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Collapse of the Building: Some Design Deficiencies

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Abstract— **The objective of this study is to present an overview of devastating effect of collapse; with the prime aim to carry out detailed investigation about real causes of collapse of the building. Normally the failure of structures is the result of structural inadequacies, foundation failure or combination of both. The study emphasises on design and analysis of a ground and four upper storeyed RCC frame structure [1] using ETABS 2013 [7] to enumerate the causes of collapse. The analysis indicates the major failure of residential building was predominantly due to structural inadequacy of improper, inadequate beam-column connections, moment transfer. Analysis reflects that the columns were not capable for carrying moment from the beam. The results reveal that in the collapsed building columns were provided with smaller cross section compared to the depth of the beam. This created Weak column-Strong beam condition. Due to which damage was largely concentrated in the ground floor columns. It was also observed that large axial forces must have created crushing failure mainly due to short column condition. The failure mechanism was also aggravated due to settlement resulted into foundation failure. This can be justified looking to the load-settlement behaviour of soil as well as SBC vs Settlement curve plotted using soil investigation data. During verification of column design, considering all other aspects, the real cause was major deficiency observed in beam – column joint. The basic principles and theoretical concept of beam-column joint were ignored during designing of the above said building.**

Index Terms— **collapsed building, failure mechanism, foundation settlement and distress, short column crushing.**

I. INTRODUCTION

In today’s growing economy, infrastructure development is also raising its pace. Many Reinforced Concrete and Brick Masonry buildings are constructed annually around the globe. With the passage of time, there are large numbers of structures which deteriorate or become unsafe to use or collapse. The reasons may be (i) change in loading, (ii) change in use, and (iii) change in design configuration, (iv) use of inferior building material or (v) natural calamities like earthquake, flood, strong winds, and fire. Popular old design philosophies such as soft storey structures are no longer considered acceptable for earthquake resistant design [6].

In spite of the best attention paid to the analysis, design, detailing and construction, it is a sad fact of life that failures do occur in practice. Failures often shatter the confidence of public in the profession of structural engineering. Failure of members or structures may take place due to errors in the aforesaid four processes, but basically due to ignorance and carelessness.

The structural engineer is required to understand the language of the structure and analyze the cause of deficiency and then suggest a suitable remedy so that such collapse can be prevented in future. Many existing structures were analyzed, designed and detailed as per recommendation of prevalent code. Such structure frequently may not qualify to current seismic requirements and therefore in-depth analysis of such structure is essential to identify and possibly control the catastrophic collapse. Generally building collapses when there is a triggering point which initiates the series of movements in structural system leading to the catastrophic condition of failure.

It is obvious from the failure patterns that the design studies on the settlement analysis of foundation systems, which takes into account soil liquefaction and liquefaction induced soil movement, are quite important. Settlement damage was aggravated by the submerged condition. Soil degradation due to development of pore water pressure resulted in large reduction in soil bearing capacity of existing dry soil, basically due to wet and moist condition of soil at foundation level. This influenced the over-stresses in the soil along the plane of rupture, leading to a shear failure of soil. Net result of above mechanism created collapse of structure. By incorporating the observations, in design of the structure it can be made safe against the future threat and one can avert the collapse.

II. OBSERVATIONS

- Most of the structural members i.e. columns, beams were deformed, cracked and crushed by generating brittle shear failure particularly below ground floor.
- Concrete of the columns below plinth level crushed locally and Reinforcement in the lower columns was buckled at several places below the ground floor had resulted into collapse of the whole structure.
- Generated shear plane weakens the ability of the column to resist the vertical load which must have created a sudden collapse of the columns.
- Load deflection properties reveal that before longitudinal shear yields in the column, there is no warning before failure generated in the columns.
- As column had no ductile detailing as well as created discontinuity in the reinforcement between column and beam, it has no ability to withstand lateral forces or loads.
- Nearly 80% columns were observed to have

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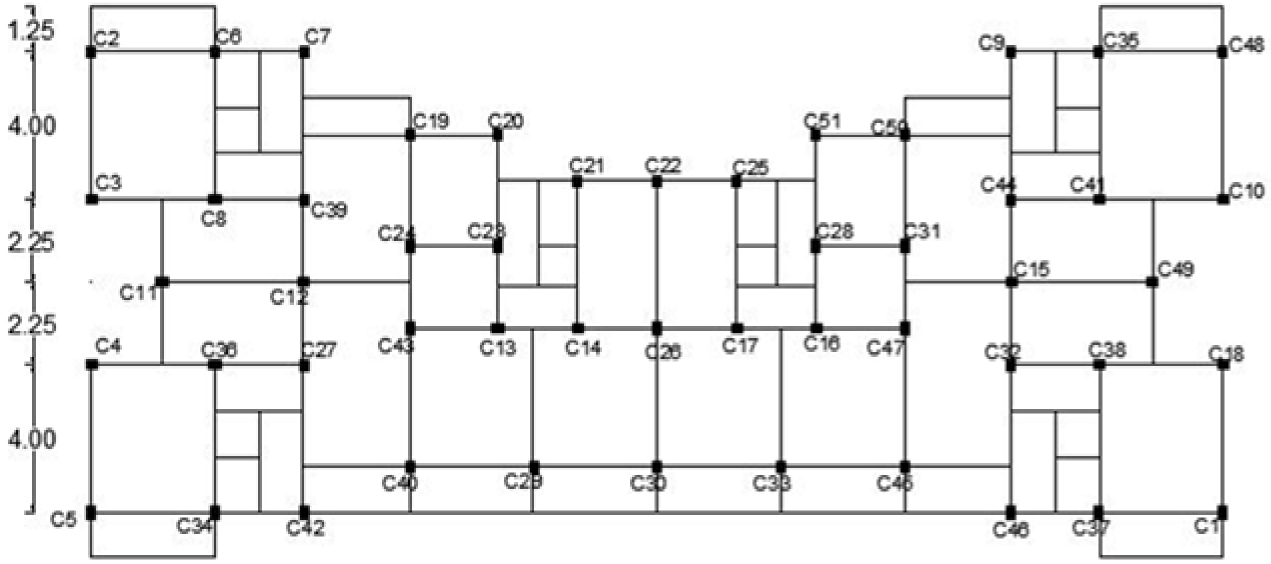

Fig. 1 Structural Layout of Collapsed Building

undergone severe damage in the form of local crushing, spalling, and severe cracking of concrete, buckling of reinforcement due to formation of sloping shear cracks.

- The sloping shear crack must have played vital role in reduction in gravity load carrying capacity of the column leading to sudden collapse of the structure.
- As specific observations couldn’t be made for the quality of concrete and specific distress locations, NDT was adopted to find the strength of concrete. NDT Testing revealed the strength of concrete to be 120 kg/cm^2 against postulated value of 150 kg/cm^2. The collapse profile of the building was nearly symmetrical except slight variation observed because of Overhead Water Tank.
- Natural water flow profiles were carried out in excavation pits to check soak-pit water intrusion in foundation pits. Test with ultramarine blue pigments mixed with subsoil water towards pits which revealed that the flow pattern over a distance of 30m occurred within a period of less than 12 hours.
- During soil testing which was carried out eight months after the rainy season, soil was found to be moist, and in some pits 30 to 40 mm water was observed above foundation base reflecting submerged saturated condition of soil.
- Soil investigations of seven undisturbed samples, indicated definite settlement tendency. The soil investigation results indicated recommended SBC to be around, 15 t/m2 with 3 cm settlement, 20 t/m^2 with 7.5 cm settlement and 25 t/m^2 with 12.5 cm settlement. The building was designed with SBC of 24.5 t/m^2 with no settlement.
- Cracks in substructure due to settlement of foundation.

III. ANALYSIS

Considered building is G+4 RCC frame [1], structural layout of the building is as shown in

Fig. 1 analyzed with standard loading condition as per IS 875:1987 part 1 & 2, using ETABS 2013 software. Undeformed and deformed 3D models of the building are as shown in Fig. 2 and Fig. 3 respectively. A new structure can be built sufficiently earthquake resistant by adoption of proper design methodology and construction quality control. Whereas the existing old structures which have mostly been planned without considering this important aspect, pose enormous seismic risk. Seismic assessment of existing structure may be force based or displacement based. Assessment of existing structure for compliance of the new standards is neither practical nor rational. Therefore, there is a need for more pragmatic approach. Such an approach is to be taken into consideration. Seismic hazard level to which the structure is to be retrofitted is another key parameter. This depends on the expected life of structure and the function of the structure. To validate the seismic response of the building in our study, response spectrum analysis has been done using zone factor as 0.16 and medium soil condition as per IS 1893:2002 part2.

IV. ACTUAL DESIGN RESULTS OF TARGETED COLUMNS

The structure must have been designed considering “simply supported action” for all the frame joints. The beams are modeled to have pinned connections with the columns. Analytical Model represents complete three dimensional characteristics of building behavior including mass distribution, strength, stiffness and deformability through a full range of global and local displacement. Design results of selected columns are summarized in Table 1[3].

It is well known from the theory of structures that the

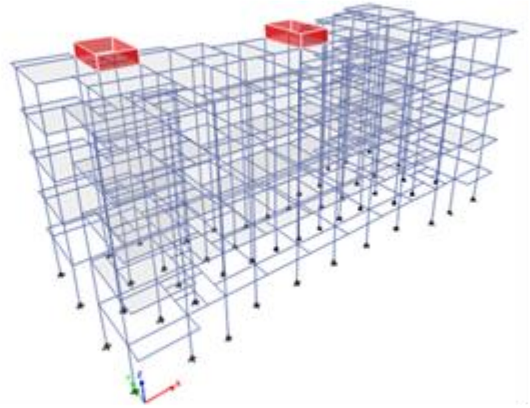

Fig. 2 Undeformed 3D Model

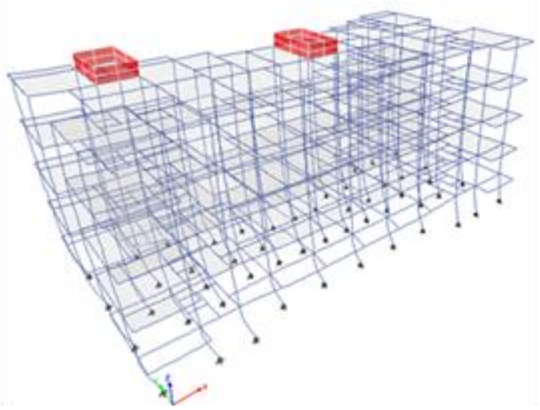

Fig. 3 Deformed 3D Model

Table 1 Design Results for Targeted Columns

Column	L_{eff}	L_{eff} / D	P	Moment @ Minor Axis	Moment @ Major Axis	Interaction Ratio Considering pt = 3%	Check
	(m)		(kN)	(kNm)	(kNm)		
C51	2.04	8.87	373.19	7.46	32.44	0.67	SAFE
C21	2.48	10.76	565.01	11.30	45.29	1.13	FAIL
C32	2.04	8.87	696.84	13.94	25.79	0.78	SAFE
C07	2.48	10.76	735.85	14.72	30.2	1.51	FAIL
C35	1.92	8.35	878.32	25.62	17.57	1.91	FAIL
C41	2.25	9.78	913.55	18.27	47.64	4.6	FAIL
C30	1.98	8.61	1007.53	20.15	27.24	4.13	FAIL

modes of failure of column depend on its slenderness ratio. Columns generally fail in three modes: (i) pure compression failure, (ii) combined compression and bending failure and (iii) failure by elastic instability as shown in Fig. 4 and Fig. 5.

As evident from the results indicated in Table 1, Slenderness ratio for columns is found to be less than 12. In columns where the lateral loads have to be resisted in addition to vertical loads by the strength of columns are considered as unbraced columns

Failure patterns indicate crushing failure in most of the columns. The reviewed literature reveals that designer must have designed for short column conditions only. After checking of actual eccentricity parameters with codal requirement, it seems that in few cases it satisfies the accidental eccentricity parameters. When eccentricity is exceeding the limiting condition, under such condition column should have been designed as column subjected to a combination of Direct Load and Moment.

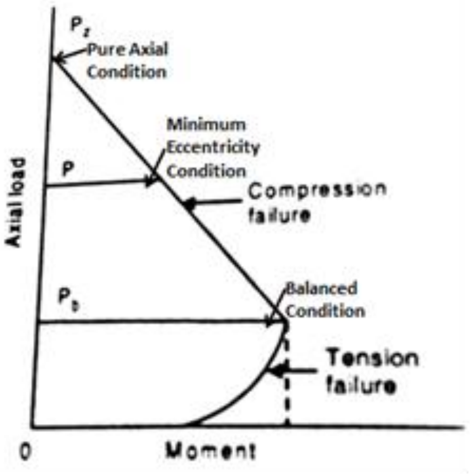

Fig. 4 Load vs Moment Curve for Column

Poor behavior of short columns is due to the fact that in earthquake, a tall column and a short column of same cross-sectional area move horizontally by same amount. Short columns possess more stiffness than the long columns. Stiffness of column means resistance to deformation. Larger is the stiffness, larger is the force required to deform it.

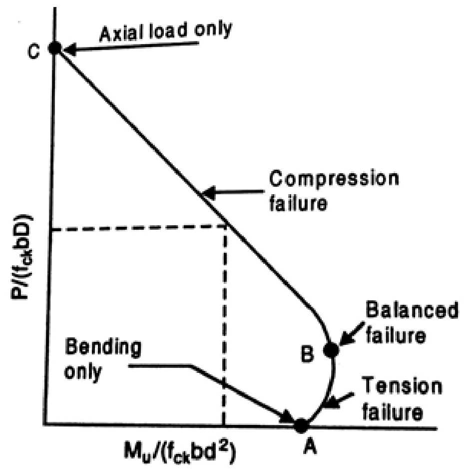

Fig. 5 Non Dimensional Interaction Diagram

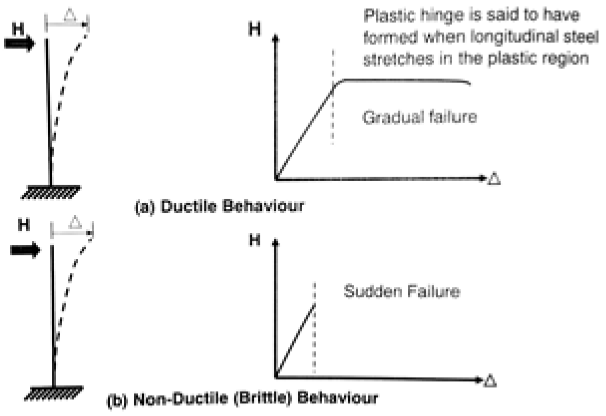

Fig. 7 Effect of Types of Failure on Overall Behaviour

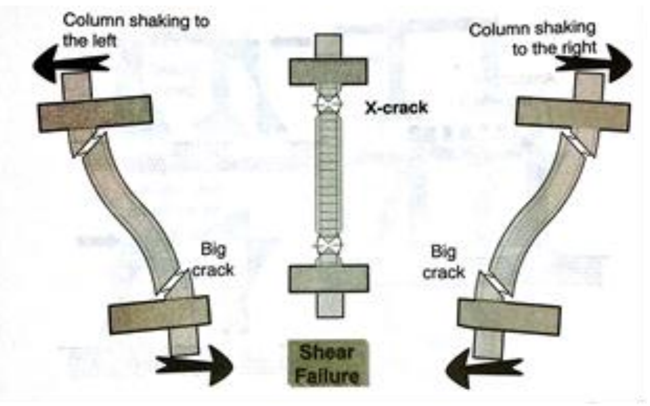

Fig. 6 Two Types of Failure in Columns of RC Moment Resisting Frames

Table 2 Capacity and Applied Moments for Columns

Column	Axial Load	Applied Moments		Moment Capacity		% Moment Deficit	Sufficiency of Reinforcement
		About Minor Axis	About Major Axis	About Minor Axis	About Major Axis		
C51	373.19	7.46	32.44	21.43	24.84	23.43	Insufficient
C21	565.01	11.30	45.29	13.09	19.25	57.50	Insufficient
C32	696.84	13.94	25.79	13.09	19.25	6.10	Insufficient
C07	735.85	14.72	30.2	11.90	15.53	48.58	Insufficient
C35	878.32	25.62	17.57	12.45	14.76	15.99	Insufficient
C41	913.55	18.27	47.64	12.04	24.84	47.86	Insufficient
C30	1007.53	20.15	27.24	16.64	20.15	17.42	Insufficient

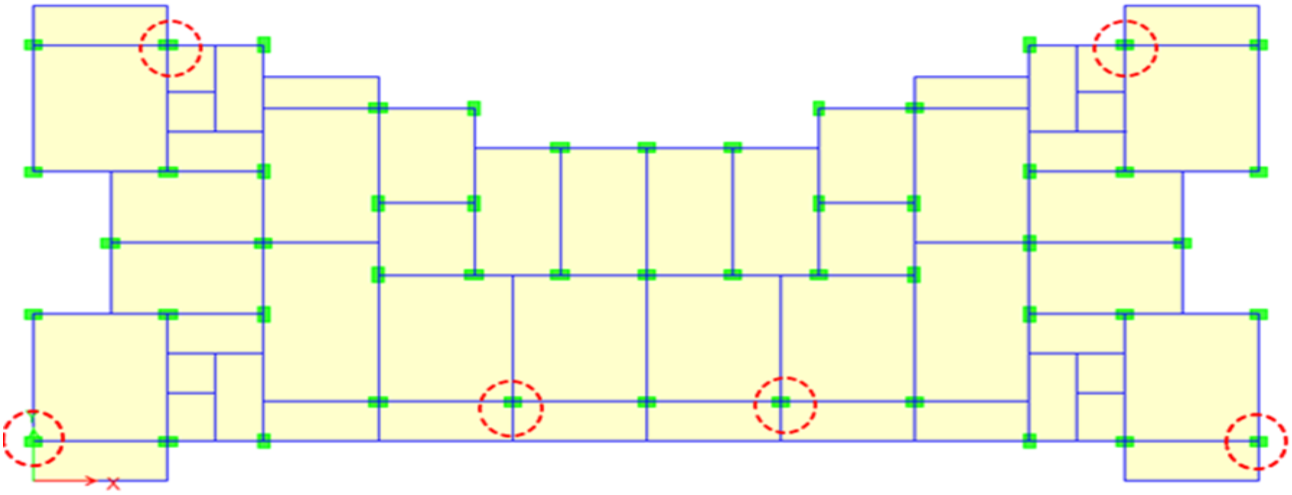

Fig. 8 Columns Suggested for Change in Orientation

If a short column is not adequately designed for such a force and moment, it can suffer significant damage during settlement of foundation or due to lateral displacement or differential settlement condition. This behavior is called “Short Column Effect”. The damage in these short columns is often in the X – shaped cracking as a result of Brittle Shear Failure resulting in Crushing Failure. Short columns fail in shear before they experience more ductile flexural yielding. The corner failures in the structure is indication of insufficient or lack of embedded length in the connection between the beam and columns. (Shown in Fig. 9)

The illustrative Fig. 6 is an indication for nature of failure created in moment resisting frame. Particularly the short columns snap whereas the slender ones bend.

The illustrative Fig. 7 is indication of an overall behavior of a ductile and a brittle column. The ductile column is stiff till yield point where plastic deformation occurs in the longitudinal reinforcing steel. This can be visualized from the diagram. The column does not fail in this condition, absorbs large horizontal deformations without significant reduction in the lateral load carrying capacity of the column.

Fig. 9 Inadequate Reinforcement Detailing of Collapsed Beam Column Joint

The brittle column snaps suddenly in shear before longitudinal steel yielding without any indication prior to failure. The development of 45º inclined shear crack is indication of brittle shear failure in the column. There is continuous reduction in the gravity load carrying capacity of the section; such phenomenon makes collapse almost certain.

The columns were originally designed for axial load only.

A comparative study was made between the moment resisting capacities of columns with the moment demands. The design axial loads and moments for the selected columns are mentioned in Table 2. The columns of the building have been grouped based on the axial load that they were subjected to. Critical columns from each group have been selected for further analysis. The overall capacity of the structure depends on the strength and deformation capacity of the individual components of the structure. Traditional linear analysis methods use lateral forces to represent design condition, whereas nonlinear methods use lateral displacement as design condition. In this case, Response Spectrum Analysis has been adopted for the analysis of the building.

Generally the column is contained in the major plane of bending or is perpendicular to the major axis of bending. This is provided to increase moment of inertia resulting into greater moment resisting capacity. The columns must always be aligned such that their strengths are larger in the frame direction. Based on this concept, the change in orientation of required columns has been suggested. The columns requiring change in their orientation are marked in Fig. 8.

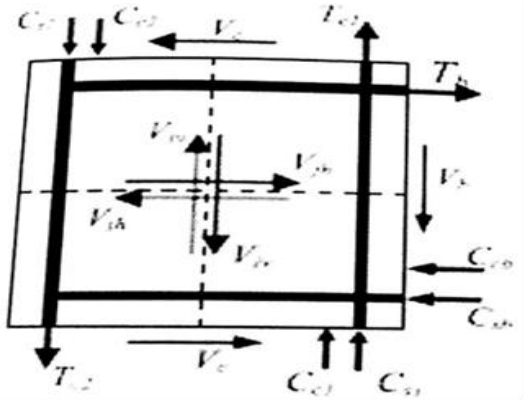

Fig. 11 Horizontal and Vertical Joint Shear

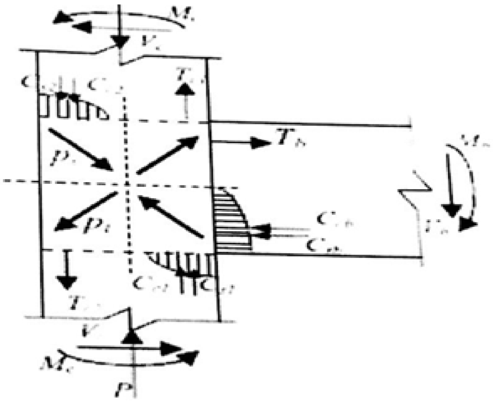

Fig. 10 Principal Stresses in Beam-Column Joint

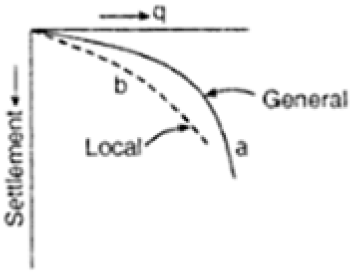

Fig. 13 Local and General Shear Failure

V. FUNDAMENTAL FAILURE MECHANISM OF FOUNDATION

The foundation of a structure is in direct contact with the ground and transmits the load of the structure to the ground. Normally, foundation should be designed to safely transmit the load to a sufficient area of the soil so that the stresses induced in the soil are within the safe limit of SBC. Fundamental mechanism occurs at plastic yielding of foundation. Shear failure was created due to combined effect of lateral and axial loads leading to formation of collapse mechanism. As per limit state of collapse each of these mechanisms can cause complete collapse of foundation; however a real failure was perhaps a nonlinear combination of above mechanism. If soil is overstressed, it may lead to shear failure resulting in the sliding of soil along the plane of rupture. This results into the collapse of the structure.

Analysis of the condition of complete bearing capacity failure usually termed as General Shear failure can be adopted by assuming that the soil behaves like an ideally plastic material.

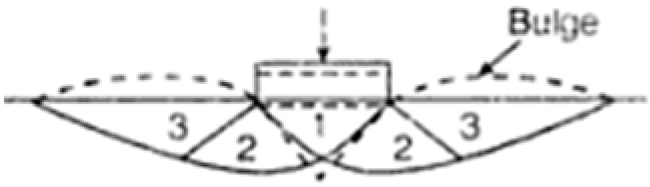

Fig. 12 Displacement for General Shear Failure

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that a slight downward movement of footing develops fully plastic zones and the soil bulges out. The load – settlement behavior of soil can be classified as General Shear Failure and Local Shear Failure as shown in Fig. 13[5]. Displacements in case of general shear failure according to Terzaghi's analysis have been shown in Fig. 12[5].

Calculation for Safe Bearing Capacity (SBC) and Safe Bearing Pressure (SBP) were carried out considering shear parameters and consolidation characteristics of the sub strata. The ultimate net bearing capacity is evaluated after taking into consideration of shape factor and depth factor of the open foundation according to IS 6403 [4].

Table 3 SBC vs Settlement Values

SBC (kN/m2)	74	176	250
Settlement (mm)	10	50	1250

Load, P (kN)	**Area of Footing (m^2)**			**% difference w.r.t. nil settlement**	**% difference w.r.t. 50mm settlement**
	Required to Permit Settlement		**Provided**		
	Nil	**50 mm**			
538.28	8.00	3.36	2.20	72.54	34.69
696.27	10.35	4.35	2.84		
917.48	13.64	5.73	3.74		
791.20	11.76	4.95	3.23		
377.79	5.62	2.36	1.54		

Table 4 Area of Footing

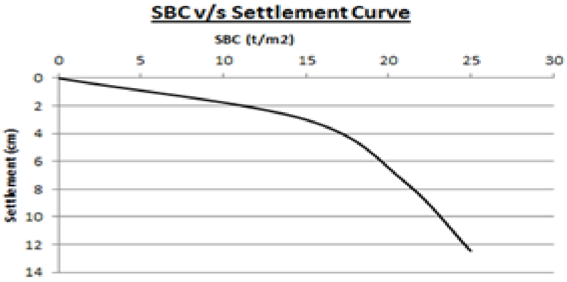

Fig. 15 SBC vs Settlement Curve

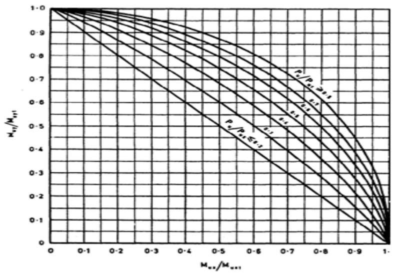

Fig. 14 Biaxial Bending in Compression Members (Chart 64 SP 16)

VI. FACTOR OF SAFETY – ESSENTIAL CRITERIA

Factor of Safety is an in-built safety measure in structural designs of buildings. Most of the consultants strictly follow codal provisions and do not encroach to the factor of safety considering from structural design, quality of individual materials and compatible harmony together.

Factor of safety provides sufficient time for occupants of the building to take up preventive measures after the first sign of distress and before unfortunate collapse. Normally, structure certainly shows several signs of distress in between these two stages of its life. Alternate load path is created within the structure as soon as the first sign of distress is visible in the form of cracking, deflection, etc.

It was noticed that structures with reduced factor of safety succumb to overstressing a lot sooner than the structures with sufficient redundancy. Structures do need regular maintenance to prevent premature malfunctioning and to avoid collapse altogether. It is inhumane to wait and not to take any action to prevent collapse.

It was observed that overall capacity of structure depends on the strength and deformation capacities of the individual components of the structure.

VII. CONCLUSION

During past few decades, number of collapse were reported. It is sad that we, structural engineering fraternity, cannot prevent collapse and avoid loss of human life. We thought it to be extremely necessary to share our finding which can help create awareness in averting building collapse. From the present study of collapse of the building regarding its performance, there are vital requirements which were ignored. First requirement is that the structure must have structural redundancy. Structural redundancy definitely assists achieving the ductility in the structural frame. Second requirement is that large number of members shall be incorporated for generating plastic hinges which minimize the damage likely to occur in structural system. Third requirement is that the orientation of column and foundation should be such that it provides resistance against overturning moments. Hence, design of foundation requires special attention to avoid the catastrophic failure of the structure. From the review of the analysis it reveals that most serious problems attributable due to Design Deficiencies. Such failures occur due to improper attention paid to the reinforcement detail, especially true w.r.t. RCC design for region of Beam-Column joint, anchorage, and discontinuities in members. By designing sufficient number of ties with appropriate confined spacing, the member can be made stronger in shear as compared to bending. This can help in avoiding sudden collapse of members. Error or deficiencies in design are brought to light after a structure has collapsed. The foundation settlement had also aggravated structural imbalance in the already deficient structure. Timely attendance to the signs of distress could have averted the ill-fated collapse of the structure.

Brittle shear failure in column and beam must be prevented if building collapse is to be prevented. This shall be achieved by designing sufficient number of ties at close distance to make the column stronger in shear than in bending. To suppress the shear failure, one must provide adequate longitudinal steel which must yield due to bending moment at the column base before shear failure occurs.

The building needs to possess at least the minimum lateral resistance specified in the standard failing which catastrophic failure takes place. Such practice is unsafe and does not meet the codal requirements. Column must have adequate seismic strength in all direction.

Most of the structures need assessment, maintenance and monitoring to ensure their integrity at a longer run. The better way is to carry out reliability based structural health assessment and life predictions of the structure under question. Structrural health monitoring concept that can detect and locate progressive deterioration in structure. To assess or evaluate the current condition of the structure and predict the remaining life of the structure can be carried out using NDT. Strength assessment using new and innovative NDT concept helps in providing sufficient information to generate knowledge to facilitate decision on the state of the structure for its repair or strengthening or retrofitting, etc. By using Non Destructive in-situ sensing and measurement of structural response for the purpose of detecting changes which may indicate damage or degradation. Measurement of strain, velocity, displacement and other smaller parameters provide data to determine the health and life of the structure. The usefulness of above suggested health assessment methodology can be made compulsory in all such buildings to control the failure.

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