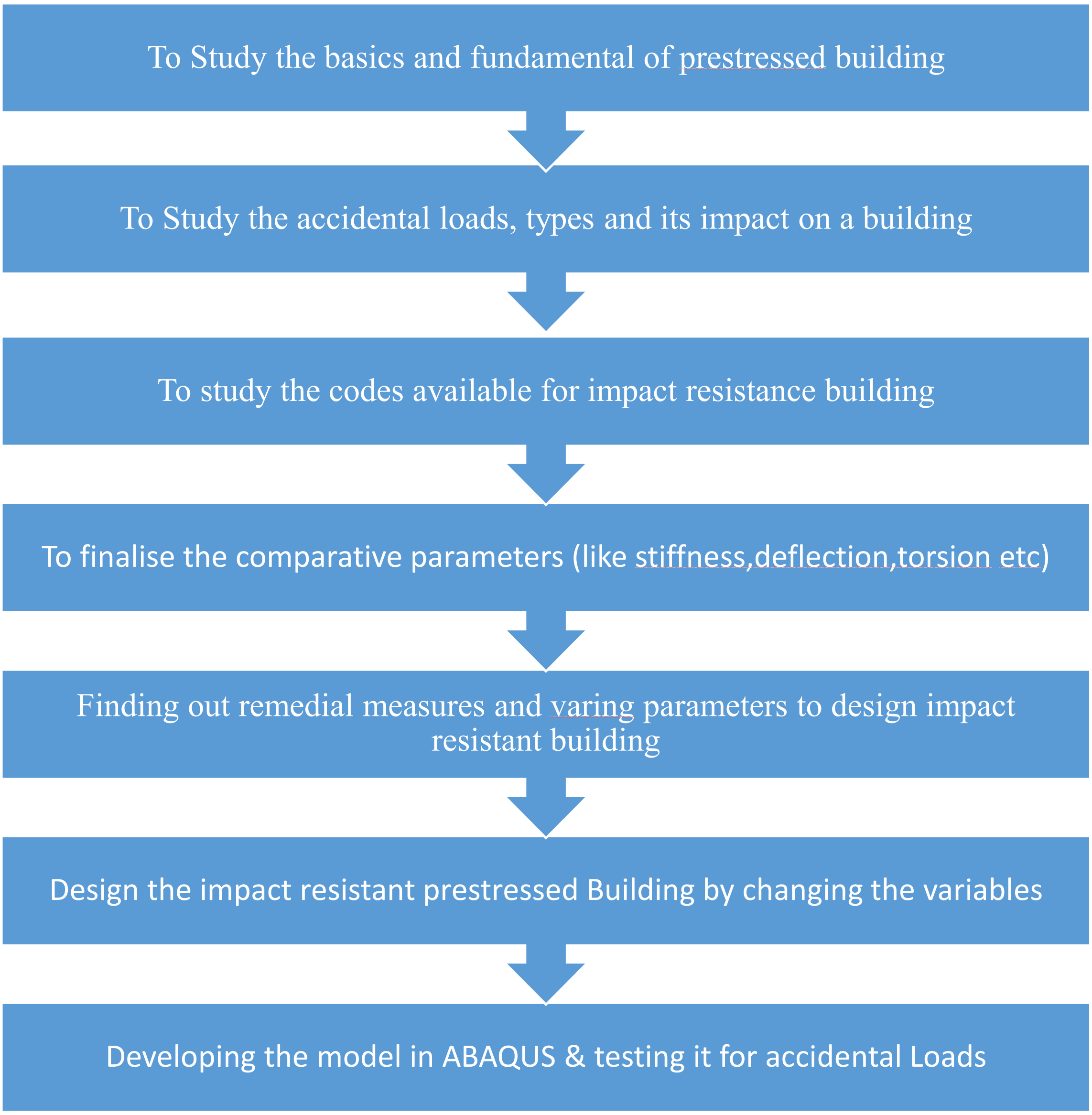
- To study the behavior of building under impact loads
- To design the impact resistant prestressed Building by using different variables used in codes like Eurocode SFS-EN 1991-1-7, Eurocode SFS-EN 1992-1-1, STO-008-02495342-2009, MDS 20-2.2008
- To Test the building model for Accidental loading In ABAQUS

1.5 Scope of work

To meet the above objective, the research work plan has been focussed on the following:

a) The Study will be carried out for Prestressed Building Particularly for Accidental loading.
b) The Modelling and Analysis of the Prestressed building will be done using ABAQUS.
c) The Study will show the Comparative results for conventional prestressed building with impact resistant building

1.6 Research Methodology



1.7 Limitation

- Experimental studies are not carried out, only numerical and analytical model study is done
-

1.8 Codes

- **Eurocode SFS-EN 1991-1-7**
- **Eurocode SFS-EN 1992-1-1**
- **STO-008-02495342-2009**
- **MDS 20-2.2008**

2. LITERATURE REVIEW

1. **Column load balancing in prestressed concrete building, By S. L. Lee,1 Fellow, ASCE, S. Tumilar,2 Member, ASCE, and H. C. Chin3**

Architectural and structural considerations in the design of the 27- story Wisma Dharmala office complex in Jakarta lead to the deployment of twin column clusters around the perimeter and interior of the tower block. Due to the large difference in axial loads between the twin columns, excessive differential axial shortening between the columns and high shear stresses in the connecting horizontal structural components are expected. To mitigate this condition, the column load balancing method is proposed, in which the cable profiles in the prestressed girders are designed not only for moment balancing but also to transfer evenly the shear forces in the girders to the twin columns in each cluster. The effect of load balancing is examined in this paper with the use of a simple analytical model. The predicted loads on the columns are also checked against field measurements taken from three pairs of twin columns from the time the columns are cast until the casting of the helipad floor.

2. **Serviceability Performance of Prestressed Concrete Buildings Taking into Account Long Term Behaviour and Construction Sequence H. L. YIP, F. T. K. AU, S. T. SMITH**

A common problem faced by engineers nowadays is the restriction on structural member dimensions due to architectural and spatial concerns. Such restrictions have resulted in the use of high strength concrete in vertical members to reduce sizes, the use of central core walls and peripheral columns to increase window areas, and the use of prestressed floors to increase spans, to name a few. Serviceability problems (e.g., cracking) may, however, arise in the long term. This paper in turn addresses two major issues associated with buildings. Firstly, the differential axial shortening between core walls and columns caused by large differences in stress levels induces additional stresses and strains in horizontal structural members, which are not normally accounted for by traditional design methods. Secondly, the post-tensioning of concrete floors gives rise to additional internal forces induced by several means such as sequential construction, and secondary "P-" effects of the high-strength slender columns. As it is almost impossible to eliminate these secondary effects completely, a series of studies have been carried out to examine their effects on the structural design of these buildings.

3. **The analysis of prestressed concrete structures and the application of recent research by peter beaumont morice, b.sc., ph.d., a.m.i.c.e.**

The Paper illustrates the application of some results of recent research on the behaviour of prestressed concrete structures. A simple set of expressions is developed for the elastic design and ultimate load-carrying capacity of prestressed members in both statically determinate and indeterminate structures. The use of these expressions in the analysis of continuous beams, portal frames, and bridge decks is discussed in the light of the results of experimental work. Some aspects of research on the effects of friction between prestressing tendons and their ducts in post-tensioned members are included, together with the principal results of a study of the transmission length in factory-made pretensioned units.

4. **Experimental and numerical study on the performance of externally prestressed reinforced high strength concrete beams with openings Ahmed M. El-Basiouny1, Hamed S. Askar1 Mohamad E,El-Zoughiby**

This study investigates experimentally and numerically the performance of externally prestressed reinforced high strength concrete (HSC) beams with central openings. Seven externally prestressed rectangular HSC beams (six with central openings and a reference solid beam) are loaded incrementally to failure. All the beams have the same dimensions, reinforcement ratio and openings of variable size. Experimentally, the results show that, the appearance of the frst fexural crack and the fexural stifness reduction are largely governed by opening height. In contrast, the opening length greatly afects the presence of the frst shear crack and the obtained values of strains in stirrups. Additionally, the opening length and height when combined can afect the strains in top- and bottom-bars and the failure load of the teste beams. Numerically, a three-dimensional nonlinear fnite element analysis using ANSYS has been carried-out to analyze seventy (70) externally prestressed HSC beams with central openings. Based on the numerical results, a general formula to predict the ultimate moment is generated and verifed. It can be used to predict the load carrying capacity of aging concrete elements with openings retroftted using external prestressing techniques

5. **Building structure failures caused by accidental loads**

The paper presents the characteristics of abnormal loads and the recommendations adopt-ed for structural design to prevent constructions from disproportionate damage and to lim-it the consequences of accidental loads in compliance with Eurocode 1 PN-EN 1991-1-7. The article describes progressive collapses and analyses the construction of two buildings: the Murrah Federal Building in Oklahoma and the Pentagon Building in Washington.

6. **Accidental Eccentricity of Story Shear for Low-Rise Office Buildings Jaime De-la-Colina; Bernardino Benítez; and Sonia E. Ruiz**

This paper presents the results of a Monte Carlo simulation study on accidental eccentricity of low-rise office buildings. The study incorporates results of a live-load survey in several office buildings in Mexico City. Probability density functions (PDF) for both intensity and position of live load are initially obtained from this survey. These PDFs are used in the simulation procedure. Additionally, the position and intensity of dead load as well as the stiffness of lateral resisting elements are assumed to be random. Stiffness among columns is assumed to be uncorrelated. Five- and 10-story building models with square and rectangular plans are used. For each case, three types of slabs are included in order to account for different live-load to dead-load ratios. This study shows the effect of the following variables on the estimation of accidental eccentricities: vertical location of the story in the building, dead-load to live-load ratio, number of columns in a story, and the direction of analysis in rectangular plans.

7. **Estimation of Accidental Torsion Effects for Seismic Design of Buildings Juan C. De la Llera, Anil K. Chopra,**

This paper presents the results of a Monte Carlo simulation study on accidental eccentricity of low-rise office buildings. The study incorporates results of a live-load survey in several office buildings in Mexico City. Probability density functions (PDF) for both intensity and position of live load are initially obtained from this survey. These PDFs are used in the simulation procedure. Additionally, the position and intensity of dead load as well as the stiffness of lateral resisting elements are assumed to be random. Stiffness among columns is assumed to be uncorrelated. Five- and 10-story building models with square and rectangular plans are used. For each case, three types of slabs are included in order to account for different live-load to dead-load ratios. This study shows the effect of the following variables on the estimation of accidental eccentricities: vertical location of the story in the building, dead-load to live-load ratio, number of columns in a story, and the direction of analysis in rectangular plans.

8. **Determining Appropriate Design Impact Loads to Roadside Structures Using Stochastic Modeling Ivar Björnsson; Sven Thelandersson; and Fredrik Carlsson**

The design and verification of built structures requires structural engineers to consider accidental loading situations. The accidental loading situation investigated in this paper is heavy-goods vehicle (HGV) collisions with roadside structures; focus is on the design of bridge-supporting structures. The impact loads were determined from Monte Carlo simulations of a probabilistic model in which highway traffic measurements and accident statistics in Sweden are input. These loads were calculated for structures adjacent to straight roads as well as roads with curvature, and include considerations of the directional load components. Comparisons were made between the simulation results and approaches given in design codes, with focus on the Eurocode. The simplified approaches provided in the code were inadequate in their treatment of these design situations. Alternative equations for calculating impact forces and energies are presented. These equations can be used for determining design values for impact forces or for conducting probability/risk-based assessments of bridge supports subjected to HGV impacts. In this way, a more consistent treatment of HGV impacts in the design of bridge structures is achieved

9. **Jun Yu; Tassilo Rinder; Alexander Stolz; Kang-Hai Tan, Dynamic Progressive Collapse of an RC Assemblage Induced by Contact Detonation (2008)**

The nature of progressive collapse is a dynamic event caused by accidental or intentional extraordinary loading. Most published experimental programs are conducted statically, without any consideration of the accidental loading and treating progressive collapse as threat independent. This paper demonstrates the more realistic process of progressive collapse in an experimental program on reinforced concrete sub assemblages collapsed by a combination of dead weight loading and contact detonation. The dynamic results are represented systematically at different aspects and compared with previous published quasi-static experiments in terms of structural mechanisms, crack patterns and local failure modes. Moreover, the dynamic increase factor (DIF) of reinforcing bars and the dynamic load amplification factor (DLAF) are investigated and discussed. Following the above comparisons and the findings in the dynamic tests, previous quasi-static test results can be linked to actual progressive collapse behaviour more convincingly. Finally, the dynamic tests also highlight the effect of contact detonation on structures, which are often not considered in quasi-static tests and design guidelines. The test results indicate that contact detonation causes uplift and out-of-plane actions to the sub assemblage before their downward movement under gravity load, in which the strain rate of reinforcement is between 10−210−2 and 10−1/s10−1/s. Moreover, the structural mechanisms are similar in both quasi-static and dynamic tests

10. **Youpo Su, Ying Tian, University of Nevada, Las Vegas, Progressive Collapse Resistance of Axially-Restrained Frame Beams, Aci Structural Journal 106(5):600-607,. September (2009)**

Twelve specimens representing reinforced concrete frame beams were tested to investigate their gravity load-carrying capacity against progressive collapse. In these tests, the beams within the frame subassemblies were restrained longitudinally against axial deformation. The tests indicated that the compressive arch action due to longitudinal restraint can significantly enhance the flexural strength of a beam subjected to vertical loads. The compressive arch action was observed to be a function of flexural reinforcement ratio and ratio of beam span to depth. The test results validated an analytical model that has considered the axial restraining effects on beam loading capacity. The application of compressive arch effect to the prevention of progressive collapse is discussed.

11. **Meng-Hao Tsai, Effect of Interior Brick-infill Partitions on the Progressive Collapse Potential of a RC Building: Linear Static Analysis Results Article, February (2009)**

Interior brick-infill partitions are usually considered as non-structural components, and only their weight is accounted for in practical structural design. In this study, the brick-infill panels are simulated by compression struts to clarify their effect on the progressive collapse potential of an earthquake-resistant RC building. Three-dimensional finite element models are constructed for the RC building subjected to sudden column loss. Linear static analyses are conducted to investigate the variation of demand-to-capacity ratio (DCR) of beam-end moment and the axial force variation of the beams adjacent to the removed column. Study results indicate that the brick-infill effect depends on their location with respect to the removed column. As they are filled in a structural bay with a shorter span adjacent to the column-removed line, more significant reduction of DCR may be achieved. However, under certain conditions, the brick infill may increase the axial tension of the two-span beam bridging the removed column.

12. **Ahmed Atta and Mohamed Taman, Using high-performance cementitious mortar and external prestressing for retrofitting of corroded reinforced concrete beams, Advances in Structural Engineering (2020)**

The effect of using high-performance polypropylene fiber–reinforced cementitious mortar on reinforced concrete beam repair was presented in this article. Results of an experimental study for the flexural performance of 13 reinforced concrete beams were presented. The corrosion level, in terms of the mass loss of steel, was estimated to be 10% and 15%. Three non-strengthened specimens were tested as a reference: one control uncorroded specimen and two control specimens corroded with 10% and 15%. Ten specimens were strengthened using different techniques; replacement of the spilled concrete at the tension zone with 40-mm-thick high-performance polypropylene fiber–reinforced cementitious mortar, using external prestressing bars at the tension zone with adding 20-mm-thick high-performance polypropylene fiber–reinforced cementitious mortar at the compression zone, and a combination of these techniques. The prestressing reinforcing bars stress was chosen to be 0.25fpy and 0.38fpy for the corroded 10% specimens and 0.25fpy for the corroded 15% specimens. A combination of 40-mm-thick high-performance polypropylene fiber–reinforced cementitious mortar at the tension side and external prestressing bars at the tension zone increased the specimen capacity by 15% and 34% compared with the uncorroded and 10% corroded control specimens, respectively. A comparative study was conducted to evaluate the efficiency of various strengthening techniques. An analytical model was proposed in order to give design guidelines.

13. **V. Kumar, M. A. Iqbal", A. K. Mittalb, Behaviour of prestressed concrete under drop impact loading, 11th International Symposium on Plasticity and Impact Mechanics, 20 (2017)**

Structures are subjected to impacts loads of low to high intensity such as developed from falling of heavy object on floors, vehicle accident with bridge columns, missile attacks during war and terrorist blasts etc. The time duration under such incident is very low. an order of few milliseconds; therefore, local and global deformation behaviour of structures was of great importance in past research. Moreover, under impact loading the material behaviour is entirely different than under static loading conditions. Therefore, in this study, impact tests have been carried out on prestressed concrete plates to identify their behaviour when subjected to drop weight impact. The prestressed concrete plates of size 0.8 m x 0.8 m and thickness 100 mm were subjected to drop impact by 242.8 kg hammer. These plates having identical material and geometrical properties except prestressing force applied for initial stressing. The compressive strength of concrete used for casting of all plates was 40 N/mm². The impact force, deflection and failure modes of the plate specimens have been studied. It was observed that with increase in applied prestressing force impact resistance capacity of plate has been increased and magnitude of peak deflection has been reduced.

14. Ahmed Atta and Mohamed Taman, PROGRESSIVE COLLAPSE, METHODS OF PREVENTION, Saimaa University of Applied Sciences (2013)

The purpose of the study was to describe the process of progressive collapse and to find more methods and approaches to design the structure for preventing from this kind of failure. And the last aim was to find Russian norms and standards and make calculations on progressive collapse of the trade center, according to them. In this way the work was commissioned by Finnmap Consulting Oy. The thesis should be interesting to design engineers working with designing the large-span structures of public use like trade centers, stadiums or sport complexes, which are going to be built in Russia. As a result, this project described and disclosed a process of progressive collapse. Finally the calculation process for preventing structure from progressive collapse was made. And further these calculations will be used for other projects as an example.

15. Tao Yang, Wanqing Chen, and Zhongqing Han, Research Article Experimental Investigation of Progressive Collapse of Prestressed Concrete Frames after the Loss of Middle Column (2020)

Accidental loads such as explosion and vehicle impact could lead to failure of one or several load-bearing members in the structures, which is likely to trigger disproportionate progressive collapse of overall structures. Prestressed concrete (PC) frame structures are usually at great risk of collapse once load-bearing members fail, because the members in PC frame structures are usually subjected to much more load than those in common reinforced concrete (RC) frame structures. To investigate the progressive collapse behaviours of PC frame structures, five one-fourth reduced scaled frame substructures were fabricated and collapse tests were conducted on them. Influence of span-to-depth ratios of frame beams and prestress action modes on the collapse performance of PC frame structures was discussed. Experimental results indicated that PC frame substructures with different prestress action modes, including bonded prestress and unbonded prestress, presented different collapse resistance capabilities and deformability. Tensile force increment of the unbonded prestressing strands almost linearly increased with the vertical displacement of the failed middle column. Catenary action is one of the most important mechanisms in resisting structural collapse. Prestressing strands and longitudinal reinforcing bars in the frame beams benefited the formation and maintaining of catenary action. +e ultimate deformability of the PC frame structures was tightly connected with the fracture of prestressing strand. In addition, a calculation method of dynamic increase factors (DIFs) suitable for PC frame structures was developed, which can be used to revise the design collapse load when static collapse analysis is conducted by the alternative path method. +e DIFs of the five substructures were discussed on the basis of the proposed method; it revealed that the DIFs corresponding to the first peak loads and the ultimate failure loads for the PC frame substructures were less than 1.49 and 1.83, respectively.

16. **Qian Kai, Feng Fu, Progressive Collapse Resistance of Precast Concrete Beam-Column Subassemblages with High-Performance Dry Connections (2019)**

Due to its relatively lower integrity, precast concrete structures are considered to be more vulnerable to progressive collapse than cast-in-place concrete structures. However, to date, majority of existing studies on progressive collapse focused on cast-in-place concrete structures, little attentions were paid to precast concrete structures. Among existing precast concrete structures, unbonded post-tensioning precast concrete structure is one of innovation dry connection structural systems, which no casting at the connections on site. Its excellent seismic performance was recognized by many studies, while studies on its progressive collapse resistance were very few. To fill this knowledge gaps, in this paper, eight half-scaled unbonded post-tensioning precast concrete beam-column sub-assemblages with different connection configurations were tested through pushdown tests to investigate their capacities and resistance mechanisms to prevent progressive collapse. The test results demonstrated various behaviors of beam-column sub-assemblages with different connection types. It was found that, as the longitudinal reinforcements were discontinuous across the beam-column joint region in the beams, flexural action observed in the cast-in-place concrete frames was not mobilized for the specimens with purely unbonded post-tensioning connections. When the specimens installed top-seat angles at the beam-column interfaces, considerable flexural action capacity could be mobilized for load resistance. Moreover, it was found that the failure modes of the specimens are distinctly different to that of conventional reinforced concrete frames or precast concrete frames with cast-in-place joints. The characteristic of compressive arch action and tensile catenary action in tested specimens is quite different to that of conventional reinforced concrete frames.

17. **Hou Jian,Ph.D.; Song Li,Ph.D.; and Liu Huanhuan, Testing and Analysis on Progressive Collapse-Resistance Behavior of RC Frame Substructures under a Side Column Removal Scenario (2016)**

This paper presents an experimental and analytical progressive collapse-resistance evaluation of reinforced concrete (RC) frame substructures under monotonic vertical displacement of a side column, simulating a column removal scenario. A two-span, two-bay, and single-story one-third scale model representing a segment of a larger space frame structure was tested. The downward displacements of the top of the removed side column are imposed until failure. Frame collapse is defined herein as the rupture of tension steel bars in the floor beams. The study provides insight into the behavior and failure modes of the frame structure under a side column loss, including the development of catenary action in the beams and tensile membrane action in the slabs. Based on the experimental observations and theoretical analysis, a simplified calculation model of progressive collapse-resistance capacity of RC frame substructures due to the loss of a side column is established, which establishes the foundation for progressive collapse assessment of RC frame structures. The reliability of the proposed model is verified by experimental results.

18. **S. M. Marjanishvili, P.E., M. ASCE, Progressive Analysis Procedure for Progressive Collapse**

Following the collapse of the World Trade Center towers in September 2001, there has been heightened interest among building owners and government entities in evaluating the progressive collapse potential of existing buildings and in designing new buildings to resist this type of collapse. The General Services Administration and Department of Defense have issued general guidelines for evaluating a building's progressive collapse potential. However, little detailed information is available to enable engineers to confidently perform a systematic progressive collapse analysis satisfying these guidelines. In this paper, we present four successively more sophisticated analysis procedures for evaluating the progressive collapse hazard: linear-elastic static; nonlinear static; linear-elastic dynamic; and nonlinear dynamic. We discuss the advantages and disadvantages of each method. We conclude that the most effective analysis procedure for progressive collapse evaluation incorporates the advantageous parts of all four procedures by systematically applying increasingly comprehensive analysis procedures to confirm that the possibility of progressive collapse is high.

19. **John Abruzzo; Alain Matta, Ph.D.; and Gary Panariello, Ph.D, Study of Mitigation Strategies for Progressive Collapse of a Reinforced Concrete Commercial Building**

This paper describes progressive collapse assessment of an existing reinforced concrete commercial building. Prescriptive guidelines available to date are evaluated in light of alternate load path predictions. The building, exceedingly meeting ACI integrity requirements and the recent United Facilities Criteria tie force provisions, is still significantly vulnerable to progressive collapse triggered by the loss of an interior column.

20. **Jun Yu, Kang-Hai Tan, Special Detailing Techniques to Improve Structural Resistance against Progressive Collapse (2014)**

Previous research work has found that catenary action can significantly increase structural resistance in addition to flexural capacity under column removal scenarios. However, whether reinforcements in beams can effectively function as ties to develop catenary action against progressive collapse is a big concern in current engineering practice because of the limited rotational capacity of RC beam-column connections. Therefore, four RC frame specimens were designed and tested to investigate their structural behavior under a column removal scenario. In addition to a specimen designed with conventional detailing in accordance with ACI 318-05, the other three specimens were designed with special detailing techniques at little or no additional cost, endeavoring to improve catenary action capacity at large deformations without reducing the structural resistance at small deformations. The special detailing included placing an additional reinforcement layer at the midheight of beam sections, partially debonding bottom reinforcing bars in the joint region, and setting partial hinges at one beam depth away from the adjacent joint interfaces. Furthermore, the nonlinear static responses obtained from the tests were used to evaluate the progressive collapse resistances of the four specimens with the consideration of dynamic effect. With systematic instrumentation, the effects of detailing techniques on structural behavior are demonstrated in this paper at different levels. In particular, the mechanism of each special detailing to affect beam-column connection rotations is illustrated and discussed in detail. Finally, suggestions on structural design against progressive collapse via catenary action are provided.

21. **Mehrdad Sasani and Serkan Sagiroglu, Gravity Load Redistribution and Progressive Collapse Resistance of 20-Story Reinforced Concrete Structure following Loss of Interior Column (2010)**

The dynamic gravity-load redistribution of Baptist Memorial Hospital in Memphis, TN, a 20-story reinforced concrete (RC) structure, is evaluated and characterized experimentally and analytically following the removal of an interior ground-floor column. The structure resisted progressive collapse with a measured maximum vertical displacement of only 9.7 mm (0.38 in.). Analytical results using the finite element method are presented, which show good agreement with the experimental data. The propagation of deformation over the height of the structure and its effects on the load redistribution are presented. The effects of the remaining and bent-out steel bars of the removed column on the response of the structure are modeled and evaluated. The response of the structure due to additional dead and live loads and with complete removal of the column (including the steel bars) is analytically evaluated.

22. **Kai Qian, M.ASCE; Yun-Hao Weng; and Bing Li, M.ASCE, Improving Behavior of Reinforced Concrete Frames to Resist Progressive Collapse through Steel Bracings**

External installation of steel braces has been proved an effective seismic strengthening or retrofitting scheme to upgrade the lateral load-resisting capacity of reinforced concrete (RC) frames. However, the effectiveness of steel bracing in improving the progressive collapse resistance potential of RC frames is vague. To fill the gap, five one-quarter-scaled specimens (one bare frame and four braced frames) were tested subject to a pushdown loading regime. The RC frames were nonseismically detailed for reference. Four braced frames with different bracing configurations were tested to evaluate the efficiency of braces for upgrading the load-resisting capacity of RC frames. A rational design method was implemented for designing the braced frames, including the connections between the braces and RC frames. Experimental results proved that steel bracing could increase the first peak load and initial stiffness of the frames significantly. Before mobilization of catenary action in RC frames, the tensile braces were fractured, but the compressive braces experienced severe buckling. Consequently, the braced specimens performed similarly to the bare frame in the catenary action stage.

23. **Rohit B. Nimse, Digesh D. Joshi, Paresh V. Patel Behavior of wet precast beam column connections under progressive collapse scenario: an experimental study**

Progressive collapse denotes a failure of a major portion of a structure that has been initiated by failure of a relatively small part of the structure such as failure of any vertical load carrying element (typically columns). Failure of large part of any structure will results into substantial loss of human lives and natural resources. Therefore, it is important to prevent progressive collapse which is also known as disproportionate collapse. Nowadays, there is an increasing trend toward construction of buildings using precast concrete. In precast concrete construction, all the components of structures are produced in controlled environment and they are being transported to the site. At site such individual components are connected appropriately. Connections are the most critical elements of any precast structure, because in past major collapse of precast structure took place because of connection failure. In this study, behavior of three different 1/3rd scaled wet precast beam column connections under progressive collapse scenario are studied and its performance is compared with monolithic connection. Precast connections are constructed by adopting different connection detailing at the junction by considering reinforced concrete corbel for two specimens and steel billet for one specimen. Performance of specimen is evaluated on the basis of ultimate load carrying capacity, maximum deflection and deflection measured along the span of the beam. From the results, it is observed that load carrying capacity and ductility of precast connections considered in this study are more than that of monolithic connections.

24. Kai, Qian; Li, Bing Slab effects on response of reinforced concrete substructures after loss of corner column (2012)

In typical cast-in-place construction, beams, columns, and slabs act as a single structural unit. Ignoring the slab contribution to the strength and ductility of beams will result in a significant underestimation of the vertical force resistance. The influence of the slab on the strength of the floor system under imposed vertical deformation is significantly greater than that anticipated by the interpretation of the current provisions for effective slab widths acting as a flange in a T-beam analysis. Therefore, to quantify the contribution of the slab toward progressive collapse of building structures in the blast environment, two series of specimens (F and S) were tested under monotonic loading to simulate axial loading in the corner column. The experimental results highlighting the behaviour, such as force displacement responses, crack patterns, and failure mechanisms, were discussed. Comparison of the performance of these two series of specimens indicated that incorporating the reinforced concrete (RC) slab into the beam-column substructures would increase the ultimate resistance capacity by up to 63.0% and significantly reduce the likelihood of progressive collapse.

25. Qian, Kai; Li, Bing, Investigation into resilience of precast concrete floors against progressive collapse (2019)

The casualties and economic loss in historic events have revealed that progressive collapse performance of buildings has to be evaluated in structural design to prevent such disastrous events. Integrity and resilience are important characteristics for buildings to prevent total collapse or disproportionate collapse once an unpredictable terrorism event unfortunately occurs. Compared to the extensive studies on behavior of cast-in-place reinforced concrete (RC) buildings for progressive collapse resistance, there is less research on precast concrete (PC) buildings to mitigate progressive collapse. Thus, in this study, three one-story, two-bay largescale frame-floor subassemblies (one RC and two PC) are tested under pushdown loading regime to investigate the effect of PC floor units and transverse beams on progressive collapse resilience of PC moment-resisting frames. It is found that the PC beams and slab systems could provide substantial compressive arch action and compressive membrane action, similar to the cast-in-place RC buildings. However, as PC slabs are discontinuous, insignificant tensile membrane action is able to develop in PC slab systems and the ultimate load capacity in enormous deformation stage is mainly attributed to the catenary action developed in PC beams.

26. **Jianwu Pan , Xian Wang , and Fang Wu, Strengthening of Precast RC Frame to Mitigate Progressive Collapse by Externally Bonded CFRP Sheets Anchored with HFRP Anchors (2018)**

Currently, the robustness of precast reinforced concrete frames is attracting wide attention. However, avoiding “strong beams and weak columns” during strengthening against progressive collapse is a key problem. To discuss this problem, an experimental study on two 1/2-scale precast frame sub assemblages under a pushdown loading regime was carried out in this paper. One specimen was strengthened with carbon fibre-reinforced polymer (CFRP) sheets on the beam sides. /e middle parts of the CFRP sheets were anchored with hybrid fibre-reinforced polymer (HFRP) anchors. Another specimen was not strengthened. /e failure mechanisms, failure modes, and strengthening effect are discussed. /e strengthening effect is very obvious in the early catenary action stage. No shearing failure develops on HFRP anchors, which proves that the anchoring method is effective. Based on the experimental results, analytical models and preventive strengthening design and construction measures to mitigate progressive collapse of the precast RC frame are proposed.

27. **Spencer E. Quiel, Clay J. Naito, Corey T. Fallon A non-emulative moment connection for progressive collapse resistance in precast concrete building frames (2019)**

This paper documents the experimental development of a new spandrel-to-column moment connection detail for progressive collapse resistance in precast concrete building frames. This study focuses on a 10-story prototype precast concrete frame building with perimeter special moment frames (SMF) that are subjected to a ground floor column removal. The experimental subassembly represents a spandrel-to-column connection on the perimeter SMF near the middle of the building face (i.e. not at the corners). The connection is non-emulative and utilizes unbonded high-strength steel post-tensioning (PT) bars which pass through ducts in the column and are anchored to the spandrels via bearing plates. The proposed design strives for construction simplicity, avoids field welding and/or grouting, and maximizes ductility by allowing the high strength steel bars to act as structural "fuses" when yielding. A full-scale quasi-static pushdown test is performed on two variants of the proposed connection: one with higher moment-rotation capacity and limited ductility, and another with lower capacity and higher ductility. The results show that the connection can reliably achieve its design yield capacity, performs well under service level demands, and can achieve moderate-to-high ductility. The experimental results are then applied to a system-level computational model of the prototype building frame under a column removal scenario. The results of a nonlinear dynamic analysis demonstrate that the system can arrest progressive collapse in the event of a single column loss scenario when either variant of the proposed connection is considered

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