Robustness: Resistance to Progressive Collapse

Raja Sekhar Yellepeddi, Zeeshan Mahmood

Abstract: Progressive collapse of structures has always been a hidden and one of the challenging topics in the field of structural engineering. It has always been difficult to design a building which is collapse resistant. This paper describes the importance of robustness and the collapse resistant methodology using bracings, for reducing the threat of the progressive collapse of multi-storey buildings. It shows the various ways of achieving the robustness of the structure.

Index Terms: Bracings, Progressive Collapse, Robustness.

I. INTRODUCTION

Local failure of one structural element may result in the failure of another structural element. Failure might thus progress throughout a major part or even all of the structure. After reviewing a couple of failure events, it is outlined why current probability based design codes are inadequate to prevent progressive collapse. It is discussed how these shortcomings might be overcome both within and outside a probabilistic framework. A pragmatic approach is suggested in which design according to current practice is complemented by additional design measures with particular regard to collapse resistance.

Structures that are insensitive to local failure, which is denoted by a limited extent of total damage, are known as robust structures. For preventing disproportionate collapse, what ultimately is required, however is not insensitivity to local failure, that is, robustness, but insensitivity to accidental circumstances – a property for which the term collapse resistance is used. Collapse resistance can be achieved through robustness, but also by other means.

There are a number of failure incidents of recent years, ranging from Ronan Point (a high-rise building in London, 1968) to World Trade Center (New York, 2001) which can mostly be identified as progressive collapse. These studies of different cases show the lack of structural robustness as a concurring cause of the collapse. Again, the triggering events are manifold.

Additional considerations are therefore necessary to ensure structural safety after an initial local failure.

II. DESIGN AGAINST PROGRESSIVE COLLAPSE

In the current procedures, the design criteria of mentioned in the current codes are retained. The theory of reliability and probability is also taken into consideration. An assessment with respect to progressive collapse and disproportionate collapse is carried out and corresponding measures are taken.

This method is not based on any kind of probabilistic or reliability theory but on pure engineering judgment and on concrete, deterministically defined design objectives that must be carried out in decision making process. Structural analysis will also be carried out deterministically.

Collapse resistance is defined as the insensitivity to the accidental circumstances, that is, to unforeseeable and low probability events. The conjunction with the predetermined design objectives can be disastrous as it can lead to a disproportionate collapse of the structure. A collapse is disproportionate when the assumable accidental circumstances lead to unacceptable total damage.

Disproportionate collapse is avoided by ensuring the collapse resistant structure. The property of collapse resistance depends both on the structure and the assumable accidental circumstances. In this regard, the structural property 'robustness' is of particular importance: a robust structure is at the same time collapse resistant.

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III. PROCEDURE

Designing a multi-storey frame structure in SAP2000:

To understand the mechanism of progressive collapse a model of 5 storey building was developed in SAP2000 and was designed as per the Indian standards.

Design Loads:

The design loads considered are as per IS 875 (part 1, part 2 and part 3 for dead, live and wind loads respectively) and the earthquake loads considered as per IS 1893 (part 2).

Results:

On analyzing the structure it was found that the members selected had lesser capacity then the demand created by the loads. So a steel design check was run in SAP to find out the optimum size of the sections. On the basis of the design preferences inputted, the complete frame of the structure is designed.

Checking progressive collapse of multi storey building using SAP2000:

The 5 storey steel building designed is analyzed for the progressive collapse under an assumed local failure. This is a threat independent event and the most probable locations of losing a column is chosen as the local failure. Two different cases are checked for it, one by removing the central column of an edge and other as the corner column of the building. Both the cases are checked for the progressive collapse for the local failure.

The hinge properties assigned to all the beams are based on the provisions provided by FEMA (Federal Emergency Management Agency).

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Raja Sekhar Yellepeddi, Civil Engineering Department, National Institute of Technology, Warangal, Warangal, India.

Zeeshan Mahmood, Civil Engineering Department, National Institute of Technology, Warangal, Warangal, India.

First pseudo static analysis will be carried out and then the results of the pseudo static analysis will be compared with the nonlinear dynamic analysis carried out on the same structure.

Nonlinear static analysis:

In nonlinear static analysis, geometric nonlinearity resulting from the large deformations can be accounted for through redistribution of loads as a result of the removal of the column, and a structure attempts to re-equilibrate to the larger spans through a change in behavior from the flexural response to the membrane response. In this analysis the loads are applied stating from zero to maximum values. At the end of the analysis, the predicted forces, moments, shear and deformations should be checked against the acceptance criteria.

Nonlinear analysis depends on the accurate representation of the material behaviour to represent inelastic response. Of particular importance is the actual behaviour of joints as they undergo inelastic deformation. But in this work it is assumed that the strength of the joint is much more than the strength of the connecting members, which means that the connections will not break in the case of progressive collapse.

In SAP2000 the Nonlinear static analysis is done using the static function with material and geometric option turned on.

Nonlinear dynamic analysis:

Nonlinear dynamic analysis gives the accurate response of the structure due to the sudden local failure. In SAP2000 it is also possible by defining a time history function which describes the sudden column failure. To carry out this process the following steps should be kept in mind:

First a point load in the upward direction is to be applied equal to the axial force in the removed column. Then carry out the nonlinear analysis for the load cases defined. Use the stiffness to carry out the time history analysis in which a sudden downward force is applied at the same place of the removed column and it will reach up-to the peak value equal to the force of the column.

A nonlinear static load case is defined considering the material nonlinearity and the P-Delta effect is not considered as the deformations are not so immense because the structure was already stable as it is analyzed for that condition. The load combination taken is

1.5 D.L. + 1.5 L.L. + 1.0 (Column reaction) from which the modified stiffness of the structure is calculated.

IV. LOCAL FAILURE AT THE CENTER OF AN EDGE

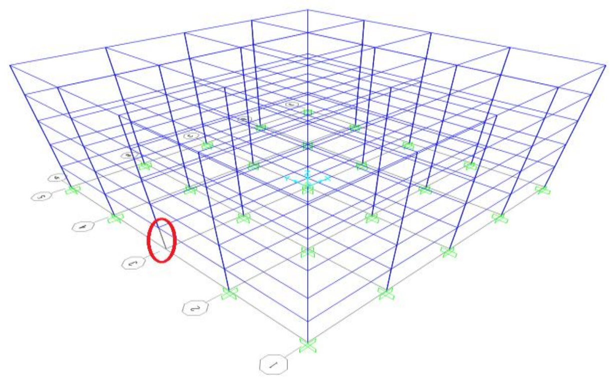

Fig: Local failure at the center of an edge

Fig shows the local failure in the building and it will be analyzed using the tools present in SAP2000. First the Nonlinear static analysis will be carried out and then the nonlinear dynamic analysis and both the cases will be compared to each other.

The internal compression force acting on the removed column is calculated and it is applied as the point load in the upward direction. Then the time history analysis is run to carry out the dynamic analysis.

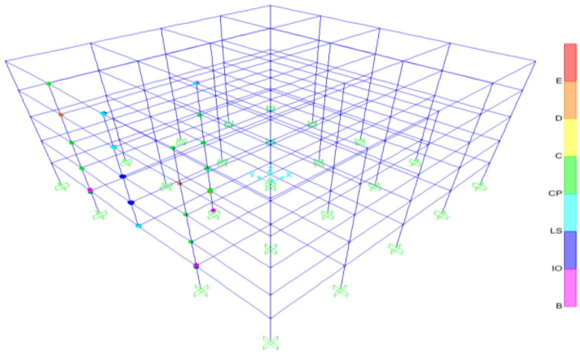

Fig: First stage of nonlinear static analysis

The first stage of nonlinear static analysis is shown. Here the hinge formations in the columns as well as beams are clearly shown. The beam in which the hinges are formed are then kept at constant moment while the columns in which there is a chances of failure is removed from the model and the new model so created is tested again till the complete structure stabilizes.

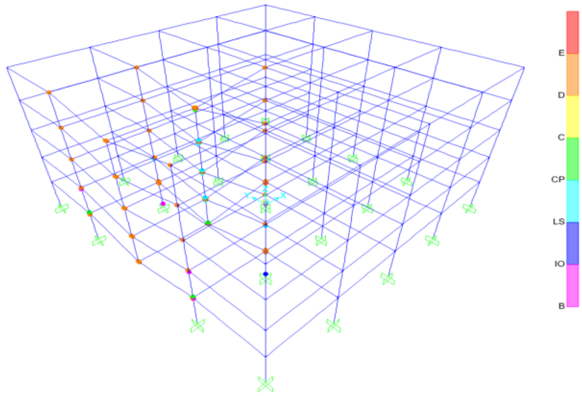

Fig: Second stage of the analysis of the modified structure

It was checked that in stage 2, there are two columns which are under the collapse stage which are again removed to carry out the further analysis of the modified structure. But it was found later on that in doing so the complete structure actually collapsed and when it was compared with the dynamic analysis of the same structure it showed similarity in the results. This pointed out that the pseudo-static method adopted was accurate.

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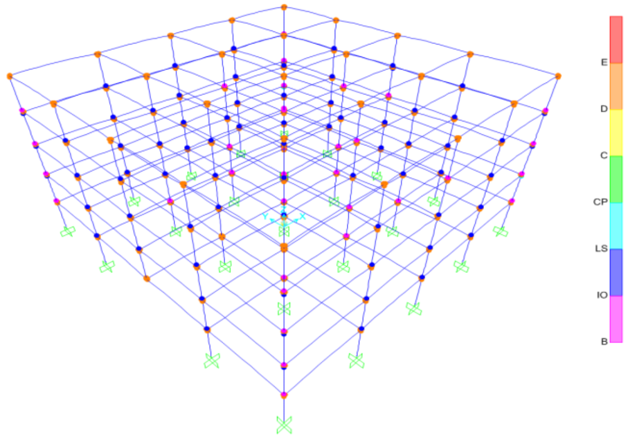

Fig: Complete failure of the structure

V. LOCAL FAILURE AT THE CORNER OF THE BUILDING

On analyzing the local failure at the corner column, it was found out that it was not so much susceptible to the progressive collapse as compared to the central column of an edge which represented the importance of the central column, yet there was a probability of its failure. Figure shows the first step of the failure**.**

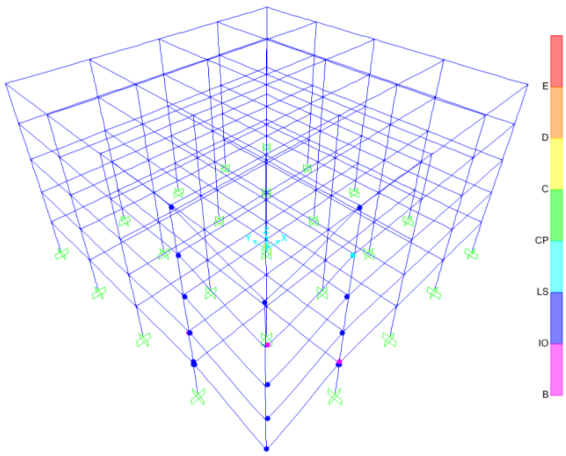

Fig: Analysis results for local failure at corner column

On carrying out the dynamic analysis of the structure, it was found out that the collapse of the complete structure is also possible just because of this local failure but it is not so intense as compared to the local failure at the center of an edge. Figure shows the chances of the complete collapse of the building.

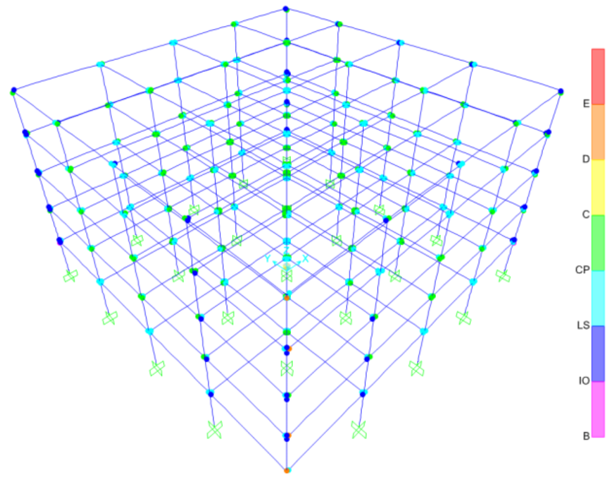

Fig: Complete collapse of building for local failure of corner column

VI. BRACINGS AS RESISTANCE TO PROGRESSIVE COLLAPSE OF MULTI STOREY BUILDING

In order to resist the progressive collapse a simple solution was provided by bracing the ground storey of the building. Bracing at the ground storey was done because of higher probability of the local failure at the ground storey of the structure. As shown in figure the building is effectively braces at the bottom and the size of the members are not as big as they are supposed to carry the loads during the accidental circumstances.

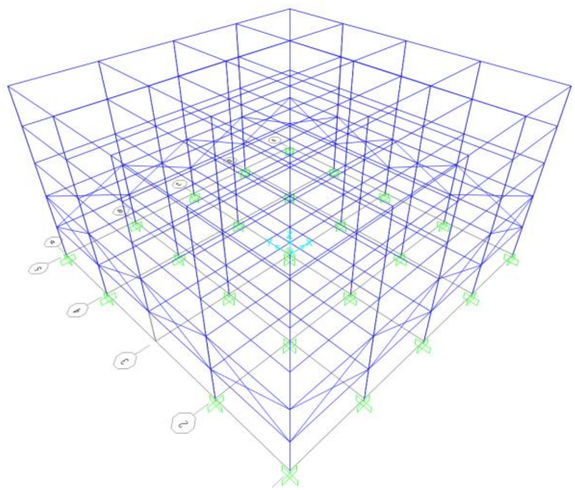

Fig: The modified structure with bracing at the ground floor

When it was analyzed the results were much more appreciated than the cases before. There was no formation of the collapse triggering mechanisms. And here it shows the importance of structural robustness.

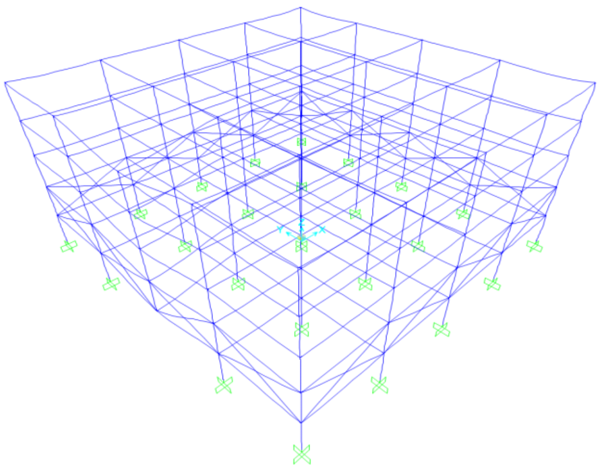

Figure: Deformed shape of the modified structure

Fig clearly shows that there the collapse triggering mechanisms have been prevented and the structure is safe enough to resist progressive collapse. No doubt that the idea is very common but the importance of these many small things can be really beneficial in resisting the progressive collapse for some landmark structures in the country. It will not be so costly as compared to completely losing the structure, and at last it is just the matter of probability of attack and the susceptibility of the structural failure.

VII. CONCLUSION

Different methods for the resistance against progressive collapse can be implemented in the structure which is not smart work, but an economical and safe method is what makes the difference. This topic is such that there are no specific set of rules and that's what make it more challenging. After assuming the local failure, it is in the hands of the engineer whether to adopt alternate load path method or method of isolation due to segmentation. It is in the hand of structural engineer to decide the types of approach considering the pros and cons of the approach, keeping the structure in mind and also the design and the types of material used and the different types of possible threats.

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AUTHOR PROFILE

Raja Sekhar Yellepeddi. B.Tech final year student of Civil Engineering, National Institute Of Technology, Warangal, India .The Branch opening ranker of his Civil Engineering batch through AIEEE. He has got good exposure in the field of Civil engineering through internships in the following:

- Summer Internship on 'Bracings in Multi-Storeyed Buildings' under Prof. G.Appa Rao in IIT Madras 2013.
- Summer Internship on 'SASW analysis of Pavements' under Prof. Jyant Kumar in IISc Bangalore 2012.
- Project on Special Notches in Fluid Mechanics, under Prof. Venkat Ratnam, NIT Warangal 2012
- Summer training in using AutoCad and Surveying in M/s Sandilya Consulting Engineers, Hyderabad 2011.

Zeeshan Mahmood. B.Tech final year student of Civil Engineering, National Institute Of Technology, Warangal, India. He has been a consistent topper in his class. He has got good exposure in the field of Civil engineering through internships in the following:

Final Year project on 'Experimental and Analytical Investigations on Behaviour of Geopolymer Concrete' under Dr. T.D.Gunneswar Rao in NIT Warangal, 2013

- Summer Internship on 'Anaerobic Digestion of Waste water' under Prof. Catherine Mulligan at Concordia University, Canada, 2013
- Summer Internship in Hyderabad Metro Rail under LnT, 2012