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Effects of Tsunami Forces on RC Framed Structure Subjected to Bracing and Shear Wall

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Abstract*— The Indian Ocean Tsunami on 26 December 2004 resulted into massive destruction to coastal communities with more than 3,00,000 people losing their lives, and causes severe damage to buildings, bridges and other infrastructure. Such catastrophic event made the coastal community realize the need for the preparedness against initial ground shaking and subsequent effects followed by Tsunami. The current study focuses on progressive collapse analysis of 10 storey reinforced concrete frame with bracing and shear wall subjected to different Tsunami forces. The Tsunami forces were calculated according to the guidelines of FEMA P-646, ASCE 7-16. The December 26, 2004 Tsunami parameters on the coast of Tamilnadu were considered for the evaluation of effect of Tsunami forces on structure. To simulate similar conditions structure was designed according to Zone-III and was subjected to Tsunami forces for the 12m, 9m and 6m runup. This study consists of two parts: 1) The calculation of Tsunami forces and application of forces on structure and 2) Progressive collapse analysis of structure by removing the vertical load bearing critical members due to Tsunami forces. The progressive collapse analysis was carried out with the help of commercially available software named ETABs 16. The critical members were removed. The analysis was carried out by referring General Services Administration (GSA-2013, Revised 2016) and Unified Facility Criteria - Department of Defense (UFC - DoD-2009, Revised 2016) guidelines. From the analysis results it was found out that structure becomes critical when Bracing and Shear wall were oriented normal to the flow of tsunami. Upon performing the progressive collapse analysis of structure which was found to be critical due to Tsunami forces reveals that the joint at which the vertical member was removed did not exceed the acceptance criteria of collapse prevention. Hence structure was able to redistribute the unbalanced gravity load and thus prevents the progressive collapse of structure.

***Keywords*— RC Frame, Shear wall and Bracing, Tsunami Forces, Nonlinear Static Analysis, Progressive Collapse.**

I. INTRODUCTION

The Tsunami is generated by the sudden change in geography (deformation) of seafloor caused by earthquake or landslide or volcanic eruption which results in displacement of the waterbed lying over the surface of seabed. Regarding the focal depth, it is also logical to believe that shallow earthquakes produce more severe Tsunami than deep earthquakes do. The displacement of water may be in horizontal or vertical direction but the most dangerous is the displacement of the water body in vertical direction which leads to gain in potential energy by the displaced water. The potential energy is converted into Kinetic energy by the gravitational force. The water body will travel with kinetic energy through the sea and will travel about 1000s of kilometres with the great speed. Regarding the focal depth the most destructive Tsunami are caused by the shallow subduction zone earthquake. Along with water Tsunami comes with large amount of debris and other floating objects which can cause detrimental effect on structure. The structure which is designed for the lateral forces may be prominent to failure or can collapse due to the worst damaging effect due to Tsunami. The damage can be either due to progressive collapse of the structure.

Progressive collapse can be inferred as a type of chain reaction in which the failure of vertical load bearing element could cause partial or total collapse of the structure. The removal of one or more vertical load bearing element can initiate progressive collapse of the structure. Once the vertical load bearing element is removed then the building's weight or unbalanced gravity load will be transferred to the neighbouring beam element or column element. If the element has enough capacity to transfer the unbalanced gravity load then the structure can resist the progressive collapse. But if it is not then structure will be prone to progressive collapse in terms of partial collapse or total collapse of structure. The members will fail until the additional load has not been stabilized. In this paper 10 storied structure is subjected to Tsunami forces for the runup measured during the 26th December 2004. The Tsunami forces are calculated according to runup measured i.e, 12m, 9m and 6m with the help of FEMA P-646. The load bearing columns as well as shear wall are removed from the first storey of the structure. Nonlinear static method is employed for the progressive collapse analysis of the structure with the help of ETABs software.

II. LITERATURE REVIEW

Sanket Nayak et.al, [1] wanted to reduce the Tsunami vulnerability of coastal structure by observing whether the structure which was designed for seismic load i.e., lateral load would be able to resist the Tsunami loading. They have compared Tsunami force with seismic base shear for a low rise structure. They have calculated the base shear with the help of different guidelines such as ASCE 7-05, Euro code 8 and IS 1893 (Part 1). The Tsunami forces were calculated with the help of FEMA 55, CCH and SMBTR. When at a particular inundation depth seismic base shear and Tsunami forces are equal they termed it as Critical height. Hence they concluded that when structure which is designed for seismic loading is said to be safe under the influence of Tsunami force if the height of the Tsunami wave does not exceed critical height. If at a particular site if inundation depth is greater than the critical height then the structure must be designed considering the load due to Tsunami also.

Ian Robertson et.al, [2] surveyed the Chile Tsunami site and based on the failure of the structural element they estimated the velocity at Talcahuano harbor as exceeding 3.2 m/s and in the coastal town of Dichato as 4.3 m/s. The velocities and depth of the Tsunami flow were less than the Indian Ocean Tsunami. Steel and Concrete building could resist these flow velocities and depth however they were vulnerable to larger floating debris and scouring action. Hence they suggested that in research and design provisions the impact due to debris and foundations need a greater attention. They also suggested that progressive Collapse prevention design must be incorporated so as to remove the uncertainty due to heavy debris impact load due to shipping containers or some large floating objects.

Yuriy Mikhaylov et.al, [3] wanted to evaluate the effect of Tsunami loading by incorporating them into the design of multistorey reinforced concrete residential and office building which were located near Tsunami prone coastlines. They designed the building according to IBC 2006 and ACI 318-08. They then analyzed the building for Tsunami bore loading in accordance with FEMA P646. They found out that multistorey reinforced concrete residential and office building can be designed as Tsunami refuge structure. Due to Tsunami forces considered in the design there were less than 8% increase in reinforcement weight and less than 3% increase in concrete volume for the building studied. The design should include the impact due to shipping container and should be designed to prevent the progressive collapse of the structure.

Abdullah Keyvani et.al, [4] wanted to investigate a proper model for the material Nonlinearity of members during the progressive collapse by incorporating only the Impact load due to Tsunami. Heavy impact would be most dangerous to the building which could lead to progressive collapse. For this purpose they performed an experimental work and compared with the analytical model. To demonstrate the catenary action and axial action axial-moment hinges were perfect to demonstrate the above said method and FEMA 356 hinges were conservative in comparison to experimental work but results were not reliable for research or practical purposes.

Harry Yeh et.al, [5] in this paper author wants to point out that reinforced concrete structure was thought to withstand during Tsunami actions but this was not the condition during the 2011 Great East Japan Tsunami. Author also demonstrated that to evaluate the global building failure buoyancy force calculations are very much important. Buoyancy force reduces the net structural body force and hence it also reduces the resistance towards the sliding and overturning of structure. The detrimental effect of buoyancy force on structure depends on foundation depth. As the buildings with the deeper foundation, the buoyancy will be mitigated more easily. When the building is flooded with water then building will have more body force to resist failure of structure.

III.DESCRIPTION OF STRUCTURAL SYSTEM

A. Modelling of RC Building

The 10 storied RC Frame building with shear wall and bracing is modelled using ETABs Software. The building considered is having 4 bays of 6.5m each and 3 bays of 6m each. The floor to floor height is taken as 3.1m. The dimension of beam is 500mm x 500mm and the column have a dimension of 700mm x 700mm. Shear wall of 300mm thickness with different types of bracings of ISMB600 are considered. The type of bracing used are X , Diagonal Type 1 & 2, V and Inverted V. The thickness of roof and floor slab is 200mm. The structural configuration of column and shear wall and bracing are same throughout the building. The dimensions of beam and slab are same for the entire structure. The columns and shear wall is assumed to be fix. The bracing is assumed to be continuous. The grade of concrete used is M30 and grade of steel used is Fe 415. The typical plan of the structure with shear wall and bracing is shown in Figure 1.

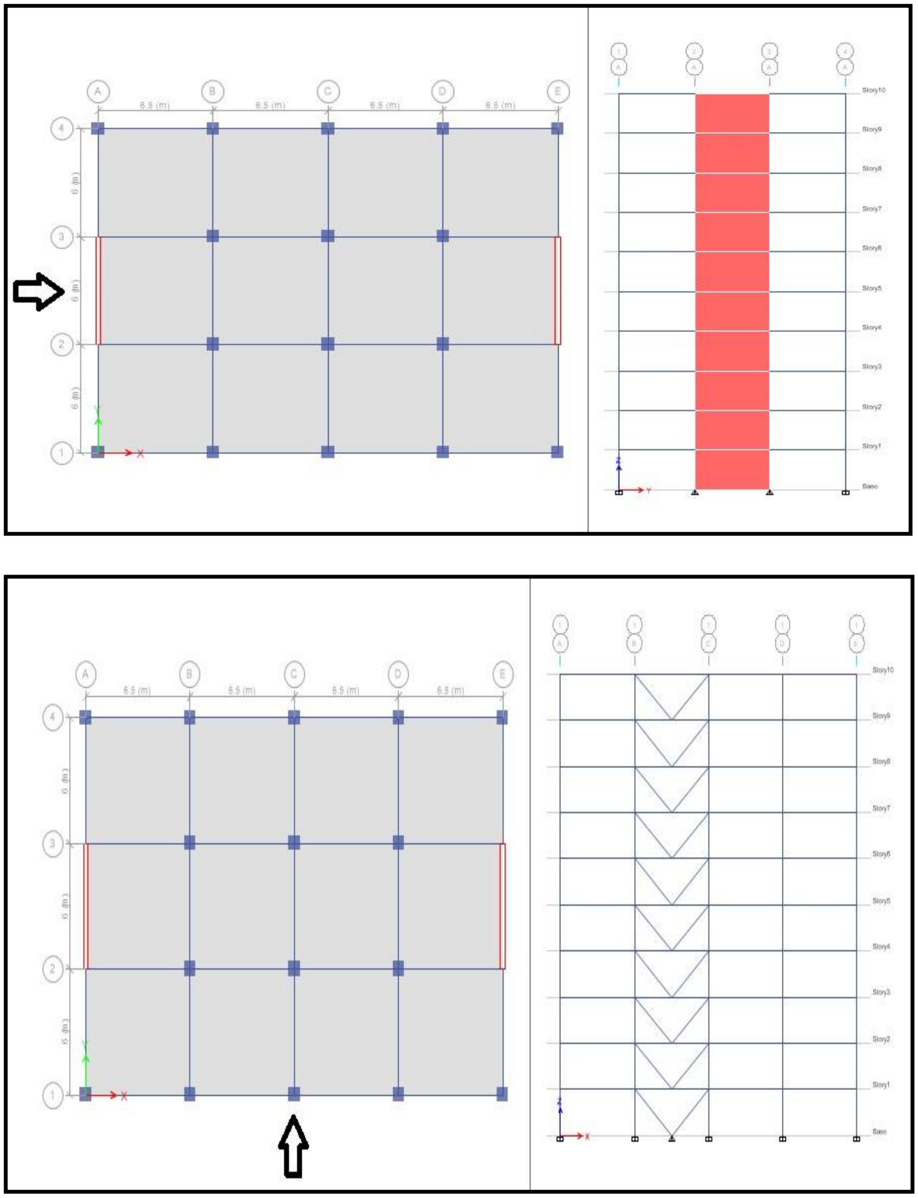


Figure 1 Typical Plan and Elevation of the Building with Shear wall and Bracing

B. Objectives

1) To evaluate Lateral Hydrostatic Force, Vertical (Buoyant) Hydrostatic Force, Hydrodynamic Force, Impact Force and Debris Damming Force.
2) To study the progressive collapse of structure with bracing and combination of bracing and shear wall subjected to Tsunami Force.
3) The parameters under study are: Base shear due to Tsunami Forces, Criticality of column due to Tsunami Forces, Vertical Displacement.

C. Scope Of Work

1) To study ETABS software and perform validation procedure.
2) To study the applications of Tsunami Forces acting along the structure.
3) Modelling of RC frame with bracing and combination of bracing with shear wall with the help of ETABS software.
4) To evaluate the Tsunami force like Hydrostatic Force, Buoyancy Force, Hydrodynamic Force, Impact Force and Debris Damming Force for the runup of 12m, 9m and 6m using FEMA-P646, ASCE7-16 and to evaluate the specific application on structure according to FEMA-P646 guidelines.

5) To carry out the progressive collapse analysis of structure by removing the vertical load bearing elements which were found to be critical due to Tsunami using GSA 2013 and UFC 2016.
6) To provide guidelines for better resistance against Tsunami Forces and Progressive Collapse.

IV. TSUNAMI FORCES

Tsunami is considered as series of waves which has the capability to create the several loading conditions on coastal structure. The different loading conditions are in the form of forces like Lateral Hydrostatic Force, Buoyant Force, Hydrodynamic Force, Impact Force, Additional Load Due to Water Retained on the Floor, Impulsive force, Debris Damming Force.

A. Lateral Hydrostatic Force

Lateral hydrostatic forces occur when standing or slowly moving water encounters a building or building component causing a lateral force on its surface.

B. Buoyant Force

The buoyant force or vertical hydrostatic forces on a structure subjected to partial or total submergence will act vertically.

C. Hydrodynamic Force

This is usually a lateral force caused by the impact of the moving mass of water and the drag forces as the water flows around the obstruction.

D. Impact Force

Impact forces are a result from debris such as wood, small boats, automobiles, etc., or any object transported by floodwaters that strikes against a building or its component.

E. Additional Load due to Water Retained on the Floor

In addition to gravity load, water retained on the floor during drawdown causes additional load on the floor.

F. Impulsive Force

Impulsive forces are caused when a leading edge of a surge of water impacts a structure.

G. Debris Damming Force

The debris when collected in front of structure either on the entire length of the structure cause damming effect due to debris.

V. PROGRESSIVE COLLAPSE

To evaluate the progressive collapse of 10 storied reinforced concrete building using Nonlinear static analysis for the different column removal case is carried out. According to the GSA-2016 guidelines the external columns are removed near the middle of the short side, near the middle of the long side and at the corner of the building. The shear wall is also removed from the structure. The columns and shear wall are removed from the ground storey of the structure. To account for the nonlinearity in the structure PMM hinges are defined in the column at their both the ends and M3 hinges are defined in the beam at both the ends and at the middle of the beam member. The nonlinear static analysis is carried out with the help of Nonlinear stage construction option available in ETABs to automate the removal of column and shear wall.

VI. ANALYSIS RESULTS

A. Tsunami

The Tsunami forces are found out with the help of FEMA P-646 and are applied on the structure as described in the FEMA P646 and ASCE 7-16 guidelines. The forces are found out when Tsunami is acting in 6m bay direction of the structure and when Tsunami is acting in 6.5m bay direction of the structure. The Tsunami forces when applied on 6m bay is termed as Tsunami Loading Case 1 and the forces applied on 6.5m bay is termed as Tsunami Loading Case 2.

1) *Tsunami Loading Case 1:* The Tsunami forces are found for the 6m bay of the structure and are applied as per the guidelines provided in FEMA P-646 and ASCE 7-16. The evaluated Tsunami forces are tabulated as follow:

Table 1 FEMA P-646 Forces for 6m Bay

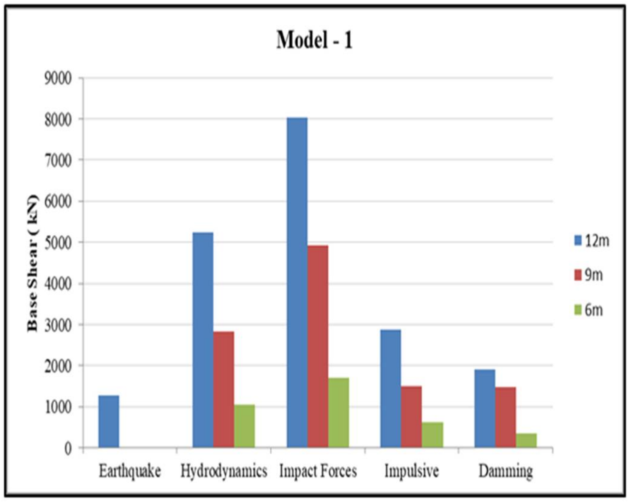
Sr. No.	Forces Equation for 6m Bay	12m Runup	9m Runup	6m Runup
1	Lateral Hydrostatic Force, $Fh = \rho sg \left(hmax - \frac{hw}{2}\right) bhw$	2217.9 kN	1435 kN	652.3 kN
2	Buoyant Force, $Fb = \rho s\, gV$	2.16 kN/m^2	27 kN/m^2	18.3 kN/m^2
3	Hydrodynamic Force, $Fd = \frac{1}{2}\rho s\, Cd\, b(hu2)_{max}$	Column 12.24 kN/m Shear wall 17.5 kN//m^2	Column 8.6 kN/m Shear wall 12.2 kN//m^2	Column 4.9 kN/m Shear wall 7 kN/m^2
4	Impact Force, $Fi = 1.3\, Umax\, [k\, md(1 + c)]^{0.5}$	Wood 598 kN Container 7435.2 kN Vehicle 26.7 kN	Wood 453.1 kN Container 4378.6 kN Vehicle 26.7 kN	Wood 224.6 kN Container 1262 kN Vehicle 26.7 kN
5	Additional Retained Water Loading On Elevated Floor, $Fr = \rho s\, ghr$	2.16 kN/m^2	27 kN/m^2	18.3 kN/m^2
6	Impulsive Force F_s = 1.5* Hydrodynamic Force	Column 18.36 kN/m Shear wall 26.2 kN//m^2	Column 12.83 kN/m Shear wall 18.3 kN//m^2	Column 7.35 kN/m Shear wall 10.4 kN/m^2
7	Damming Effects of Water Borne Debris, $Fdm = \frac{1}{2}\rho s\, Cd\, b(hu2)_{max}$	Column 12.24 kN/m Shear wall 17.5 kN//m^2	Column 8.6 kN/m Shear wall 12.2 kN//m^2	Column 4.9 kN/m Shear wall 7 kN/m^2

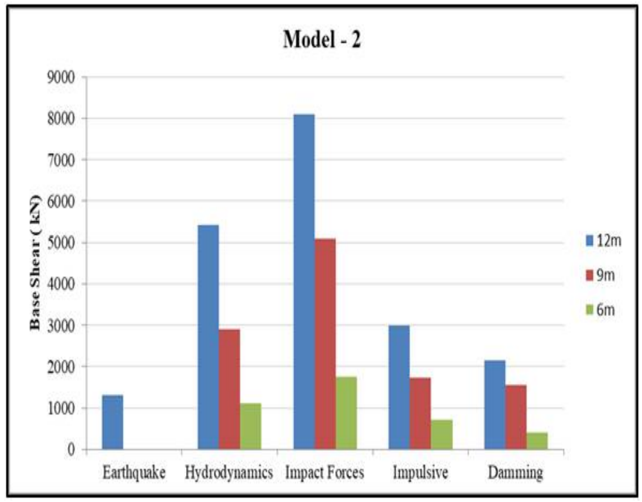
2) *Tsunami Loading Case 2:* The Tsunami forces are found for the 6.5m bay of the structure and are applied as per the guidelines provided in FEMA P-646 and ASCE 7-16. The evaluated Tsunami forces are tabulated as follow:

Table 2 FEMA P-646 Forces for 6.5m Bay

Sr. No.	Forces Equation for 6.5m Bay	12m Runup	9m Runup	6m Runup
1	Lateral Hydrostatic Force, $F_h = \rho_s g \left(h_{max} - \frac{h_w}{2}\right) b h_w$	2403 kN	1555 kN	706.7 kN
2	Buoyant Force, $F_b = \rho_s gV$	2.16 kN/m^2	27 kN/m^2	18.3 kN/m^2
3	Hydrodynamic Force, $F_d = \frac{1}{2}\rho_s C_d b(hu^2)_{max}$	Column 12.24 kN/m Shear wall 17.5 kN//m^2	Column 8.6 kN/m Shear wall 12.2 kN//m^2	Column 4.9 kN/m Shear wall 7 kN/m^2
4	Impact Force, $F_i = 1.3\, U_{max} [k\, md(1+c)]^{0.5}$	Wood 598 kN Container 7435.2 kN Vehicle 26.7 kN	Wood 453.1 kN Container 4378.6 kN Vehicle 26.7 kN	Wood 224.6 kN Container 1262 kN Vehicle 26.7 kN
5	Additional Retained Water Loading On Elevated Floor, $F_r = \rho_s gh_r$	2.16 kN/m^2	27 kN/m^2	18.3 kN/m^2
6	Impulsive Force $F_s = 1.5^*$ Hydrodynamic Force	Column 18.36 kN/m Shear wall 26.2 kN//m^2	Column 12.83 kN/m Shear wall 18.3 kN//m^2	Column 7.35 kN/m Shear wall 10.4 kN/m^2
7	Damming Effects of Water Borne Debris, $F_{dm} = \frac{1}{2}\rho_s C_d b(hu^2)_{max}$	Column 12.24 kN/m Shear wall 17.5 kN//m^2	Column 8.6 kN/m Shear wall 12.2 kN//m^2	Column 4.9 kN/m Shear wall 7 kN/m^2

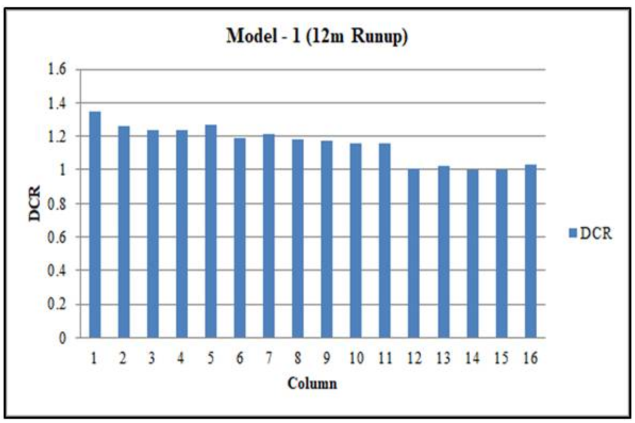
3) *Base shear Due to Earthquake and Tsunami Forces:* The base shear due to earthquake and Tsunami forces are evaluated for the two Tsunami loading Cases and are plotted as shown below.

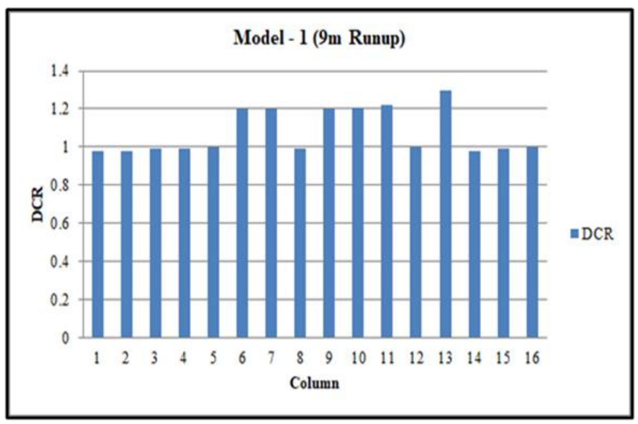


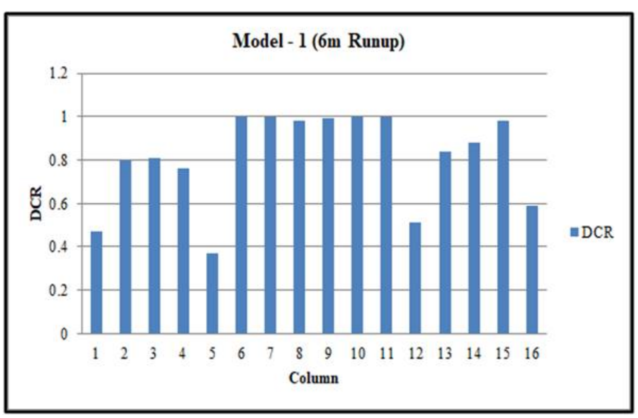


B. Demand Capacity Ratio (DCR)

The DCR value is obtained for individual column and is plotted as shown below.







C. Progressive Collapse

The progressive collapse analysis is carried out by removing the critical columns and shear wall as per the GSA-2016 guidelines. The columns C1, C3, C5 and Shear wall are removed from the structure.

Critical Model from Worst Load Combination	Removed Structure	Vertical Displacement at Joint of Removed Structure (mm)	Collapse Criteria = 0.2L = 0.2*6000 = 1200 mm
Model – 13	C1	167.523	Not Satisfied
	C2	115.497	Not Satisfied
	C3	127.342	Not Satisfied
	C4	159.258	Not Satisfied
	C5	153.628	Not Satisfied
	C6	150.961	Not Satisfied
	C7	156.385	Not Satisfied
	C8	156.546	Not Satisfied
	C9	158.097	Not Satisfied
	C10	149.867	Not Satisfied
	C11	154.034	Not Satisfied
	C12	157.362	Not Satisfied
	C13	156.983	Not Satisfied
	C14	167.530	Not Satisfied
	C15	130.856	Not Satisfied
	C16	135.093	Not Satisfied
	SW	124.527	Not Satisfied

VII. CONCLUSION

During catastrophic event like Tsunami the forces generated by the Tsunami can be one of the reasons for the progressive collapse of structure. Hence to evaluate the effect of Tsunami forces on structure forces were evaluated with the help of FEMA-P646 and ASCE 7-16 for the runup height of 12m, 9m and 6m on a 10 storeyed RC Frame with Bracing and Shear wall placed at different locations. The Tsunami forces were applied on structure in different directions and the critical column members were determined. The critical members were removed and the structure was checked for the progressive collapse analysis. The following conclusions were drawn.

A. It was found that when the base shear of structure due to Tsunami was greater than or equal to 12 times the base shear due to earthquake then almost all the columns were found to reach their capacity or have been overstressed. Hence it can be said that when the structure which was designed for earthquake can act as Tsunami resistant structure until and unless base shear due to Tsunami does not exceed 12 times the base shear due to earthquake for the particular zone of earthquake.

B. From the DCR results of column member it was found that when the structure is impacted by Tsunami forces with the Bracing or Shear wall facing the Tsunami force the base shear will be high in that particular direction rather than the direction in which the Tsunami strikes the structure having no Bracing or Shear wall.

C. This study suggests that structures with X and Inverted V Bracing combined with Shear wall were found to be the most effective as there were no columns which were overstressed or reach their capacity for the 12m, 9m and 6m runup in either direction of flow of water and hence the functional requirement is met.

D. The displacement results show that when column at the middle of bay was removed the displacement was less than the other removal cases. The maximum vertical displacement found out to be 167.53 mm at the joint of removed column which did not exceed the criteria of collapse of that is 1200 mm (0.2L). Hence structure was able to redistribute the unbalanced gravity load and thus prevents progressive collapse of structure.

VIII. FUTURE SCOPE

A. From the application of Tsunami Forces , Tsunami Resistant structure and guidelines for it can be made.

B. Evaluation of Ductility factor, Redundancy factor, Over strength factor, Damping can be carried out for structure subjected to Tsunami Forces.

C. Computation of Response Reduction Factor for building subjected to Tsunami Hazard.

D. Effects of Quintuple Friction Pendulum System on building when Tsunami is striking on it.

E. Design of Tsunami Resistant Structure situated on slopping ground.

F. Progressive Collapse Analysis of Bridge structure subjected to Tsunami Forces.

G. Influence of Tsunami Forces on structure considering Soil Structure Interaction.

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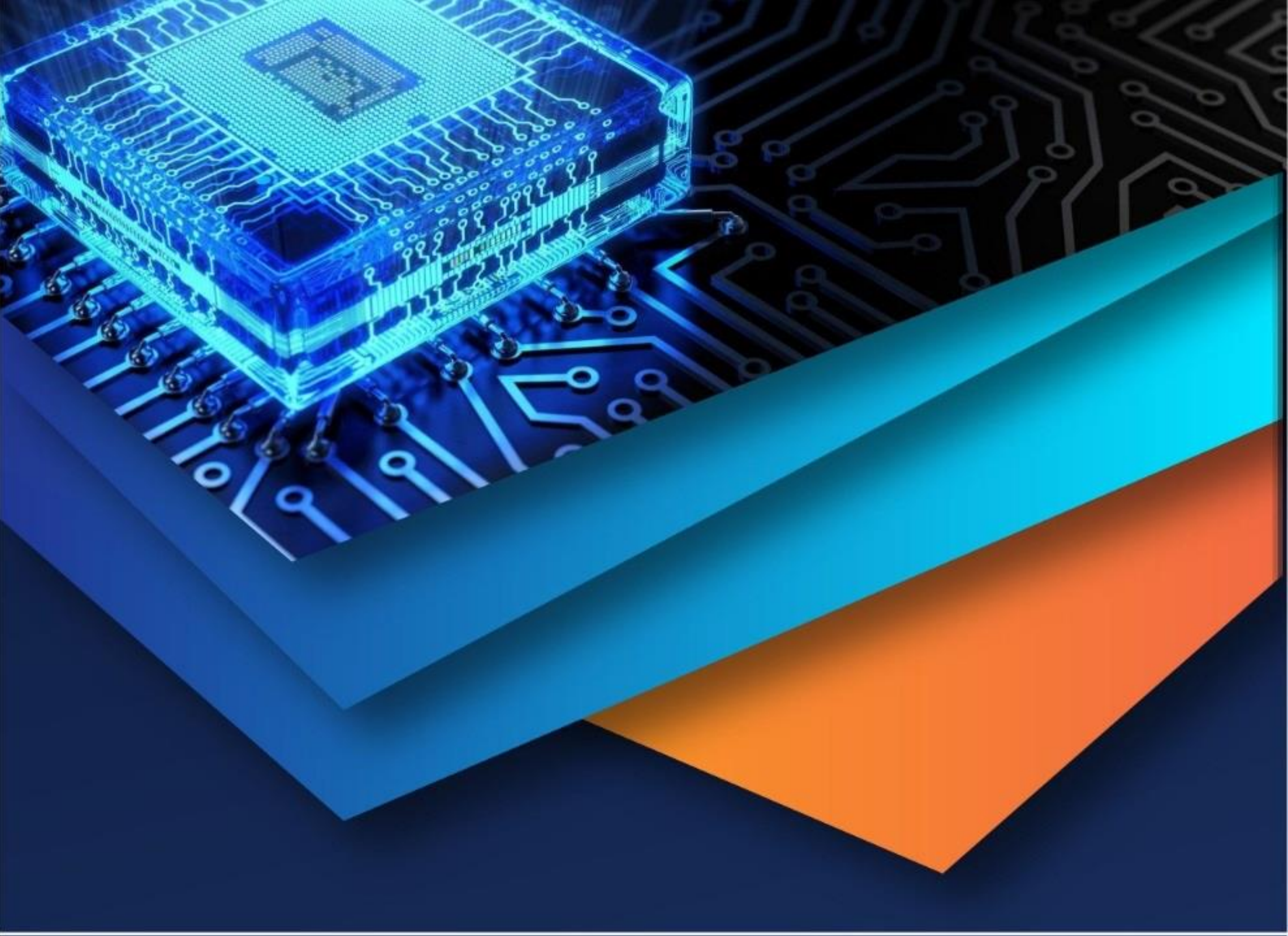

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