Chapter 1

Vulnerability of Reinforced Concrete Structures Subjected to Flood

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Additional information is available at the end of the chapter

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1. Introduction

Floods are one of the most widespread and destructive natural disasters occurring in the world (Singh and Sharma 2009), and with the increase in constructions along river courses and concentration of population around floodplain areas, flood-induced damages have been continuously increasing. The annual disaster record reveals that flood occurrence increased about ten folds over the past five decades (Scheuren et al. 2007). Thus, floods are posing a great threat and challenge to planers, design engineers, insurance industries, policy makers, and to the governments.

Structural and non-structural measures can be used to deal with floods (Sagala 2006). Structural measures include a set of works aiming to reduce one or more hydraulic parameters like runoff volume, peak discharge, rise in water level, duration of flood, flow velocity, etc. Non-structural measures involve a wide range of measures to reduce flood risk through flood forecasting and early warning systems, emergency plans, and posing land use regulations and policies. The futuristic reinforced concrete buildings can be considered as a symbol of modern civilization. These buildings are usually constructed based on the guide lines given by the standard code books (like IS:456:2000, for India). Unfortunately, the code provisions consider the seismic loads and wind effects alone, while accounting the dead and live design loads, and exclude the flood loads. This implies the necessity to bring out corrective measures that can be adopted to reduce vulnerability before harm occurrences.

This chapter focuses on both the incorporation of flood loads during the design stage and the assessment of flood vulnerability of reinforced concrete buildings. Vulnerability is expressed as a fraction of ground floor height and assumes that flood water at most immerse the building up to ground floor level. The importance of the outcome arises from the need of a strengthening solution to avoid failure of new or existing structures during floods.

1.1. Forces due to flood

The physical forces which act on the buildings include hydrostatic loads (Fig.1.), hydrodynamic loads (Fig.2.), and impact loads, and these loads can be exacerbated by the effects of water scouring soil from around and below the foundation (FEMA, 2001). The *hydrostatic loads* are both lateral (pressures) and vertical (buoyant) in nature. The lateral forces result from differences in interior and exterior water surface elevations. As the floodwaters rise, the higher water on the exterior of the building acts inward against the walls of the building. Sufficient lateral pressures may cause permanent deflections and damage to structural elements within the building. The buoyant forces are the vertical uplift of the structure due to the displacement of water, just as a boat displaces water causing it to float. These uplift forces may be the result of the actual building materials (the floating nature of wood products), or due to air on the interior of a tightly built structure. When the buoyant forces associated with the flood exceed the weight of the building components and the connections to the foundation system, the structure may float from its foundation.

The water flowing around the building during a flood creates *hydrodynamic loads* on the structure. These loads are the frontal impact loads from the upstream flow, the drag on the sides of the building, and the suction on the rear face of the building as the floodwaters flow around the structure. The magnitude of the hydrodynamic loads depends on both the velocity of water and the shape of the structure. Like the hydrostatic pressures, these lateral pressures may cause the collapsing of either structural walls or floors.

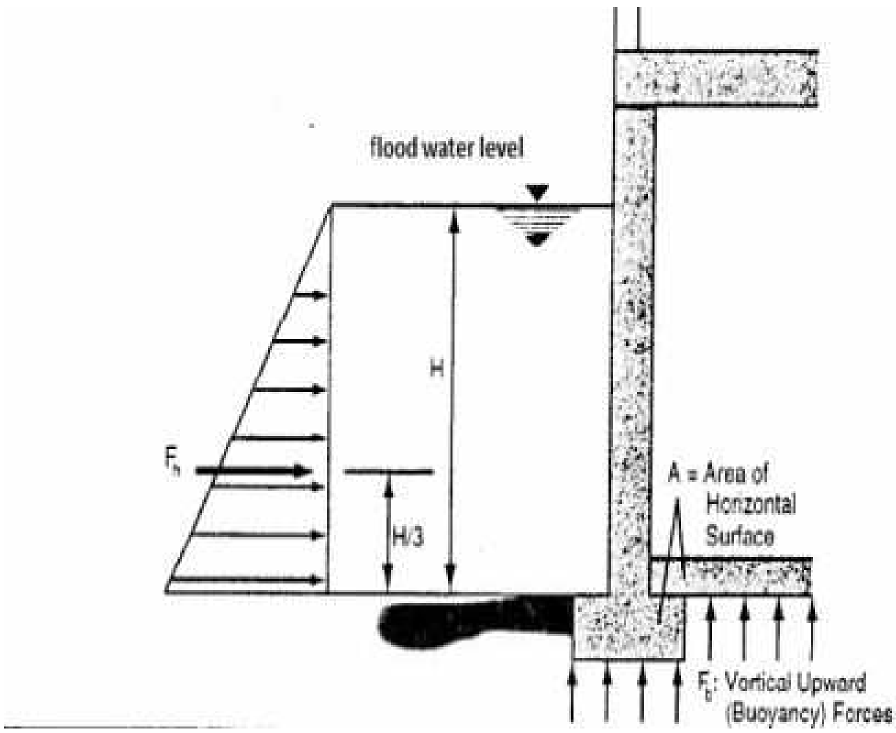

Figure 1. Schematic sketch of hydrostatic force (FEMA, 2001)

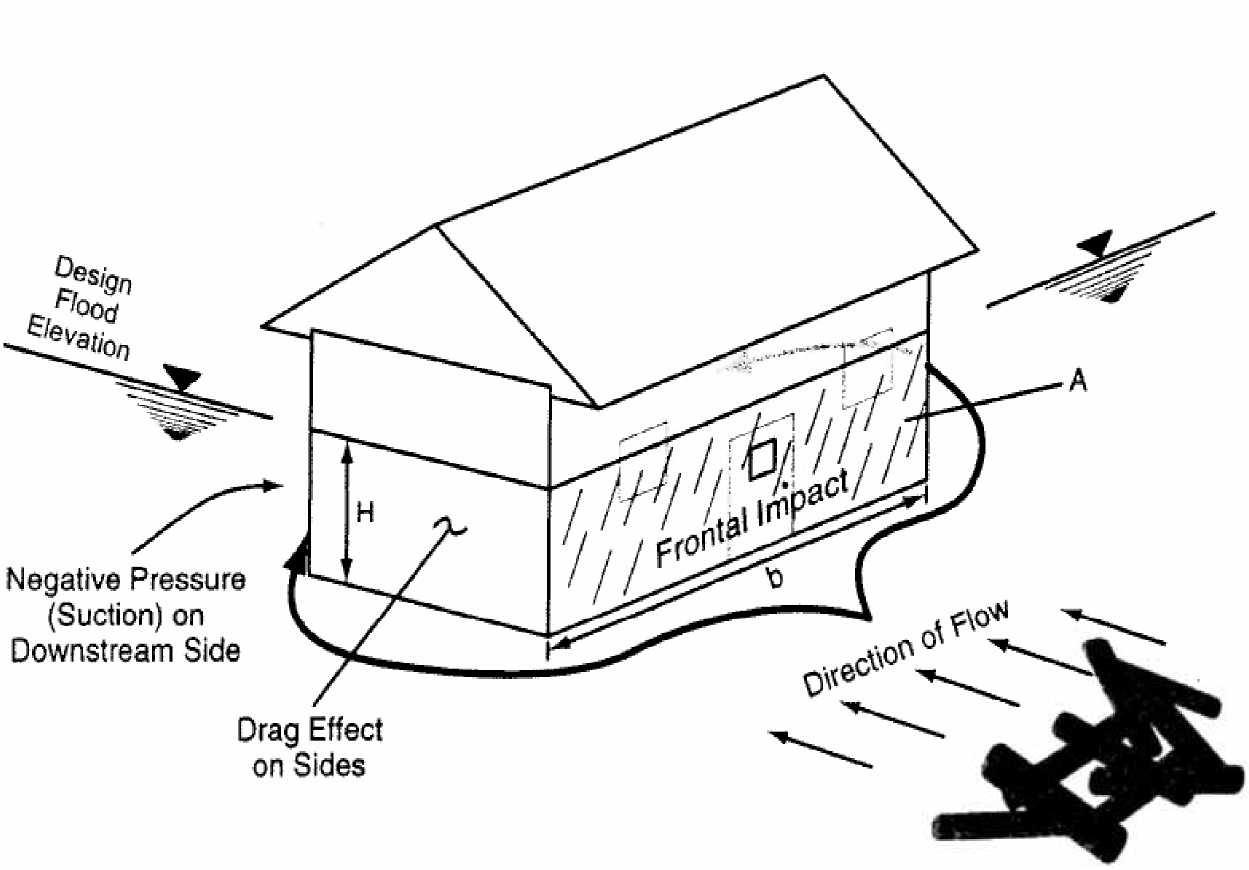

Figure 2. Schematic sketch of hydrodynamic force (FEMA, 2001)

Impact loads during floods may be the direct forces associated with waves, as typically encountered during coastal flooding, or the impact of debris floating in the waters, including logs, building components, and even vehicles. Impact loads can be destructive because the forces associated with them may be an order of magnitude higher than the hydrostatic and hydrodynamic. Floating debris can have devastating effects, as they apply large and/or concentrated loads to the structural elements of the building.

2. Literature review

FEMA (2001) published a manual focusing on the retrofitting of family residences subject to flooding without wave action. The measures include elevation of the structure in place, relocation of the structure, construction of barriers, dry flood proofing and wet flood proofing. The analyses necessary to determine flood-related hazard factors are also presented.

Kelman (2002), in a dissertation on Physical Flood Vulnerability of Residential Properties in Coastal Eastern England, examined the lateral pressure from flood differential depth between inside and outside a residence.

Kelman and Spenc (2004) categorised flood actions on buildings as energy transfers, forces, pressures, or the consequences of water or contaminant contact.

Messener and Meyer (2005) argued that the challenge consists in understanding the interrelations and social dynamics of flood risk perception, preparedness, vulnerability, flood damage and flood management, and to take this into account in a modern design of damage analysis and risk management.

Sagala (2006) examines the physical vulnerability to flood and people's coping mechanisms in flood prone residential areas in Naga city of Philippines. Six structural types of buildings were chosen and for each type of vulnerability curves (flood depth/damage) were plotted. Results indicate that buildings with plywood walls and wooden floors are the most vulnerable while the type with hollow block walls and concrete floors is the least vulnerable.

Arulselvan et al. (2007) conducted an experimental investigation on the influence of brick masonry infill in a reinforced cement concrete frame and validated outcomes by comparing them with theoretical results obtained by finite element analysis. Until the cracks developed in the infill, the contribution of infill to both stiffness and lateral stiffness was found to be very significant. The strains measured in infilled beams and columns were 20% less than bare frame beams up to failure of brick walls.

Haugen and Kaynia (2008) presented a method for prediction of damage in a structure impacted by a debris flow of known magnitude. The method uses the principles of dynamic response of structures to earthquake excitation, and fragility curves proposed in HAZUS for estimation of the structural vulnerability, by the damage state probability. The model was tested on a debris flow in Italy and it gave probabilities between 34% and 66% for reaching the damage levels which actually occurred for five out of six structures.

Kreibich et al. (2009) investigated the importance of flow velocity, water depth and combinations of these two parameters on various types of damages to buildings and roads. A significant influence of flow velocity on damage to roads was found, in contrast to a minor influence on monetary losses and business interruption. The energy head is suggested as a suitable flood impact parameter for reliable forecasting of structural damage to residential buildings.

Lopez et al. (2010) developed a methodology to estimate flood vulnerability to buildings, in either riverine or coastal settings, based on the aggregated damage to individual building components. Building vulnerability is modelled based on analytical representations of the failure mechanisms of individual building components.

3. Methodology

The present work focuses on the assessment of flood physical vulnerability of building expressed as a factor of ground floor height. The influence of design variation zones or boundary conditions has been also investigated. The methodology is schematized in Fig.3.

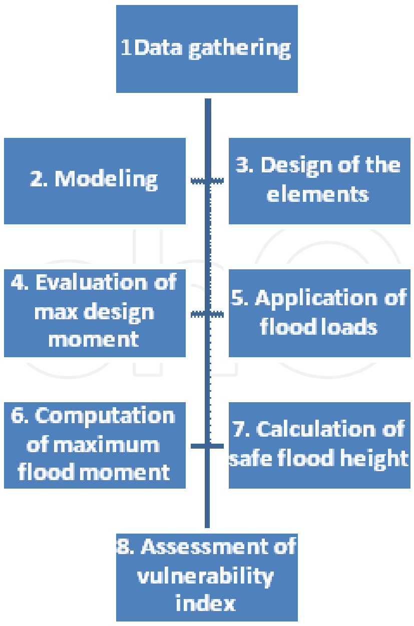

Figure 3. The steps of the methodology

3.1. Building details

The building configuration used for the study is regular, with plan dimensions 9m×18m. Table 1 lists the data associated with a four storey reinforced concrete building considered for the analysis, while the plan and elevation of the building are shown in Fig.4. and Fig.5., respectively. In Fig.4., the direction of interest refers the perpendicular direction of flood.

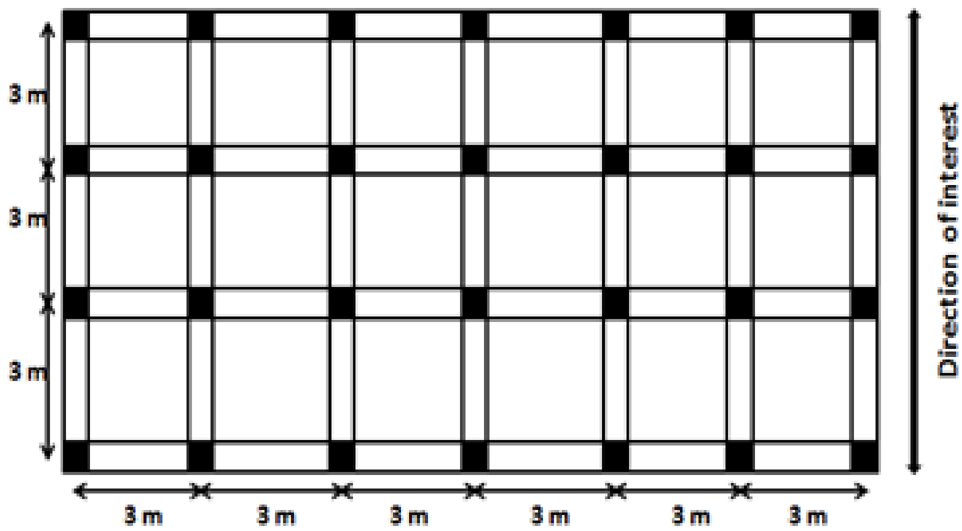

Figure 4. Plan of considered building

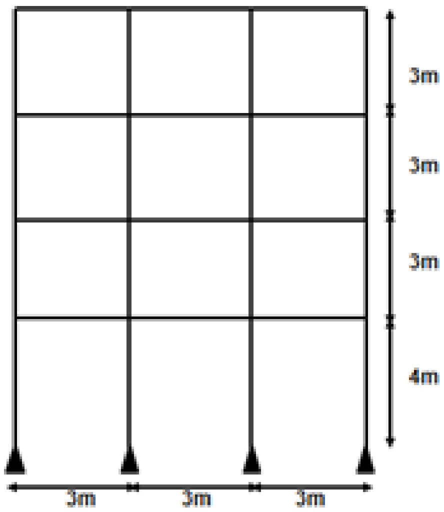

Figure 5. Elevation of frame

Ground floor height	4m
Remaining floors height	3m
No. of bays in X direction	6
No. of bays in Y direction	3
Bay width	3m in both X and Y directions
Column size	300mmx300mm
Beam size	250mmx300mm
Masonry wall thickness	230mm
Slab thickness	120mm
Unit weight of the concrete	25 kN/m^3
Unit weight of masonry	20 kN/m^3
Elastic modulus of steel	2×10^8 kN/m^2
Yield strength of steel	415 N/mm^2
Young's modulus of concrete	25×10^6 kN/m^2
Poisson ratio of concrete	0.2
Compressive strength of concrete	20 N/mm^2
Young's modulus of masonry	13.8×10^6 kN/m^2
Poisson ratio of masonry	0.25
Floor finish load	0.5kN/m^2
Terrace water proofing (TWF) load	1.5kN/m^2
Live load on roof	1.5kN/m^2
Live load on floor	3kN/m^2

Table 1. Reinforced concrete building details

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3.2. Modelling

To compute the critical effect, the flood was assumed to act along the 18m side and an intermediate 2D frame along 9m side was considered for the study. Three frame models were used, a) bare frame model, without any partition walls (Fig. 6.); b) frame with light weight partition wall; c) frame with structural infill wall (Fig. 7.). The infill walls were modelled as a diagonal strut having width 230mm, very low moment of inertia, modulus of elasticity 13800 N/mm^2 and Poisson ratio 0.25. The weight of light weight partition walls were considered negligible. Hence, frame models for both bare frame and frame with light weight partition walls were similar but the difference will come in to the picture while applying flood load.

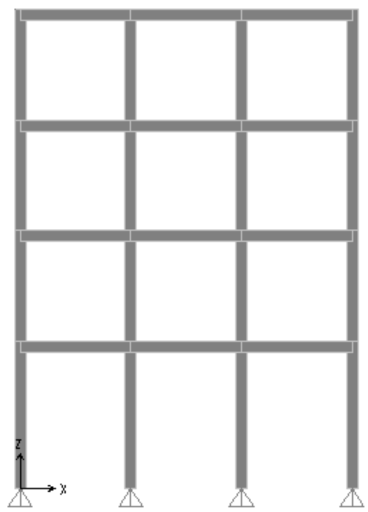

Figure 6. Bare frame SAP model

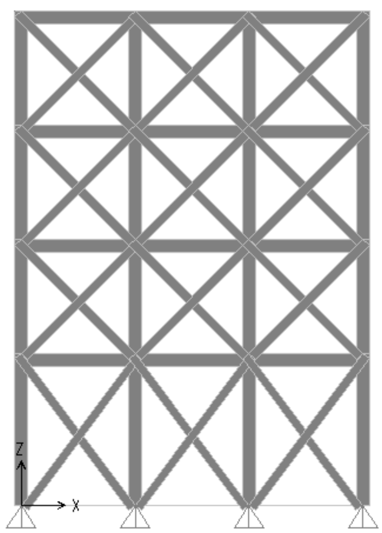

Figure 7. Frame with structural infill walls

3.3. Analysis

The procedure consists of linear static and linear dynamic analysis. When the linear static or dynamic procedures are used for seismic evaluation, the design seismic forces, the distribution of applied loads over the height of the buildings, and the corresponding displacements are determined using a linearly elastic analysis. The various steps involved in SAP model analysis are the following:

- Modelling of frame sections.
- Defining and assigning material properties and section properties.
- Assigning support conditions.
- Defining and assigning load patterns and load cases.
- Assigning load combinations.
- Setting up of analysis option.
- Running analysis.
- Inferring the results.

The load combinations considered for the study are:

a) 1.5 (DL + IL) b) 1.2 (DL + IL ± EL)

c) 1.5 (DL ± EL) d) 0.9 DL ± 1.5 EL

Analyses were carried out for six different conditions of seismic zones, flood duration, flood water height, flood forces, frame models, and support conditions, to obtain the maximum design moment, flood moment and lateral displacements.

3.4. Calculation of design moment

The earthquake load calculations were made for all the zones and all the models analysed, and designed for IS 456:2000. Here, the earthquake zones are considered to demonstrate the different structural variations but not the multi-hazard conditions (Table 2). The design moment is lower for fixed support condition than hinged condition.

Seismic zone	II	III	IV	V
Seismic intensity	Low	Moderate	Severe	Very severe
Z	0.1	0.16	0.24	0.36

Table 2. Zone factor (Ref. IS 1893-2002)

3.5. Calculation of flood loads

Flood loads are assumed to act as: a) hydrostatic loads; b) impact loads as equivalent static loads; c) impact loads as dynamic loads, considering the duration of flood. The hydrostatic loads consist of both lateral pressures and buoyancy forces. Lateral pressure is calculated using the formula $P_s = \gamma\ h_f$ (in kN/m^2), where γ = 9.81 kN/m^3 for water, and h_f is the water depth in meters. Since lateral hydrostatic loads are acting as triangular loads, the resultant hydrostatic load (F_f) acts at $h_f/3$ distance from ground level. Buoyancy force has a significant effect either if the building is surrounded by water or in submerged condition. Here, the flood is considered as slow moving; hence the effect of buoyancy is neglected. Impact loads are velocity dependent loads. As no codes or design books are available for incorporating the impact effects, the magnitude of these loads is arbitrarily considered as a factor of hydrostatic force acting laterally as UDL over the surface. Table 3 shows the magnitude of flood loads acting on the column for the frame models.

h_f (m)	F_f (kN)	Impact UDL (kN/m)	
		$0.1\gamma h_f$	$0.2\gamma h_f$
2	5.89	0.59	1.18
3	13.24	0.88	1.77
4	23.54	1.18	2.35

Table 3. Flood loads on frame models

The flood loads are assumed as dynamic loads by considering the duration of flood t_d. The dynamic displacement and dynamic flood moment are found using a deformation response factor (R). R is the ratio dynamic to static displacement caused by the flood force. The dynamic flood load is assumed as a rectangular pulse (Fig.8.).

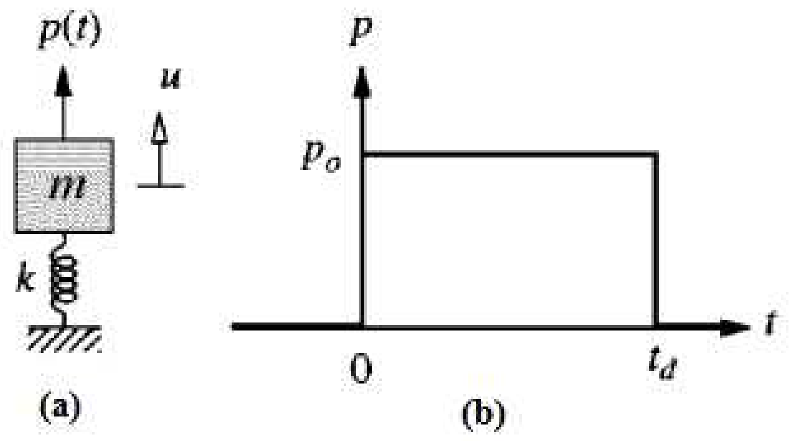

Figure 8. a) SDF system (b) Rectangular pulse load (Chopra, 2009)

The governing equation is:

$$m\ddot{u} + ku = p(t) = \begin{cases} p_0 & t \leq t_d \\ 0 & t \geq t_d \end{cases} \tag{1}$$

The R value obtained after solving the equation 2 is (Chopra 2009):

$$R = \frac{u}{u_{st}} = \begin{cases} 2 \sin \pi \frac{t_d}{T_n} & \frac{t_d}{T_n} \leq \frac{1}{2} \\ 2 & \frac{t_d}{T_n} \geq \frac{1}{2} \end{cases} \tag{2}$$

Where, u is the dynamic displacement, u_{st} is the static displacement, t_d is the flood duration and T_n is the fundamental natural time period of the structure. The t_d/T_n ratios and corresponding R values used are shown in Table 4. R = 1 indicates the flood as static while R = 2 indicates suddenly applied flood load. Since the flood assumed for the study is slow moving, R will always lies in between 1 and 2.

t_d/T_n	1/6	1/4	1/3	1/2
R	1.000	1.4142	1.7321	2.000

Table 4. Deformation response factor

3.6. Calculation of flood moment and height

Afterwards, analyses have to be carried out for different frame models in each zone with different boundary conditions, and the maximum flood moment in each case must be evaluated. The safe flood height is the height of flood up to which the structure is safe. It is obtained by plotting the moment due to hydrostatic force versus flood height: height corresponding to the design moment gives the safe flood height (h_f, safe).

The vulnerability index is assessed as a factor of ground floor height. It indicates the extent of damage that a flood can cause if the water reaches up to ground floor height. It is calculated using the equation (3).

$$Vulnerability\ index = \frac{ground\ \ floor\ height\ \text{-}\ safe\ \ flood\ height}{ground\ \ floor\ height} \tag{3}$$

4. Experimental results

The analysis was carried out for three frame models under different conditions of:

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- Flood loadings: static, equivalent static, and dynamic loads;
- Support conditions: hinged and fixed;
- Seismic zones;
- Flood water height: 2m, 3m and 4m;
- Flood duration: $T_n/6$, $T_n/4$, $T_n/3$ and $T_n/2$.

For each zone, earthquake loads were assessed for all the zones and all the models designed for IS 456:2000. The earthquake zones (Table 5) are considered to demonstrate the different structural variations but not the multi-hazard conditions. The maxima design moments for both the bare frame and the frame with light weight partition walls are similar, since the weight of partition wall is considered as negligible. The sizes of frame sections, selected according to these moments, are given in Table 6. For the frame with structural infill, the infill walls were modelled as diagonal structures. After applying flood loads, for different frame models and in each zone, for hinged support condition, the maximum flood moment in each case was evaluated. Assuming flood heights of 2m, 3m and 4m from ground level, maxima moments were also obtained (Table 7). Because of the free movement of water in between the columns of the bare frame, the flood moment for bare frame model is very low if compared to the other models.

Zone	Bare Frame	Light weight infill	Structural infill
II	33.56	33.56	64.90
III	45.00	45.00	92.66
IV	62.26	62.26	128.58
V	86.40	86.40	184.09

Table 5. Maximum design moments in kN-m

Frame model	Column size	Beam size
Bare Frame	300 x 300	250 x 300
Light weight infill	300 x 300	250 x 300
Structural infill	350 x 350	300 x 350

Table 6. Frame cross-sections in mm

h_f (m)	Bare Frame	Light weight infill	Structural infill
2	5.74	32.14	30.09
3	9.45	97.58	83.94
4	20.18	205.84	166.33

Table 7. Flood moment due to hydrostatic force (without impact factor) in kN-m

Impact force is assumed to act as UDL, and its value is arbitrarily taken as a factor of hydrostatic force. The impact factors considered are 0.1 and 0.2. For all the models, the moments are linearly increasing as impact load increases, because impact force is considered as a factor of hydrostatic load (Table 8). Non-linearity will come only while considering flood duration. Flood is assumed to act as dynamic rectangular load with flood duration t_d and the maximum flood moment obtained in each case is shown in Table 9.

h_f (m)	Bare Frame		Light weight infill		Structural infill	
	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$
2	5.74	5.74	36.67	41.20	33.62	37.16
3	10.69	11.92	109.92	122.27	92.5228	101.10
4	22.53	24.89	229.40	252.96	180.05	193.77

Table 8. Moment due to hydrostatic and equivalent static impact forces in kN-m

Zone	Bare frame				Frame with partitions			
	R=1	**R=1.4142**	**R=1.7321**	**R=2**	**R=1**	**R=1.4142**	**R=1.7321**	**R=2**
II	33.56	47.46	58.13	67.12	64.90	91.78	112.41	129.80
III	45.00	63.64	77.95	90.00	92.66	131.04	160.49	185.32
IV	62.26	88.05	107.84	124.52	128.58	181.84	222.71	257.16
V	86.40	122.18	149.65	172.80	184.09	260.35	318.87	368.19

Table 9. Flood moment due to dynamic flood forces in kN-m

Frame type	R=1	R=1.414	R=1.732	R=2
Bare frame and Frame with light weight infill	0.0448	0.0673	0.0897	0.1345
Frame with masonry infill	0.0092	0.0139	0.0185	0.0277

Table 10. Duration of flood (td) in sec

The fundamental frequency and duration of flood will be the same for both the frames. Also, the flood moment obtained is the same for frame with structural and non-structural partitions, because the contact area of flood water is the same for both frames. The safe flood height is obtained by plotting the moment due to hydrostatic force versus flood height. For example, for a frame with light weight partition wall in Zone II, design moment is 33.56 kN-m (Table 5) and its maximum moment due to hydrostatic loading is shown in Table 11. From the graph, the safe flood height corresponding to design moment 33.5596 is 2.0276 m.

h_f (m)	Max flood moment (kN-m)
2	32.14
3	97.58
4	205.84

Table 11. Maximum flood moment for the frame with light weight partition wall in Zone II.

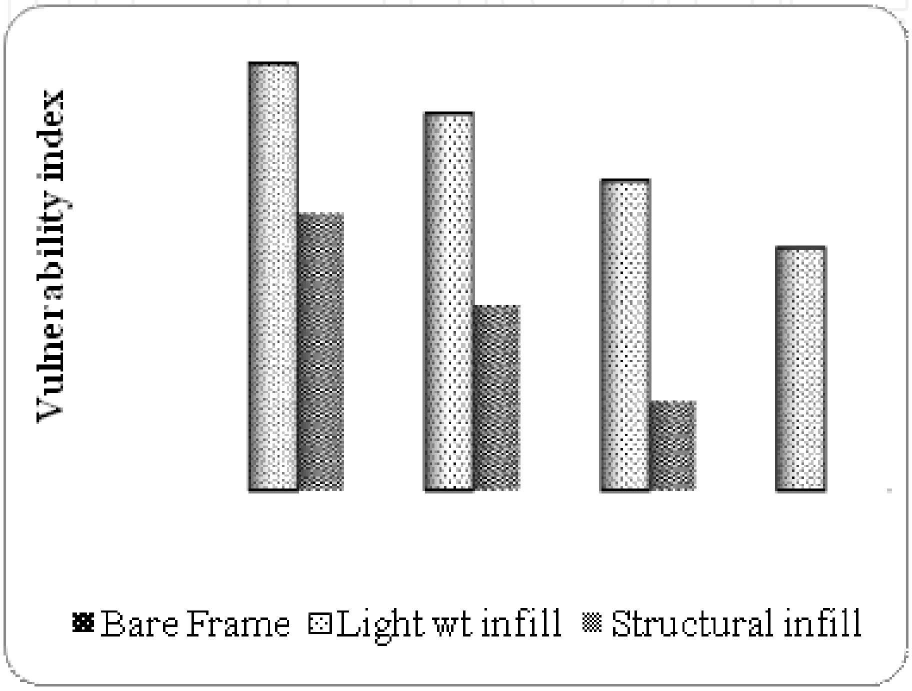

Figure 9. Variation of vulnerability in various zones

The vulnerability index of frame with light weight partition wall is high (49.3%) if compared to the other frames (Fig.8.). For frame with structural infill it only reaches a maximum of 32%, while it is zero for bare frame model. Vulnerability indexes obtained due to hydrostatic and equivalent static impact forces show that the highest values pertain to frame with light weight partition wall (Table 12). Vulnerability indexes obtained due to dynamic flood forces in various zones for different flood duration are shown in Table 13.

Zone	Bare Frame		Light weight infill		Structural infill	
	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$
II	0	0	0.518	0.539	0.347	0.371
III	0	0	0.461	0.484	0.244	0.27
IV	0	0	0.391	0.416	0.134	0.163
V	0	0	0.311	0.339	0	0.027

Table 12. Vulnerability due to hydrostatic and equivalent static impact forces

Bare frame				
R	1	1.414	1.732	2
Zone II	0	0.142	0.300	0.393
Zone III	0	0.061	0.233	0.336
Zone IV	0	0.000	0.160	0.272
Zone V	0	0.000	0.085	0.208
Frame with light weight infill				
Zone II	0.493	0.642	0.707	0.747
Zone III	0.435	0.600	0.674	0.717
Zone IV	0.362	0.549	0.632	0.681
Zone V	0.279	0.490	0.584	0.639
Frame with structural infill				
Zone II	0.320	0.519	0.607	0.660
Zone III	0.214	0.444	0.546	0.607
Zone IV	0.103	0.365	0.482	0.551
Zone V	0.000	0.266	0.401	0.481

Table 13. Vulnerability index due to dynamic flood forces

The storey drifts are evaluated from the lateral joint displacements. According to IS 1893-2002 Cl.7.11.1, the maximum storey drift is 0.004 H, where H is the height of the building. In this study, H = 13 m and hence the maximum allowable storey drift is 52 mm. The frame with structural infill wall has low storey drift if compared to bare frame, because infill walls have significant effect in resisting lateral storey drift (Table 14). For the frame with light weight partition wall, storey drift reaches 71.32mm, which is more than that specified for seismic resistant building (Table 15). Hence a frame with non-structural partitions with hinged support is not preferred in flood prone areas.

h_f (m)	Bare Frame	Light weight infill	Structural infill
2	0.634	5.939	0.084
3	2.017	19.696	0.205
4	4.665	46.242	0.466

Table 14. Storey drifts due to hydrostatic forces

h_f (m)	Bare Frame		Light weight infill		Structural infill	
	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$
2	0.807	0.98	7.666	9.393	0.1	0.116
3	2.578	3.138	25.372	30.975	0.264	0.324
4	5.918	7.172	58.78	71.317	0.616	0.766

Table 15. Storey drifts due to hydrostatic and equivalent static forces

The relative cost for any frame model is calculated with respect to the design moment of bare frame model in zone II (Eq. 4):

$$Cost\ relative_{zone\ III,IV,V} = \frac{DM_{zone\ III,IV,V} - DM_{zone\ II\ (bare)}}{DM_{zone\ II\ (bare)}} \tag{4}$$

Where $DM_{zoneIII,IV,V}$ are the design moments in zones III, IV and V for frame with partitions, and $DM_{zoneII(bare)}$ is the design bending moment of bare frame in zone II.

The relative costs for the three frame models are shown in Table 16. The graph of relative cost versus vulnerability index shows that for the frame with light weight partition wall the cost is increasing but the vulnerability is not reducing that much. Moreover, even though the initial cost is higher for frame with structural partitions, its vulnerability is lower if compared to frame with non-structural partitions (Fig.10.).

Zone	Bare Frame		Light weight infill		Structural infill	
	DM	cost relative	DM	cost relative	DM	cost relative
II	33.560	0	33.560	0	64.898	1
III	45.001	0.341	45.001	0.341	92.658	1.761
IV	62.259	0.855	62.259	0.855	128.579	2.831
V	86.398	1.574	86.398	1.574	184.094	4.486

Table 16. Relative cost as a factor of design moment for three frame models

The vulnerability obtained for different flood loadings is compared with partitions, zones and flood duration (Fig.11. and 12). Dynamic load with R = 1.4142 is used for comparing the results with static results. Frame with light weight infill wall is more vulnerable (64.2%) and bare frame is less vulnerable (14.2%). This is due to the free movement of water in between the columns of the bare frame, so that the contact area of flood water is very low if compared to the other frames. For the frame with masonry infill, vulnerability is less compared to light weight partition, even though the flood moment is the same for both the cases. It is due to the structural action of masonry infill against the lateral flood load.

Comparing vulnerability for different flood loadings to seismic zones (Fig.13.), for the frame with light weight infill, vulnerability is higher in Zone II (64.2%) and it reduces as zone increases (zone V: 49%). For frame with masonry infill, vulnerability is reaching zero as zone varies from II (51.9%) to V (Fig.14.). This is because the design moment of building in zone V is higher if compared to zone II and hence the building in zone V will be more resistive to flood.

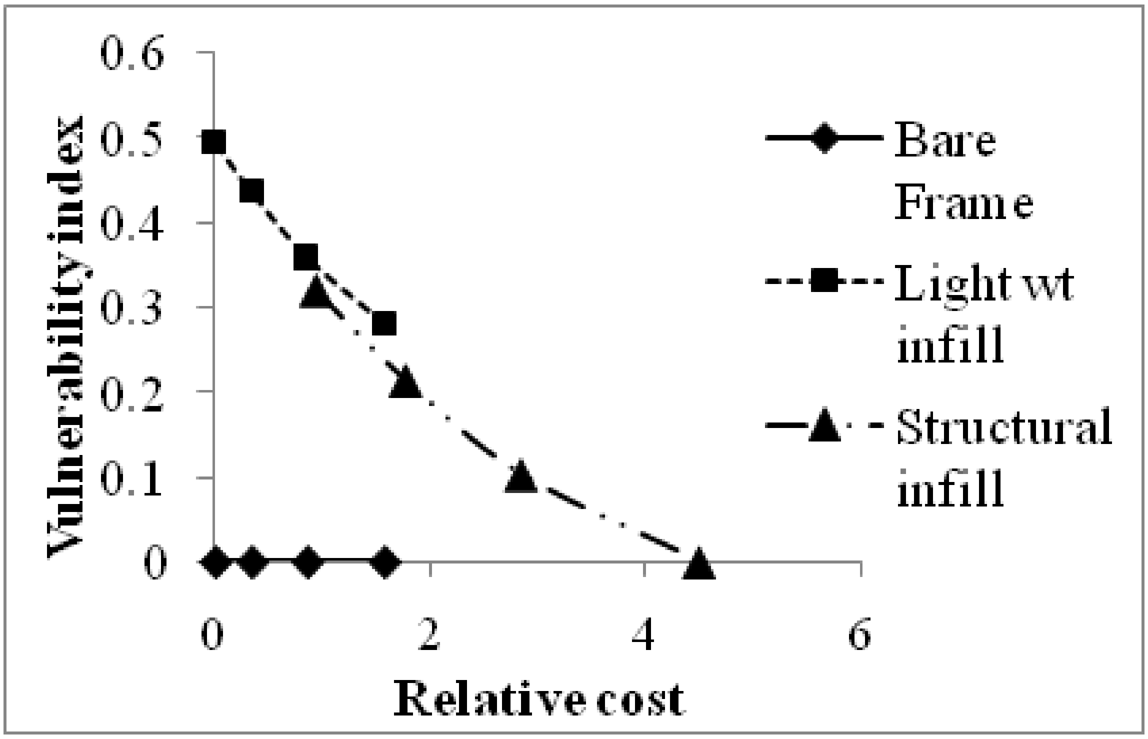

Figure 10. Variation of vulnerability against cost

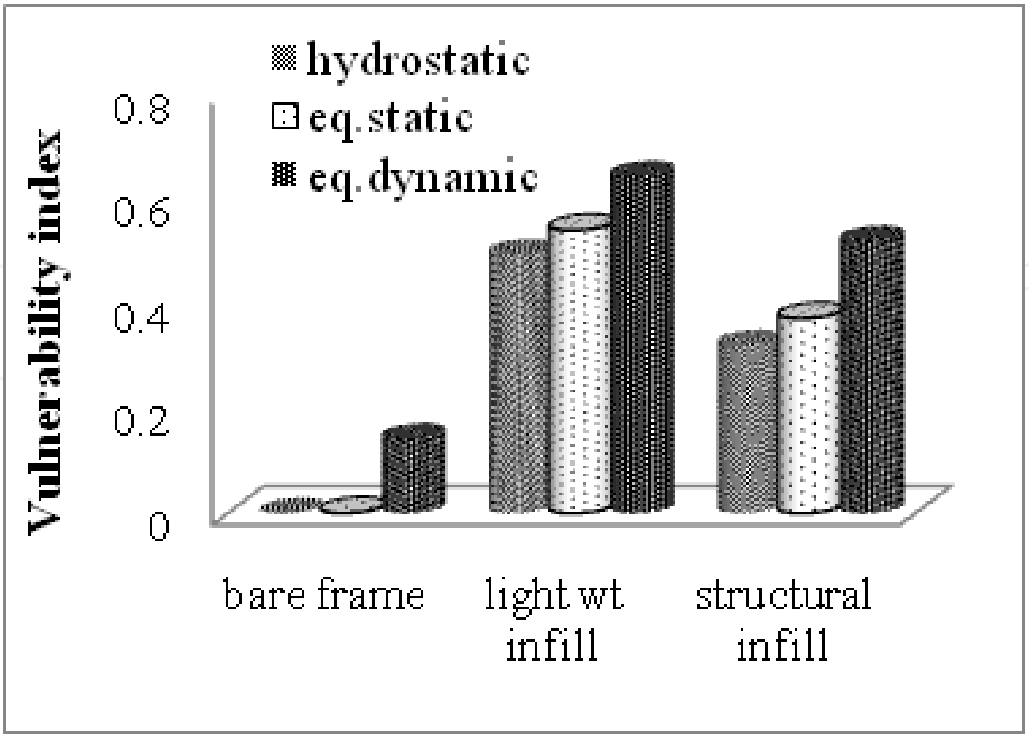

Figure 11. Vulnerability for different frame models in different flood loading conditions in Zone II

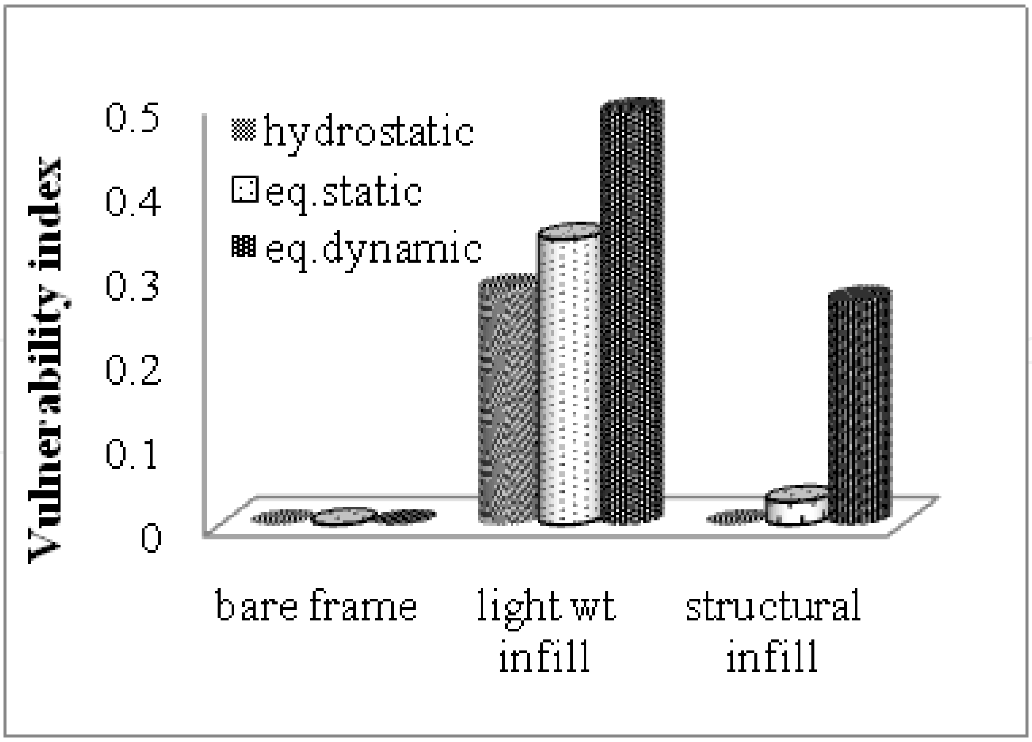

Figure 12. Vulnerability for different frame models in different flood loading conditions in Zone V

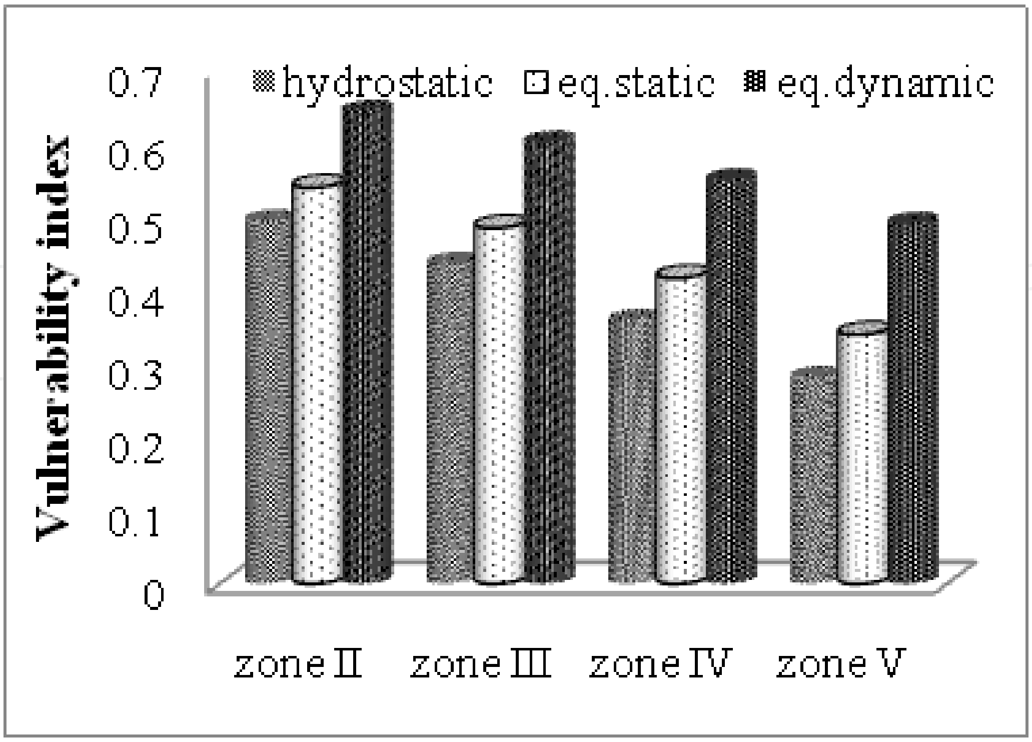

Figure 13. Vulnerability for light weight infill frame under different flood loading conditions in different zones

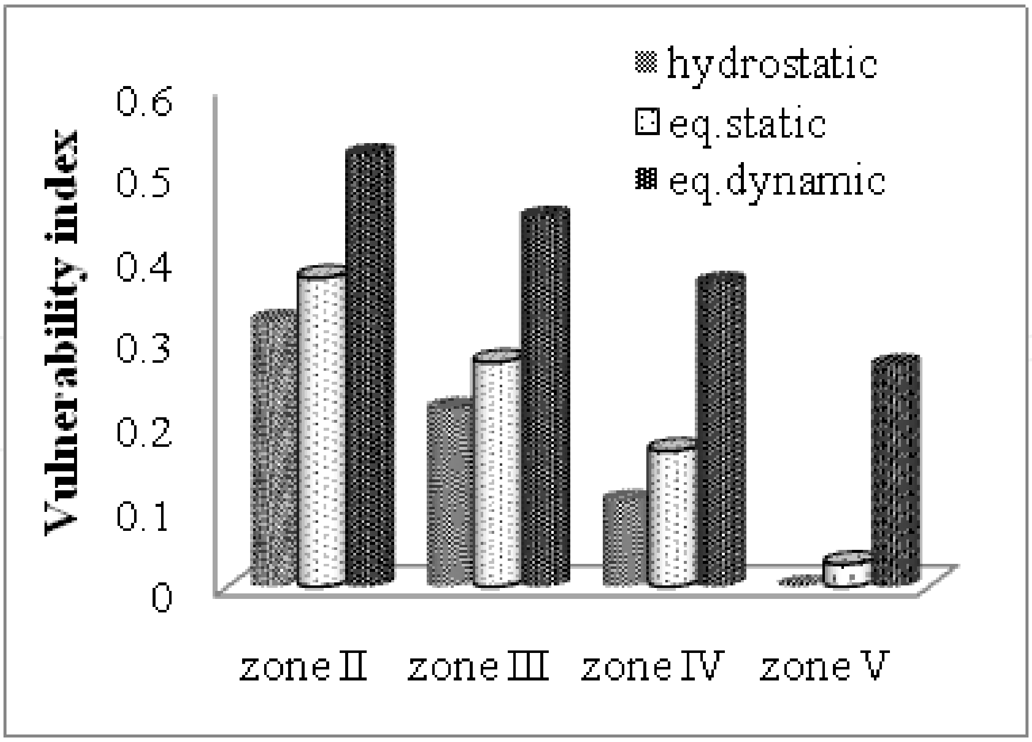

Figure 14. Vulnerability masonry infill frame under different flood loading conditions in different zones

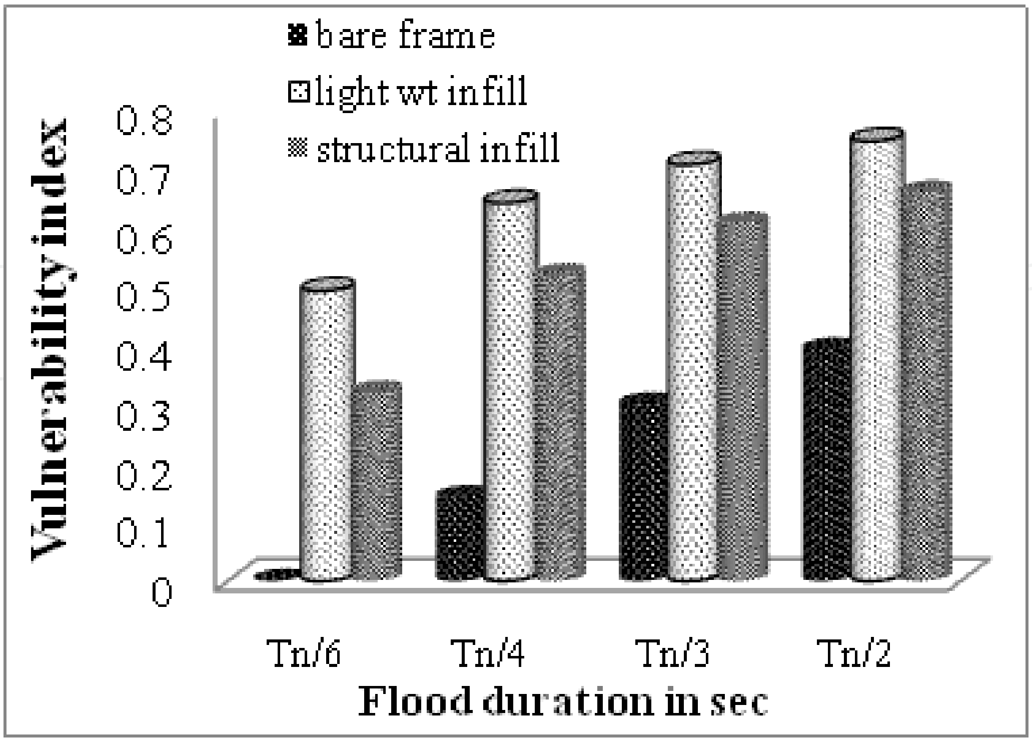

Figure 15. Vulnerability for different frame models under different flood duration in Zone II

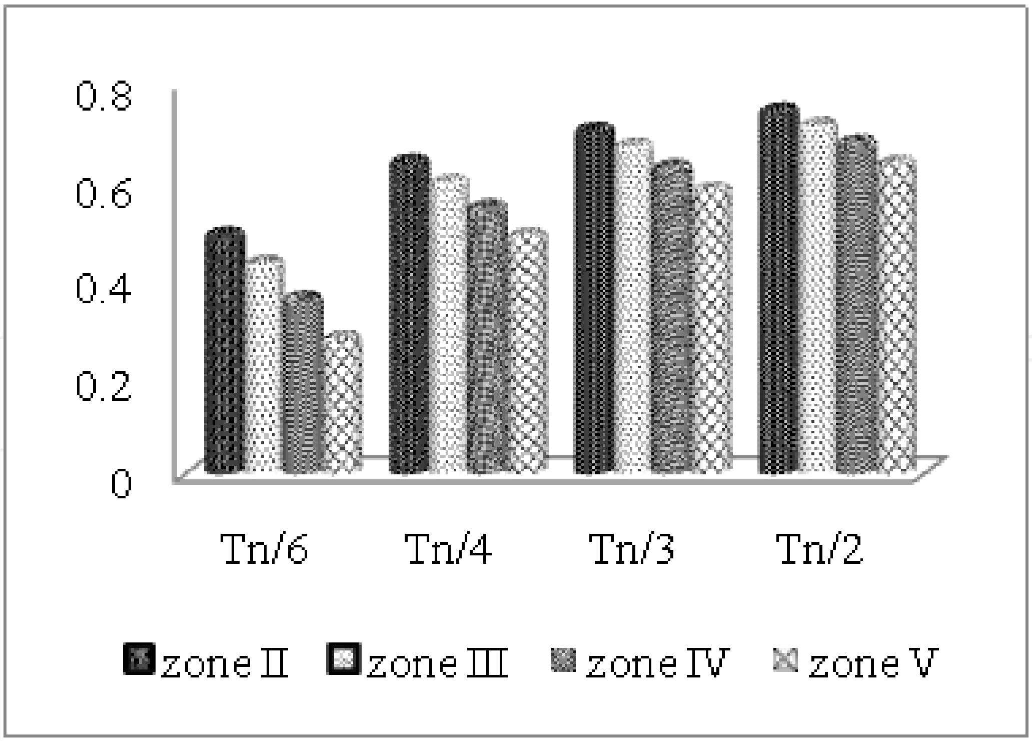

Figure 16. Vulnerability for the frame with light weight infill in different zones

Analysing different frame models under different flood duration in Zone II (Fig.15.), vulnerability increases with the duration of flood, but it is lower for bare frame (39.3%) if compared to frame with partitions (74.7% for light weight infill and 66% for frame with structural infill). It is due to the free movement of flood water between the columns of bare frame. The results of vulnerability for the frame with light weight infill (Fig. 16.), show that a building in zone V with flood duration $T_n/3$ is less vulnerable (58.4%) than a building in zone II with flood duration of $T_n/2$ (64.2%).

The analysis was carried out for all the cases, keeping the support of columns as fixed. The earthquake load calculations were made for all the zones and all the models analysed and designed as per IS 456:2000, for each zone and maximum design moments (Table 17). The maximum moment is lower for the fixed support condition, so the cross sections required is lower when compared to hinge support condition. The sizes of frame sections are given in Table 18. Fig. 18. shows the variation of flood moments for different frame models due to hydrostatic force. The flood moments parabolically increase as flood water height increases.

Zone	Bare Frame	Light weight infill	Structural infill
II	16.1389	16.1389	33.6639
III	25.3319	25.3319	49.3
IV	30.6598	30.6598	69.5349
V	42.6198	42.6198	100.8072

Table 17. Maximum design moment in kN-m

Frame model	Column size	Beam size
Bare Frame	250 x 250	250 x 300
Light wt infill	250 x 250	250 x 300
Structural infill	300 x 300	250 x 300

Table 18. Frame cross-sections in mm

The maximum moments obtained from the analysis for fixed support condition are shown in Table 19. For all frame models, the moments linearly increase as impact load increases. This is because, for the present case, impact force is considered as factor of hydrostatic load. Non-linearity will come only while considering flood duration. The duration of flood load (td) considered for various R values for hinged support condition are shown in Table 20 and the flood moments due to dynamic flood loads in various zones for fixed support condition are

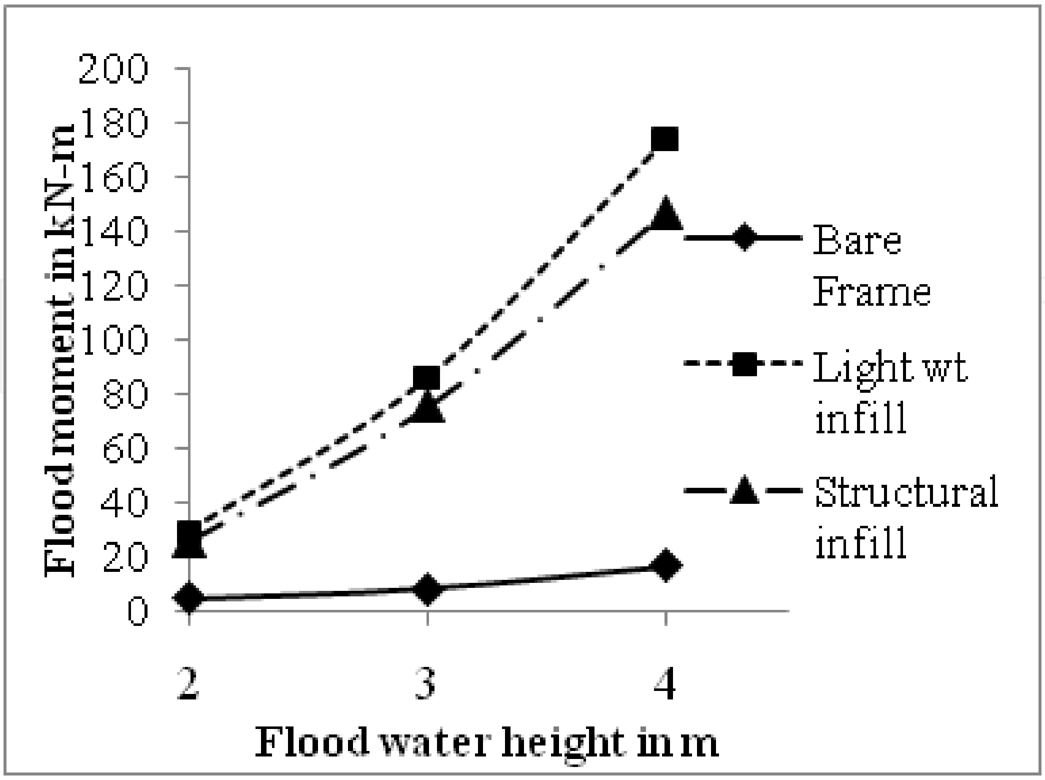

Figure 17. Variation of flood moment to hydrostatic force (without impact factor) with water height

shown in Table 21. Vulnerability for the bare frame is zero in all the seismic zones but it is non-zero for frame with partitions (Fig. 17.). This is due to the free movement of water in between the columns of the bare frame, so that the contact area of flood water will be low if compared the other frames. The vulnerability of frame with light weight partition wall is very high (60.3%), while for frame with structural infill it reaches 44.6% and it is not present for bare frame model.

Vulnerability indexes obtained due to hydrostatic and dynamic impact forces for fixed support condition are shown in Table 22 and 23, respectively.

hf (m)	Bare Frame		Light weight infill		Structural infill	
	0.1γhf	0.2γhf	0.1γhf	0.2γhf	0.1γhf	0.2γhf
2	4.4614	4.462	35.7516	42.4092	31.2512	36.9778
3	9.6472	11.2901	102.16	118.589	87.7618	100.1991
4	19.6866	22.5464	202.5541	231.1526	164.8106	182.9759

Table 19. Moment due to hydrostatic and impact forces in kN-m

Frame type	R=1	R=1.414	R=1.732	R=2
Bare frame	0.0401	0.0601	0.0801	0.1202
Frame with masonry infill	0.0098	0.0147	0.0196	0.0294

Table 20. Duration of flood (t_d) in sec

Zone	Bare frame				Frame with structural infill			
	R=1	R=1.4142	R=1.7321	R=2	R=1	R=1.4142	R=1.7321	R=2
II	16.14	22.82	27.95	32.28	33.66	47.61	58.31	67.33
III	25.33	35.82	43.88	50.66	49.30	69.72	85.39	98.60
IV	30.66	43.36	53.11	61.32	69.53	98.34	120.44	139.07
V	42.62	60.27	73.82	85.24	100.81	142.56	174.61	201.61

Table 21. Flood moment due to dynamic flood forces in kN-m

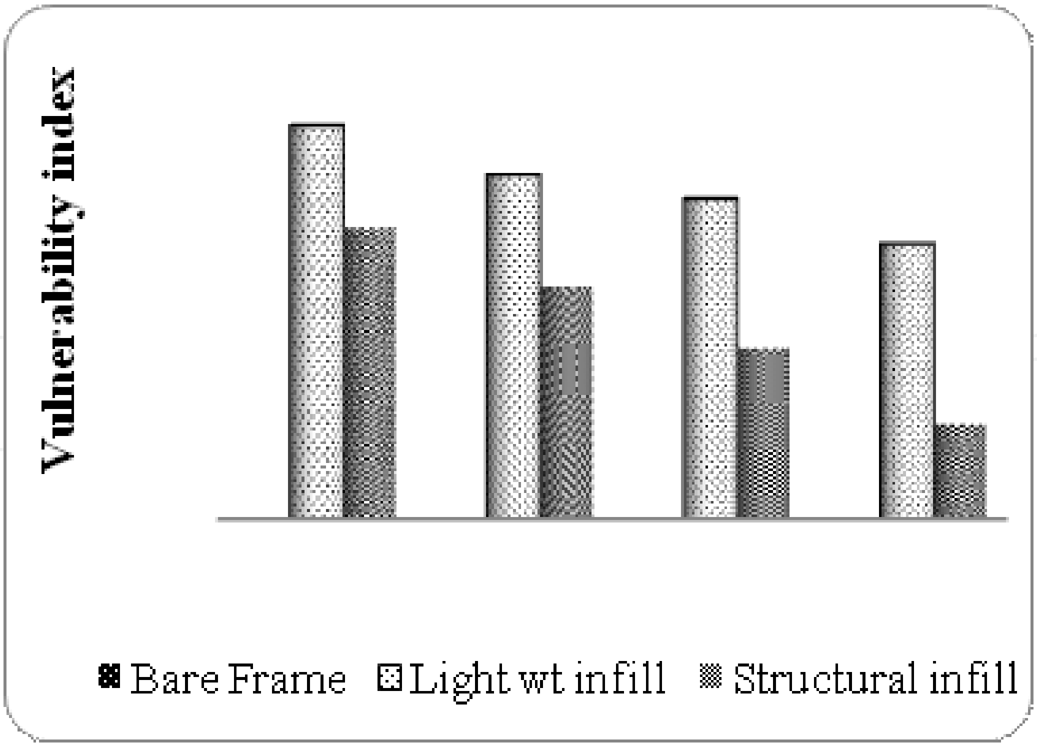

Figure 18. Variation of vulnerability in various zones

Zone	Bare Frame		Light weight infill		Structural infill	
	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$
II	0	0	0.638	0.663	0.488	0.523
III	0	0	0.566	0.596	0.400	0.438
IV	0	0	0.531	0.564	0.308	0.348
V	0	0	0.466	0.501	0.193	0.235

Table 22. Vulnerability index due to hydrostatic and impact forces

Bare frame				
R	**1**	**1.414**	**1.732**	**2**
Zone II	0.000	0.298	0.427	0.503
Zone III	0.000	0.178	0.329	0.419
Zone IV	0.000	0.128	0.288	0.383
Zone V	0.000	0.040	0.217	0.321
Frame with light weight infill				
Zone II	0.603	0.719	0.771	0.802
Zone III	0.528	0.666	0.727	0.764
Zone IV	0.491	0.640	0.706	0.746
Zone V	0.422	0.592	0.667	0.711
Frame with structural infill				
Zone II	0.445	0.608	0.680	0.723
Zone III	0.355	0.544	0.628	0.678
Zone IV	0.262	0.478	0.574	0.631
Zone V	0.145	0.396	0.507	0.573

Table 23. Vulnerability index due to dynamic flood forces

The storey drift is lower for fixed support condition and the maximum value concerns the frame with light weight partition walls (Fig. 19.). The frame with structural infill wall show the smallest storey drift: this indicates the significance of infill in resisting lateral storey drift. Storey drift reaches the maximum of 20.188 mm for the frame with light weight partition walls, which is less than that specified for seismic resistant building (Table 24).

For the frame with structural infill wall, even though the initial relative cost is high, the vulnerability is lower if compared to frame with non-structural partition walls (Table 25).

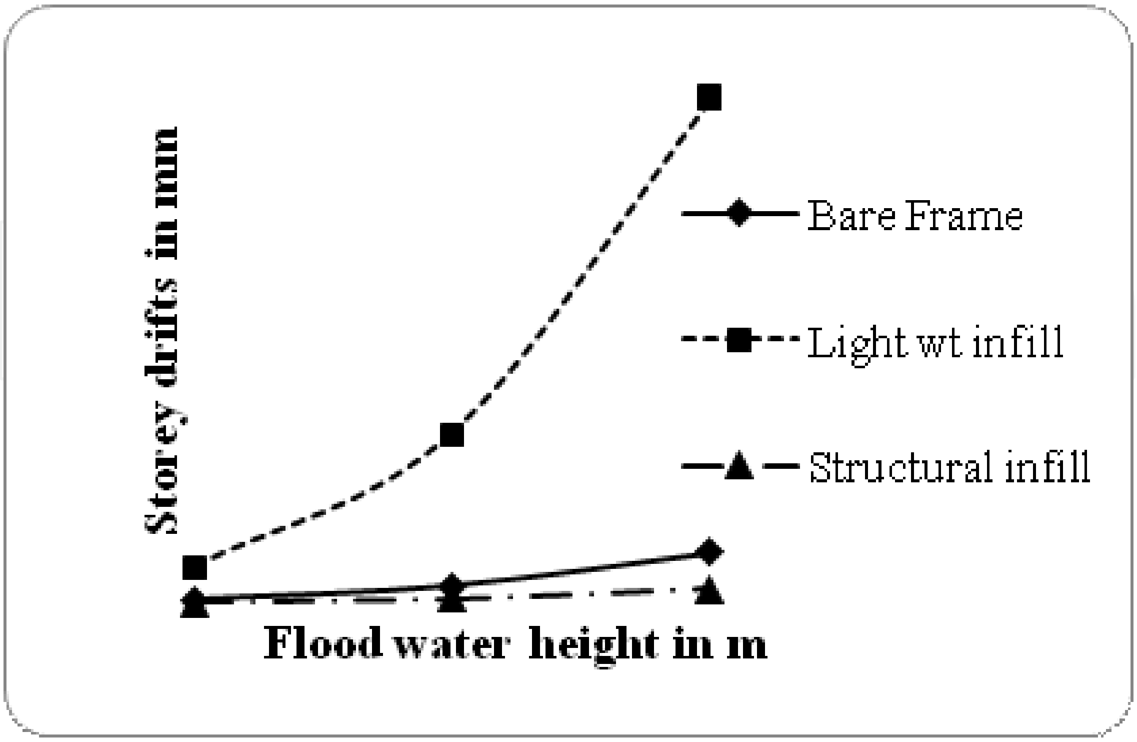

Figure 19. Variation of storey drift with flood water height

h_f (m)	Bare Frame		Light weight infill		Structural infill	
	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$	$0.1\gamma h_f$	$0.2\gamma h_f$
2	0.18	0.22	1.24	1.64	0.09	0.103
3	0.605	0.778	5.497	7.229	0.22	0.274
4	1.618	2.074	15.621	20.188	0.534	0.68

Table 24. Storey drifts due to hydrostatic and impact forces in mm

Zone	Bare Frame		Light weight infill		Structural infill	
	DM	cost relative	DM	cost relative	DM	cost relative
II	16.139	0.000	16.139	0.000	33.664	1.086
III	25.332	0.570	25.332	0.570	49.300	2.055
IV	30.660	0.900	30.660	0.900	69.535	3.309
V	42.620	1.641	42.620	1.641	100.807	5.246

Table 25. Relative cost as a factor of design moment for three frame models

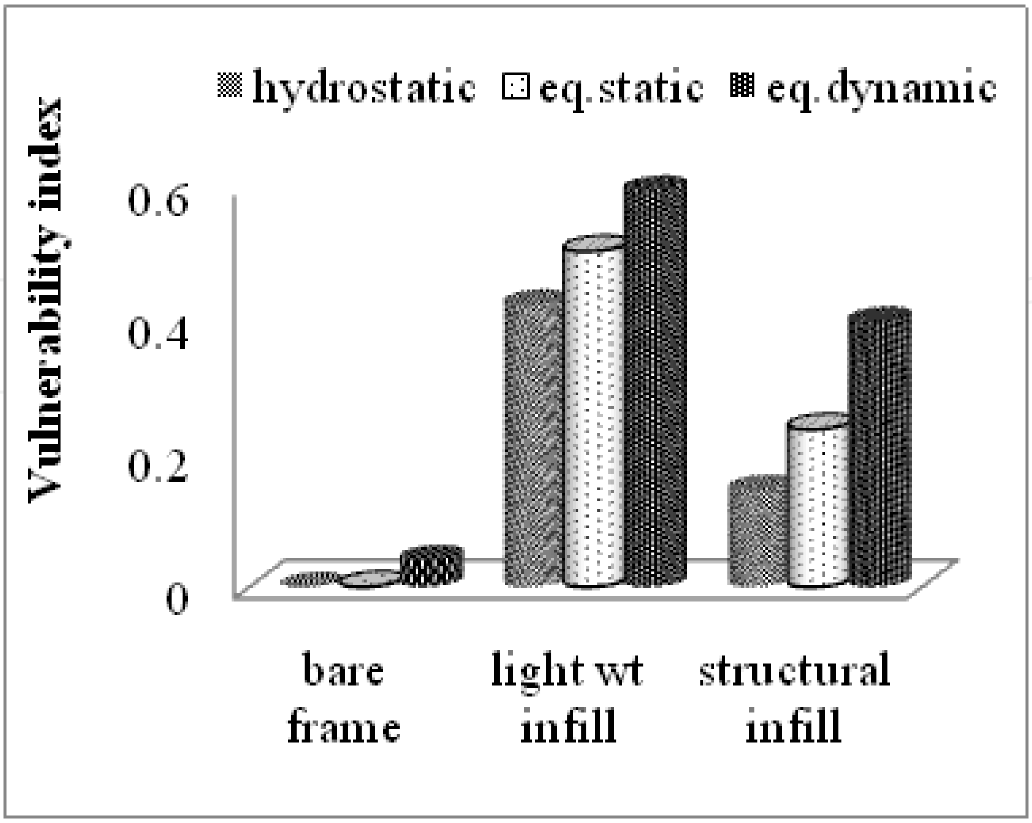

Figure 20. Vulnerability for different frame models under different flood loading conditions in Zone V

The vulnerability results obtained for different flood loadings are compared with respect to partitions (Fig. 20. and 21.). The frame with light weight infill wall is more vulnerable and bare frame is least vulnerable. This is due to the free movement of water in between the columns of the bare frame so that the contact area of flood water is lower if compared to the other frames. For the frame with masonry infill, vulnerability is lower if compared to light weight partition, even though the flood moment is the same for both the cases (Fig. 20.). It is due to the structural action of masonry infill against the lateral flood load.

The vulnerability reduces from zone II to zone V because the design moment in zone V is higher if compared to zone II and hence the building is more resistive to flood. The variation of vulnerability for the frame with light weight infill and with masonry infill under different flood loading conditions in different zones are shown in Fig. 22. and 23, respectively.

For the frame with light weight infill, vulnerability is higher in Zone II (71.9%) and it reduced as zone increases (Fig. 22.). For frame with masonry infill, vulnerability is higher in Zone II (60.8%) and it decreases as zone increases (Fig. 23.). This is because the design moment of building in zone V is higher if compared to zone II and hence the building in zone V will be more resistant to flood.

The vulnerability results obtained for different flood loadings are compared with respect to seismic zones (Fig. 24. and 25.). As the duration of flood increases, vulnerability increases (Fig. 24.); vulnerability is lower for bare frame than for frame with partitions. A building in zone V

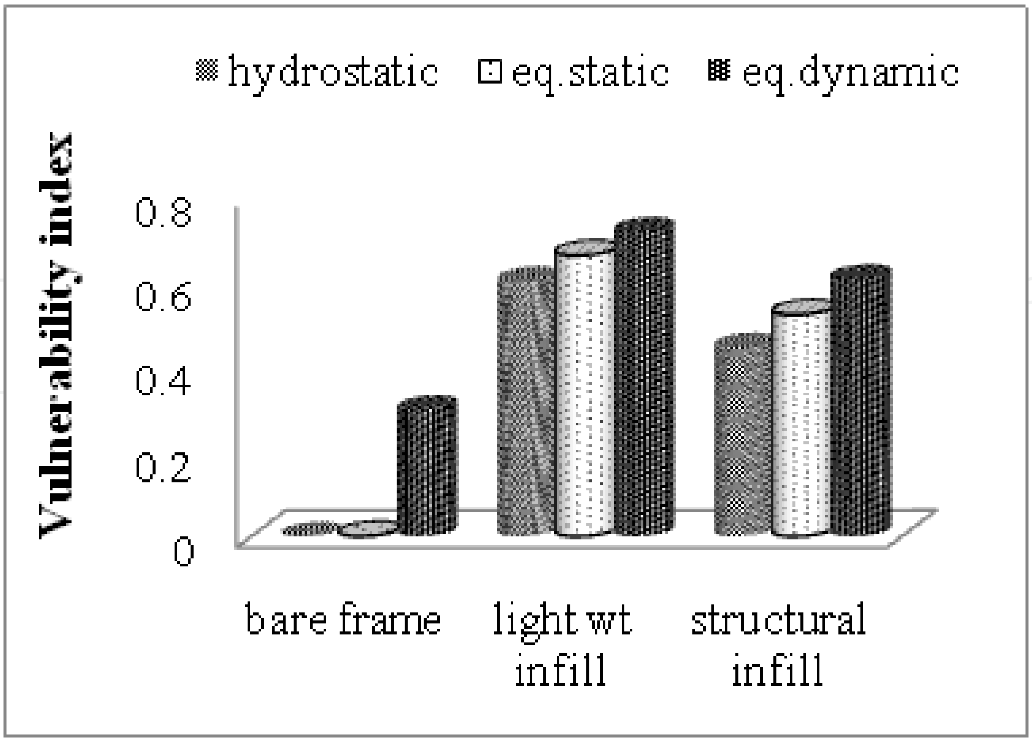

Figure 21. Vulnerability for different frame models under different flood loading conditions in Zone II

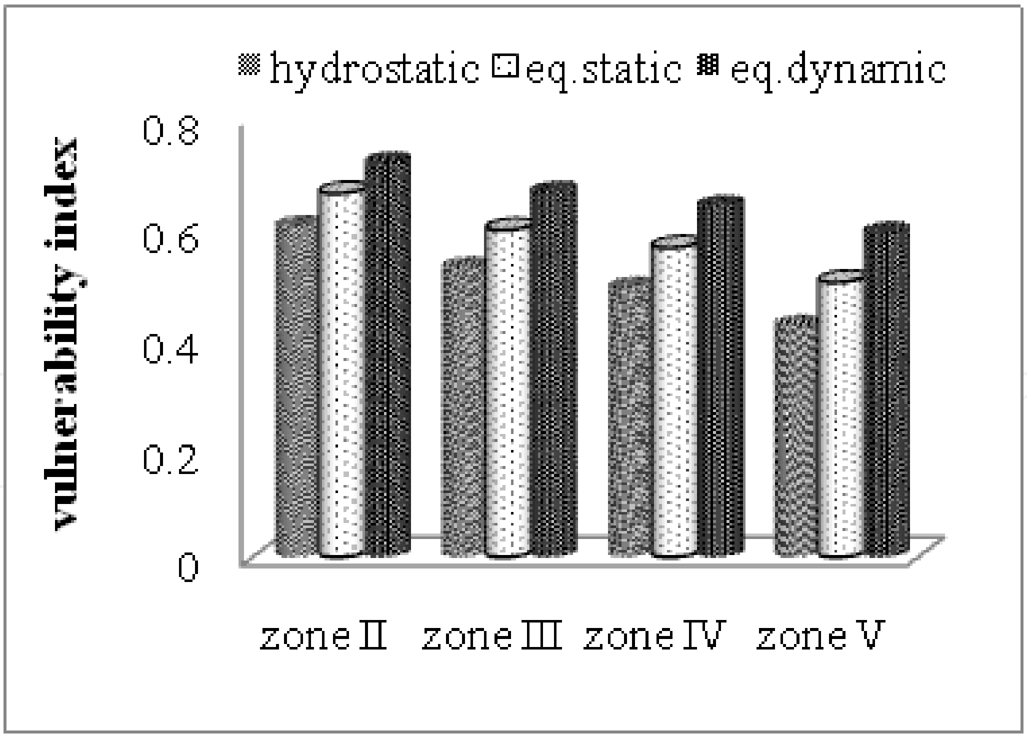

Figure 22. Vulnerability for the frame with light weight infill under different flood loading conditions in different zones

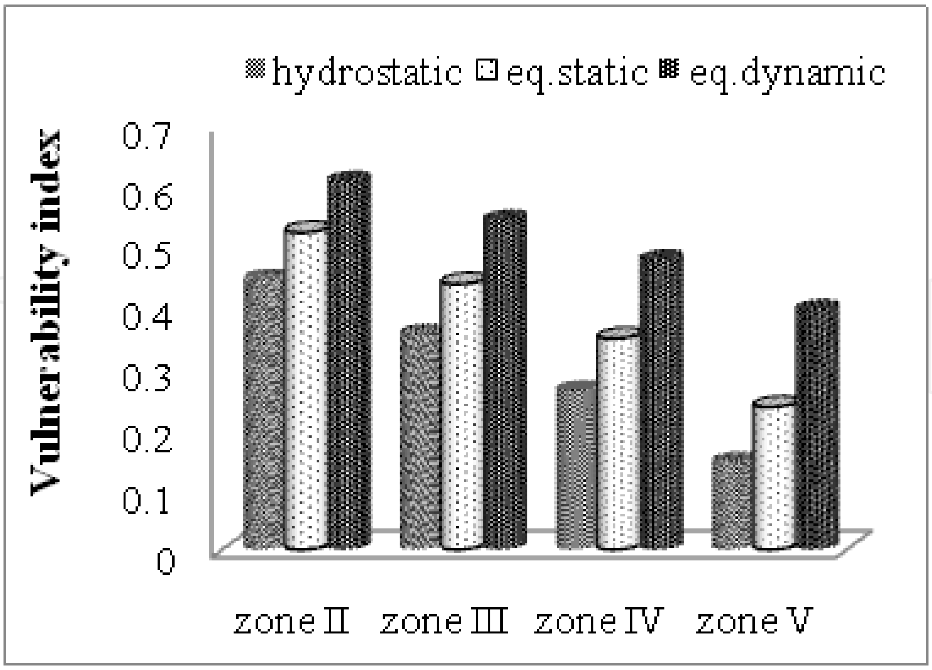

Figure 23. Vulnerability for the frame with masonry infill under different flood loading conditions in different zones

with flood duration $T_n/3$ is less vulnerable (66.7%) than a building in zone II with flood duration of $T_n/2$ (71.9%) (Fig. 25.), hence vulnerability is higher for building subjected to longer floods even if it also depends on the seismic zone.

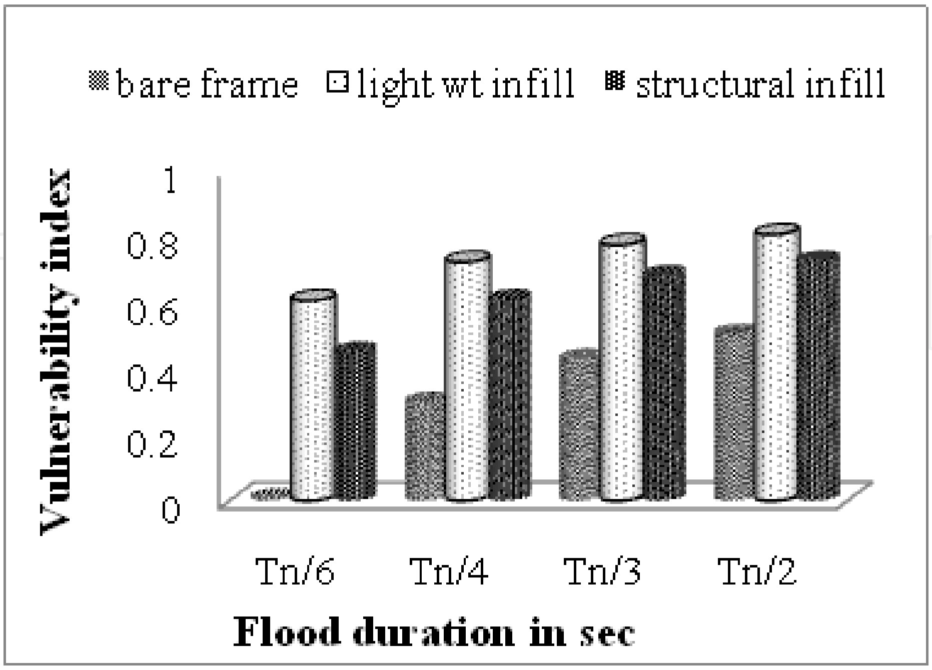

Figure 24. Vulnerability for different frame models under different flood duration in Zone II

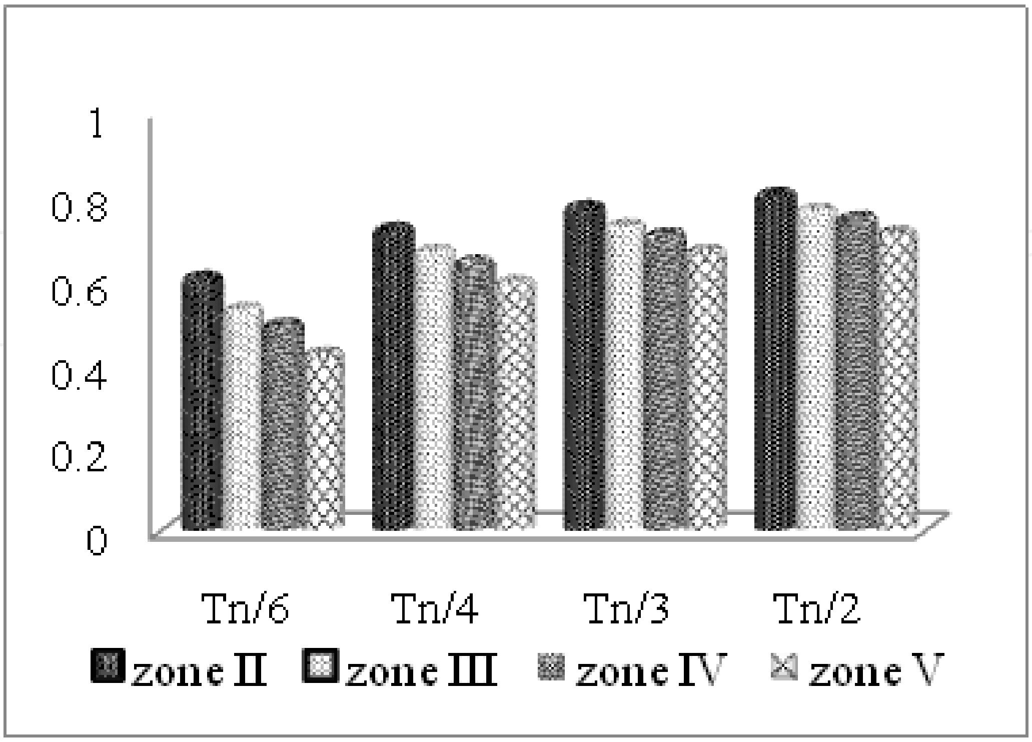

Figure 25. Vulnerability for the frame with light weight infill in different zones

5. Conclusions

Flood physical vulnerability deals with the level of loss that elements at risk or built environment suffer from the occurrence of flooding. This study aims to find out the flood vulnerability limit as a factor of ground floor height under flood forces and to quantify flood load. Three frame models were modelled and the effects of flood forces in each frame were analysed. The significance of infill walls in resisting lateral storey drift during flood is also investigated. The main conclusions of the analysis are:

- The flood moments parabolically increase as flood water height increases and linearly increase as impact load increases.
- The vulnerability of frame with light weight partition wall, for hinged support condition, reaches 64.2% for dynamic flood forces, that is very high if compared to the other frames.
- For frame with light weight partition wall in hinged support condition, storey drift reaches 71.32 mm, which is more than the value specified for seismic resistant building.
- The vulnerability of frame with light weight partition wall, for fixed support condition, is up to 60% in zone II which is very high if compared to the other frames.

- Storey drift for frame with light weight partition wall in fixed support condition is found to be less than hinged condition. The maximum value of storey drift for frame with light weight partition wall is 20.188mm.
- Even though the initial cost is more for frame with structural partitions, its vulnerability is very low if compared to frame with non-structural partitions.
- Buildings in zone II is most vulnerable and the vulnerability is reducing as zone increases. It reaches zero for frame with structural infill ass zone varies from zone II to zone V. This is because the design moment of building in zone V is higher if compared to zone II and hence the building in zone V is more resistive to flood.

Frame with light weight partition wall result as the most vulnerable and bare frame is least vulnerable. Hence frame with non-structural partitions like plywood are not preferred in flood prone areas. The storey drift for the frame with structural infill walls is very low if compared to the other frame models and this indicates the significance of infill in resisting lateral storey drift. Soft storied buildings are less vulnerable compared to ordinary buildings and this depends on the free movement of water in between the columns. Results also indicate the real need of considering the flood loads in the design procedure of reinforced concrete buildings.

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