The Impact Analysis of RC Structures under the Influence of Tsunami Generated Debris

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Abstract

Tsunami resistant buildings, where the lower level is elevated by means of RC columns to allow the free flow of tsunami waves, recently constructed in many tsunami prone countries. However these columns are very vulnerable to impact due to water-borne massive debris. Tsunami field survey observations showed the building destruction is often exacerbated by the impact of tsunami water-borne massive objects such as automobiles, wooden logs, boats, empty storage tanks and shipping containers. This paper emphasis, the impact of tsunami water-borne massive objects (debris) on RC buildings which are located in the vicinity of the shoreline in Tsunami-prone coastal areas in India A G+3 frame model building is analyzed using software SAP2000v14 prior to impact simulation. Linear static analysis is conducted to investigate response from structural elements due to impact of wooden log. The study concludes, Small masses converted to large impact when speed of waves increases. Corner column of a building and impact above the water level is proved to be more vulnerable. Such buildings need an effective protection against debris to control simulation of heavy forces in structural columns.

Keywords: Tsunami, Debris, Wooden log, Impact force, displacements, Hydrodynamic force, and coast line structures, tsunami runup etc.

1. Introduction

The 26th December 2004, tsunami had worst affected communities situated along the coast line of the Indian Ocean including Sri Lanka, Thailand, The Maldives Islands and the littoral zones of several West African countries. The 26 December 2004 earthquake, which was 4th strongest earthquake recorded since 1900 (M 9.1) generated below the sea bed and resulted in vertical displacement of the sea floor. The displacement triggered a tsunami that killed almost 2, 30,000 people and cause billions of dollars in form of damage. People living on the coastline near the epicentre of the earthquake had very little time to move higher ground to escape. Asian tsunami took around 2 hrs to reach coast of Tamil nadu, Kerala, West Bengal etc. The tsunami heights observed in these states were ranges from 2 m to 5.5 m

The recent Tohuku earthquake and ensuring tsunami in Japan is one of the most catastrophic events in the history of tsunami events. On March 11, 2011 a Moment Magnitude of 9.0 earthquakes struck off the northern coast of Japan. This earthquake generated a tsunami that rose up to 41m above sea level and killed over 20, 000 peoples, devastating a widespread region and causing an estimated $ 300 billion in economic losses. The infrastructure of hundreds of cities and villages in the Indonesia, Thailand, Japan, India and Sri Lanka like countries was severely affected by the impact of the tsunami waves. Many of the structures was completely damaged and collapsed. Some of them toppled down due to high pressure tsunami waves.

The damaged caused by the tsunami clearly reveals inadequate design of columns, joints as well as retaining structures. The recent investigation of the 11 March 2011 Japan Tsunami had been revealed that the drifted objects by tsunami like wooden log, cars, small sized ships, shipping containers, floating wooden buildings etc increased damages on the buildings and structures

This paper focuses on the forces generated by the water born debris on structural elements. Study also highlights the critical position of column in the structural system when wooden debris hits the structure, this paper also emphasis on the critical location of impact load on a critical column of a structure. Fig.1 shows the recent photograph of tsunami driven debris in form of cars and boats in Japan 2011. This cars and ships float with water and strike the structure. Under this paper we studied the impact from wooden logs only.

"**Figure 1** boats and cars as debris in 11 March 2011, Japan Tsunami" *(Sourcehttp://www.thelargest.net)*

1.1 Impact of the Tsunamis on Indian landmasses

A) The impact of the tsunami was immediate and highest in the Andaman and Nicobar Island as they were lying on the tsunami source.

B) A maximum tsunami run-up height of 7 m was observed at Malacca in car Nicobar Island. The maximum tsunami run-up height is defined as the vertical water surface elevation reached by the tsunami above sea level.

C) The tsunami took about 150 min to reach the East coast of India. The worst affected was the coastline along *Tamil Nadu* coast, from Chennai in the north to Nagapattinam in the south. Relatively, the Andhra Pradesh coast suffered less.

D) The tsunami is reported to have encroached 500m to 2 km inland at various places owing to the flatness of several beaches. Tide gauge recorder at Vishakhapatnam port in Andhra Pradesh showed tsunami heights to be about 1.4 m at 09:05h *(IST)*.

E) The 350-km-long of the shoreline of *Tamil Nadu* state from *Pulicat* in the south was affected to varied degrees. The tsunami run-up height varied between 2.5 m and 4.5 m in these regions after applying tidal tables published by Survey of India.

1.2 Coastline Survey of Tamil Nadu State

We focused on Tamil Nadu coastline, in our study. This is the state which was affected more in the 26 Dec 2004 tsunami. The topography of Tamil Nadu coast indicates, the coastal line has flatter slope which has an elevation of 0.6 m to 1.5 m with respect

to the sea level. This means tsunami waves can travel very rapidly and gain maximum speed, thus increasing the level of damage and loss of human life in nearby areas. Fig.2 shows exact view of the shoreline in *Kalpakkam (Tamil Nadu)* Details of tsunami run-up surveys along the coast of Tamil Nadu is given in Table 1. This survey gives the idea about the maximum tsunami inundation in one particular area for calculation of tsunami forces for design of tsunami resistant structures (Evacuation Shelter) in future.

"**Figure 2** Kalpakkam (Tamil Nadu) in past 1980" *(Source – PWD Government of Tamil Nadu)*

On 26th Dec 2004 tsunami event, Tamil Nadu state faces waves of varying heights, these waves travel at a speed of 8.33m/sec. They carries fisherman boats, automobiles, wooden logs etc along with them and can reach max 1.2 km inland. An earthquake of M 8 or more in Indian Ocean will cause waves of 10-15 m in Tamil Nadu and Kerala. The structures located in this region must be properly designed to sustain not only earthquake but also the tsunami effect.

"**Table 1** Details of tsunami runup surveys along the coast of Tamil Nadu" *(Source – R. K. Chadha)*

Sr No	Location	Runup Elevation (m)	Lateral Inundation (m)
1.	Pulicat	3.2	160
2.	Pattinapakam	2.7	145
3.	Kovalam	4.3	180
4.	Kalpakkam	4.1	360
5.	Periakalapet	3.9	170
6.	Puttupatanam	2.6	-
7.	Devanaampatna	2.5	700
8.	Parangipettai	2.8	400
9.	Tarangambadi	4.4	400
10.	Nagapattinam	5.2	800

2. Tsunami Induced Forces and Codes

There is very little guidance provided by structural design codes for the forces induced by tsunami and their effects on coastal construction. A set of generalized equations were created from currently available building codes and published literatures, which contain information and recommended equations on flooding, breaking waves and providing a brief description, along with the existing analytical and empirical formulae to calculate each of the components. These forces are lateral hydrostatic force, buoyant force, hydrodynamic force, surge force, impact force, and breaking wave forces. This study deals with only two types of loading on structure due to tsunami; these are hydrodynamic forces and impact forces. *FEMA P646* and *CCH* give effective empirical formulae to calculate these forces.

2.1 Hydrodynamic force (F_D)

When the water flows around a structure, hydrodynamic forces are applied to the structure as a whole and to individual structural components. These forces are induced by the flow of water moving at moderate to high velocity, and are a function of fluid density, flow velocity and structure geometry.

$$F_D = \frac{1}{2} \rho \, C_D \, A \, u^2$$

Where,

F_D = Total drag force in direction of flow (KN),

C_D = Drag coefficient,

A = Projected area of the body normal to the flow direction (m^2),

u = Bore velocity or flow velocity at location of structure (m/s),

B = Breadth of the structure in the plane normal to direction of flow (m),

h = Flow depth (m) and

(hu^2) = Combination represents the maximum momentum flux per unit mass

$$(hu^2)_{max} = gR^2 \left(0.125 - 0.235 \frac{Z}{R} + 0.11 \left(\frac{Z}{R} \right)^2 \right)$$

Where,

g = acceleration due to gravity (m/sec^2),

R = design runup elevation (m) and

Z = ground elevation at the base of the structure (m)

2.2 Impact force (F_i)

A high-speed tsunami bore travelling inland carries debris such as floating automobiles, floating pieces of wooden buildings, drift wood, small boats, ships or any object transported by floodwaters, induces significant forces on a building, leading to structural damage or collapse. Estimating its magnitude is the most likely cause of error in the calculation because there are numerous variables that could affect this type of force.

These variables could range from an accurate estimate of the objects weight and duration of impact. The velocity and location of the waterborne object can be assumed equal to the flood velocity and the water surface level, respectively.

The estimation of impact force is governed by stiffness of both the debris and structure elements. The water born debris (woods, logs, cars, ships, etc) may have their own stiffness (stiffness depends on the dimensions of the member). This debris hits the structure or structural element in their travelling path and creates tremendous impact in the structure. This impact is absorbed or reduced by the stiffness of individual structural systems. *FEMA P646* considered the stiffness of these two objects in the calculation as effective stiffness.

$$F_i = C_m \, u_{max} \sqrt{K \, m}$$

Where,

C_m = Added mass coefficient,

u_{max} = Maximum flow velocity carrying the debris at the site,

m = Mass of the debris (Kg) and

k = The effective stiffness for the debris and impacted object.

It is recommended that the added mass coefficient be taken as Cm = 2

$$u_{max} = \sqrt{2gR \left(1 - \frac{z}{R} \right)}$$

u_{max} Depends upon the location of building and topography of the shoreline, this velocity is for light weight debris, which can move rapidly with water.

Here,

g = Acceleration due to gravity = 9.81 N/sce^2

R = Design runup height = $1.3 \times R^*$

Z = Ground elevation at the base of structure

The velocities of water borne objects are assumed to be the same as the flood velocity. The object is assumed to be at or near the water surface level when it strikes the building. Unlike other forces, impact forces are assumed to act locally on a single member of the structure at the elevation of the water surface, as shown in Fig.3
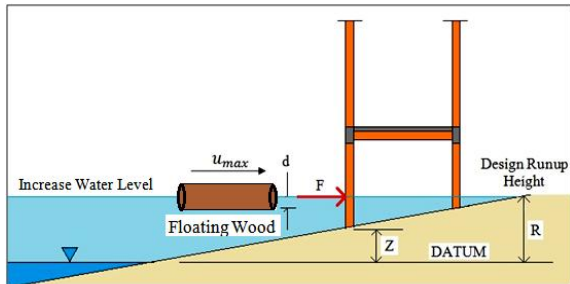
"Figure 3 Phenomena and location of debris impacting a structure"

The magnitude of the debris impact force depends on mass and velocity. Smaller (lighter) debris requiring little or no draft to float and can travel at higher velocities but larger (heavier) debris requiring larger depths to float, so travel with less velocities. Use of maximum flow velocity without consideration of the depth required to float large debris would be unnecessarily conservative.

Debris impact forces should be evaluated considering the location of the structure and potential debris in the surrounding area. For example, it is likely that floating debris would consist primarily of driftwood, logs and pier pilings for most coastal towns, whereas for some large port areas, the debris could be shipping containers. Locations near yacht marinas or fishing harbours should consider possible impact from boats that break their moorings

The equation given by *FEMA* requires the mass and stiffness properties of the debris. The approximate values of *m* and *k* for common waterborne debris are listed in Table 2 Mass and stiffness properties for other types of debris will need to be derived or estimated as part of the design process.

2.3 Recommendation by FEMA P646

Debris impact forces F_i are short duration loads, due to impact of large floating objects with individual structural components. Since large floating objects are not carried by the leading edge of the surge, the effect of the debris impact is combined with hydrodynamic drag forces, F_d but not impulsive (Surge) forces F_s. Although many floating objects may impact a building during a tsunami event, the

probability of two or more impacts occurring simultaneously is considered small. Therefore, only one impact should be considered to occur at any point in time. Both the individual structural component and the overall structure must be designed to resist the impact force in combination with all other loads (except impulsive forces)

Fig.4 shows the application of above forces on a building or structural element.

"**Table 2** Mass and stiffness of some water born debris *(FEMA P646)*"

Sr. No	Type of debris	Mass, (Kg)	Effective Stiffness (N/m)
1	Lumber or	450	2.4×10^6
2	Family cars	1500	3.10×10^7
3	Small boats	1550	3.05×10^7
4	20-feet Shipping Containers	2200	1.5×10^9
5	40-feet Shipping Containers	3300	6.5×10^9

2.4 Dimensions and mass of debris

The nature of debris depends upon the location of building and surrounding area. If building is located in ship yard area then most probable debris are shipping containers, wooden houses collapse due to water pressure and moves with water as impact missile, in a city area the family cars floats with water and hits the structure *(observed in Dec. 2004 Asian Tsunami and 11 March 2011 Japan Tsunami).* Table 3 gives mass and dimensions of general observed debris near shoreline of tsunami prone areas
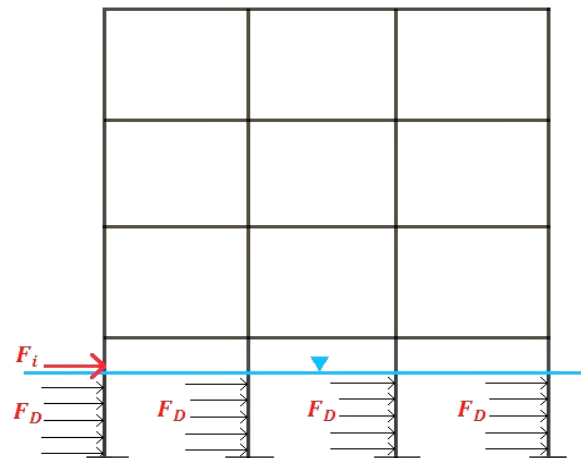
"**Figure 4** Application of design forces on building."

"Table 3 Dimensions and mass of water born debris"
(www.google.co.in)

| Debris (Wooden Logs)	Dimensions and Weight (Kg)
	5.5 m ✕ 0.25 m
	6.5 m ✕ 0.30 m
	8.5 m ✕ 0.35 m
	Weights
	450 to 650 Kg

3. Modelling Parameters

To study the behaviour of structural elements of a building when subjected to tsunami water born debris impact loading in a tsunami event, a G+3 storey building is considered. The building is a Hotel Building which is situated very close to shore line *(600 m from shore line)*, keeping longer side parallel to shoreline.

The study focuses on the point, weather the designed building as an earthquake resistant structure can resist the impact of tsunami driven debris and the adequacy in the behaviour of structural elements particularly columns on ground floor. We will use a *SAP2000 v14* for analysis of the structure against debris impact forces. Static linear analysis is carried out for different cases. Displacement and base shear of structure for different types of debris studied.

From geological investigation, the coastline along Tamil nadu has a flatter slope. The ground elevation available near shoreline is only 0.6 m – 1.5 m. For study purpose we keep the ground elevation as 1 m (Z =1 m).

3.1 Model Configuration

The proposed model plan for study is shown in fig.5
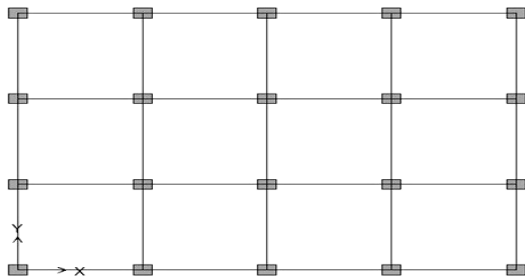
"**Figure 5** Model plan considered in the study"

Plan dimension of structure = 20 m × 12 m
No of bays in X-direction = 4
No of bays in Y-direction = 3
Spacing of bays in X-direction = 5 m
Spacing of bays in Y-direction = 4 m
Height of all typical floors = 3.4 m
Height of ground floor (Parking) = 2.5 m
Height of parapet wall = 1 m (all around the periphery of roof floor)
No of Columns = 20
Type of foundation – Isolated footing

3.2 Loadings Considered in Analysis

Loadings and loading combinations are considered as given in *IS 1893-2002 (Part-I)*

1. Dead Load
2. Live Load on Typical floors – 4.5 KN/m^2
3. Live Load on Terrace – 2 KN/m^2
4. Tsunami waves parallel to longer side

The parameters essential for tsunami analysis based on location of structure are listed in Table 5 with reference to *FEMA P646*.

3.3 Sizes of Structural Members and Material Specifications

The sizes of structural components to serve as an earthquake resistant structure are prescribed in Table 4. The safety of members was checked under *SAP 2000 v14*. This implies the structure constructed near shoreline area is somehow safe against earthquake forces.

The concrete and steel used in the study had a grade M30 and Fe 415 respectively.
Concrete density was taken as 25 KN/m^3 and that of infill wall was 20KN/m^3. The modulus of elasticity of concrete 27386 N/mm^2 and that of infill wall 8800 N/mm^2 *(based on Tamil Nadu State brick quality)*, the poisons ratio for concrete and infill was 0.2 and 0.15 respectively.

Table 5 gives the possible tsunami height available in the area around the building. Under this study we took only two heights of tsunamis acting on a structure. The first height is 2.25m which is based on 2004 tsunami event and 4.85m which is in future, if tsunami will take place.

"**Table 4** Location and sizes of the structural elements

Sr. No	Structural Member	Size
1	Columns on GF	500 mm × 350 mm
2	Columns on Typical Floors	550 mm × 350 mm
3	Beams on Ground Floor	500 mm × 300 mm
4	Beams on Typical Floors	300 mm × 250 mm
5	Thickness of slab	150 mm
6	Exterior and Interior wall thickness	230 mm

"**Table 5** Values of Inundation height and tsunami height for building elevation (Z=1)"

Values of 'R*'	Design values of 'R'	Tsunami Height (m)
2.5	3.25	2.25
3.0	3.90	2.90
3.5	4.55	3.55
4.0	5.20	4.20
4.5	5.85	4.85
5.5	7.15	6.15
6.0	7.80	6.80
6.5	8.45	7.45
7.0	9.10	8.10
7.5	9.75	8.75

4. Structural Problem

Debris travels along with the sea water and acquire same velocity that tsunami wave has. These floating debris can move anywhere without a particular direction. They strike the obstacles in there travelling path and creates tremendous impact on the surface of the obstacle. We didn't have any idea regarding their location of impact and amount of impact. When debris hits the structure forces are generated in the member and the amount of forces depends upon the location of impact. Here we can locate the critical column in our model by considering impact in all possible 3 ways along longer side.

We considered a wooden log as debris, which flows with water and hits the structure at different locations

as shown in fig.6. We apply the impact at the centre, next to centre and corner column of modelled structure. The critical location among the three is decided based on the axial thrust developed in the column, bending moments developed in columns and the shear capacity of the column.
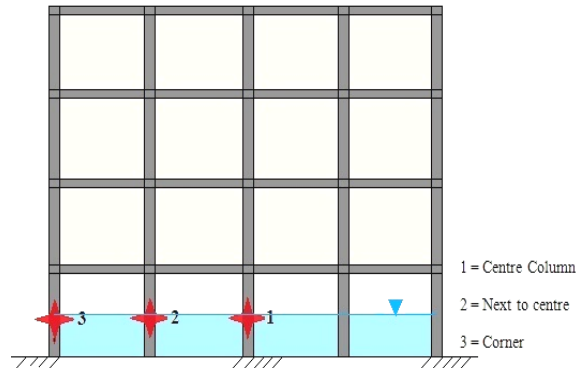

"**Figure 6** Different locations of impact in a structure"

To study the performance point of the structure when subjected to the impact force is one of the important parameter. In that study we can apply the impact force on different locations on one of particular column element, which is most critical from previous results. Debris may hit the structure exactly on the same point at the available water level or may be it differs by some margin in hitting the structure as above or below the water level. *CCH* suggested that the debris with draft may hit the structure 0.5 m above or 0.5 m below the existing water level. We applied the impact load at water level and 0.5 m below and above water level i.e. at 1.75 m and 2.75 m on column element and observed the behaviour of column with reference to displacements, bending moment and shear forces.

4.1 Modelling in SAP 2000 v14

The structure is modeled using *SAP2000 v14*, the structural properties and loading are defined as per *IS 456-2000* and *IS 1893-2002 (Part-I)*. The infill walls are modeled as equivalent diagonal strut. The impact load from debris is applied only on a single element of the structure. This load acts as a point load in the direction of tsunami waves. Hydrodynamic load is always acting with water on all structural components. This may be acting as a uniformly distributed load on each element of structure as shown in fig.7
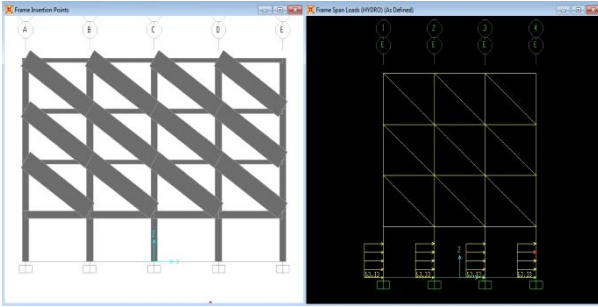
"**Figure 7** Modelled building with infill walls and loadings in SAP2000 v14"

5. Results and Discussions

For comparison between different components of a structure (Columns), some of the critical columns by primary observations are selected and their locations are shown in the fig.8
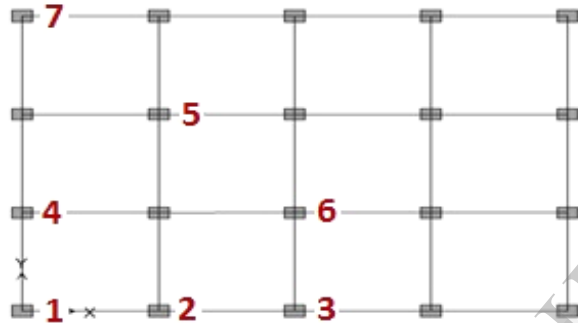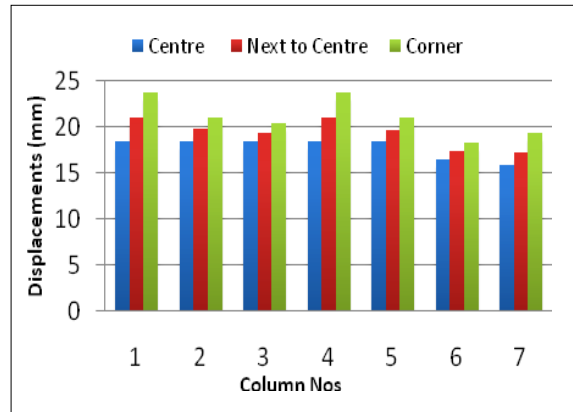

"**Figure 8** Location of different columns considered in the study"
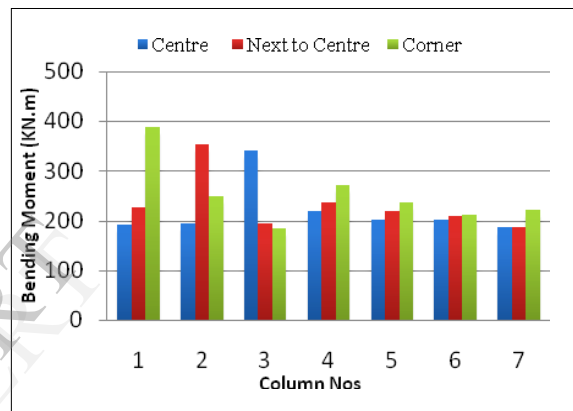
5.1 Different forces developed for 2.25 m Tsunami waves

Fig.9 to Fig.14 shows all graphical results
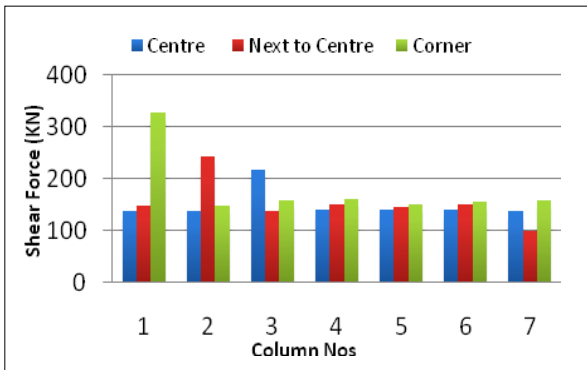
"**Figure 9** Shear forces developed in columns"

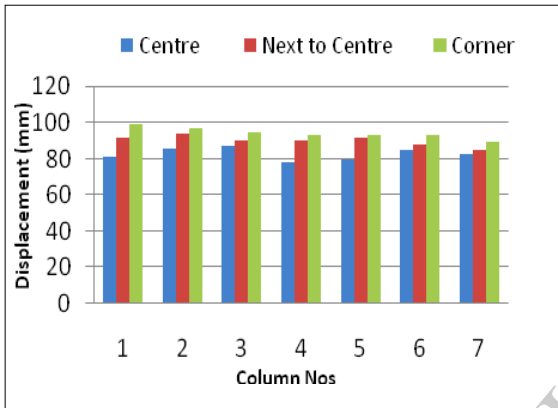"**Figure 10** Displacements developed in columns"

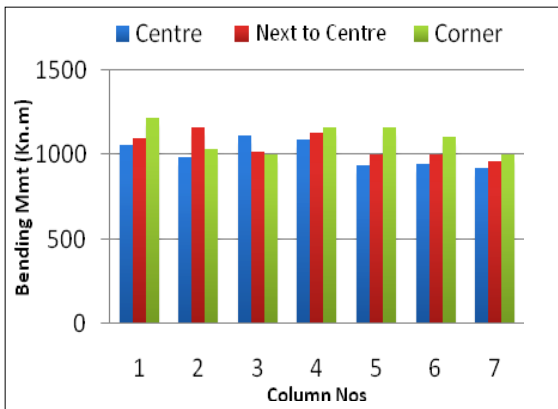"**Figure 11** Bending moments developed in columns"

Hydrodynamic forces are acting on every component of structure but impact forces applied on only particular member. We applied impact force on central column of building (3), next to centre (2) and on corner column (1) of a building. The analysis results gave shear force *(SF)*, displacements *(D)* and bending moment *(BM)* generated in selected column against impact forces. When an impact force is applied at central column (No-3 in fig. 8), all SF, D and BM are maximum only for applied column, but when similar force is applied on corner column (No-1 in fig. 8), of a building all forces are maximum not only in applied column but also in all columns of a building. Similar results we obtained when the tsunami height is 4.85m and impact occurs at this water level on different columns considered in the study.
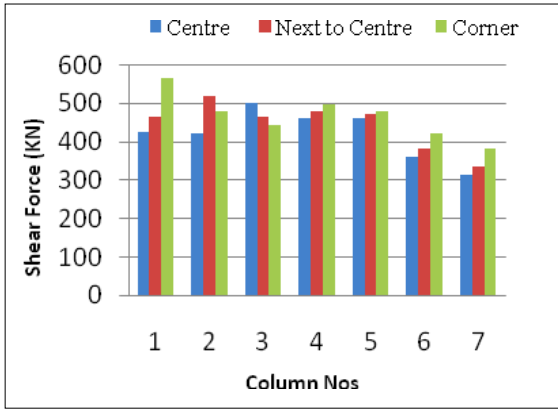
**"Figure 12** Shear forces developed in columns for tsunami height 4.85 m"

"Figure 13 Displacements developed in columns for tsunami height 4.85 m"

"Figure 14 Bending moments developed in columns for tsunami height 4.85m"

The graphical plots clearly indicates when impact occur on corner column (No-1 in fig.8) of a building all forces in members are maximum, which implies the corner columns of a building are more critical. We found the percentage increase in the forces in columns for different locations of impact.
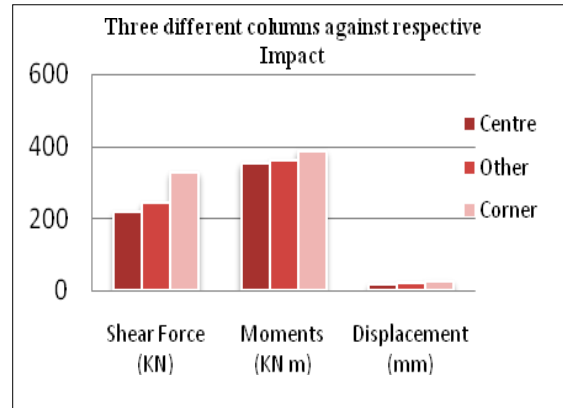

"Figure 15 Forces in three different columns for same impact load (Wooden log)"

The average percentage increase in the forces on corner column over other column is calculated. This increase implies corner columns are more critical than any other column of a building against tsunami generated debris impact.

5.2 Critical point for application of the impact load on column.

Under this study we analyzed GF critical column (corner column) against impact load for three different locations on column. The locations are considered 0.5 m above and 0.5 m below the existing water level in tsunami event *(CCH)*. The comparative study is based on the forces generated in member such as shear force, bending moments and displacements.

The results showed that, the forces are maximum when impact at 2.75 m (i.e. 0.5 m above water level). Some forces like shear force and bending moments are maximum when impact is at 1.75 m (i.e. 0.5 m below water level), but this is only for impacted column. When we deal with whole building geometry it was found that, forces in other members are more when impact is at 2.75 m on corner column. So we conclude that, for whole structural behaviour critical impacting location is 0.5 m above the tsunami water level.
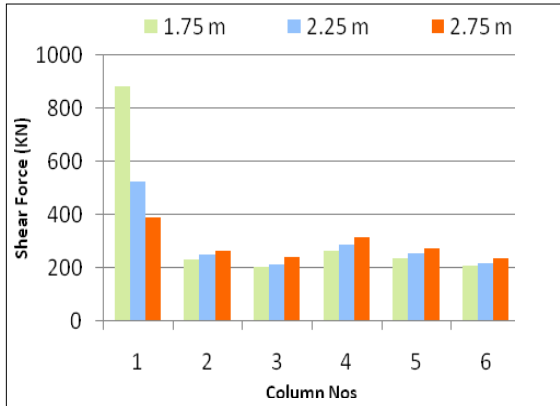
"**Figure 16** Shear forces in columns for different
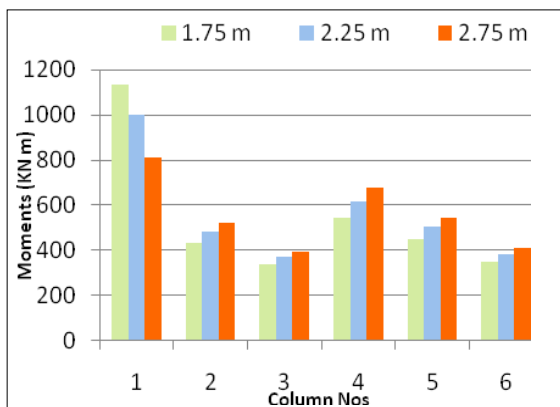
location of impact"

"Figure 17 Bending moments in columns for different
location of impact"

"**Figure 18** Displacements in column for different
location of impact"

5.3 Increase in forces when impact is at 0.5 m above water level

We studied the impact location 0.5 m above the tsunami water level on corner column is more critical.
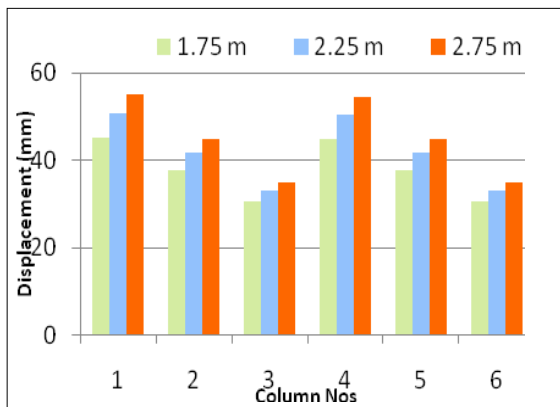
This location (2.75 m) acquires more forces not only in corner column but also on other columns of a building. Here we found the percentage increase of forces in column no 4 (Behind the corner column of a building) against impact on corner column at 2.75 m over other two locations of impact (1.75 m and 2.25 m).

The amount of Shear force and displacement increases by same percentage as *12%,* but bending moment in the members increases with little bit higher percentage as *14%.* This increment shows that, when impact location is above water level the forces are increases in all other structural members of a building. Fig 19 shows the difference in the forces at column no-4, for three different impact locations on a single corner column of a building.
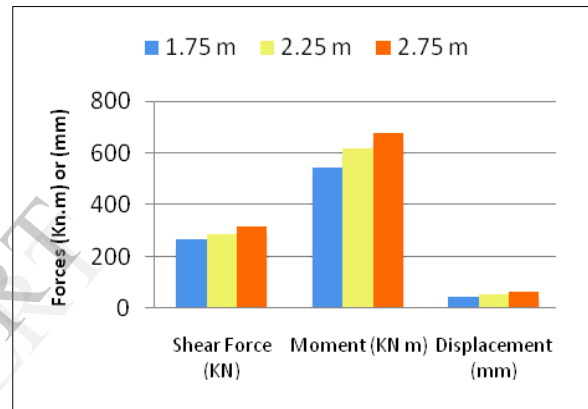
"**Figure 19** Forces in column no-4 when impact at
corner column"

6. Conclusions

Based on the observations from response of reinforced concrete structural elements to the debris impact loads through different cases the following concluding remarks have been arrived.

1) In case when impact is at first floor, the forces in ground floor column are increases with *60%* increase in axial force, *75%* increase in bending moments, *11%* increase in shear forces, but displacements increases only *1.5%,* this means both columns deforms simultaneously with same magnitude.

2) The corner columns of a building are more vulnerable to debris impact forces (Wooden log). When we compare three different columns of a building, axial forces increases by *46%,* bending moments increases by *8%,* shear forces increases by *30%* and

displacements increases by *24%* in corner column over other columns.

3)   The impact at 0.5 m above water level is more critical point on a structural element for application of impact force. Impact at this point increases the forces in all other columns of a building with increase in *9%* in a axial force, *14%* in bending moments, *12%* in both shear force and displacements over other two locations of impact, (at water level and 0.5 m below water level)

4)   Impact on a central column of a building develops nearly same amount of forces in all columns, this implies that, symmetry of a structure also plays a vital role in reducing the tsunami driven debris impact forces along with hydrodynamic forces.

5)   Small to medium height reinforced concrete frame buildings, with considerably small sizes of structural elements may result in failure of column due to impact forces (negative nature forces are developed)

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