Behavior of RC Structures Under Tsunami Triggered by The Great East Japan Earthquake

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SUMMARY:
Type The Great East Japan Earthquake on March 11, 2011 is the most powerful know earthquake that has hit Japan with a magnitude of 9.0 and epicentre at 129 km of Sendai city of the Tohoku region (East-North region of Japan). The earthquake triggered destructive tsunami with run up height of up to 38 meters that affect mainly cities located on the Pacific Ocean coast of the Tohoku region. In general the wooden structures were destroyed completely by the tsunami when the water depth reached or exceeded the first floor height. The steel (frame) structures did not collapse in general by the tsunami action however heavy damages of walls, panels, ceilings and other non-structural elements were observed. Reinforced concrete buildings did not collapse in general and resist better the action of the tsunami however, non-structural components were severely damages. In this report the characteristics of the damages and behaviour of RC buildings during the tsunami action is discussed based on the field survey of damages in some cities located on the coast of the affected zone. The analysis has permitted to understand the behaviour of this kind of building and some recommendations are obtained for their use to take refuge from the tsunami in places where natural topography make impossible to reach hilltops or other safer places.

Keywords: RC building, Tsunami, The Great East Japan Earthquake

1. INTRODUCTION

An earthquake with a magnitude of Mw 9.0 struck the north-east part of Japan (Tohoku region), on 11 March 2011 at 14:46 local time. This earthquake is the most powerful know earthquake that has hit Japan with its epicentre located at 129 km of Sendai city of east-north region of Japan. The earthquake triggered a destructive tsunami with run up height of up to 40 meters. The tsunami affects mainly cities located on the Pacific Ocean coast of Iwate, Miyagi and Fukushima prefectures in the Tohoku region, and also Ibaraki prefecture in Kanto region.

Wooden structures were destroyed by the tsunami action when the water depth reaches or covers at least the first floor of the building. These wooden structures were the most vulnerable constructions that were washed up by the tsunami. Steel frame structures and steel trusses that are used mainly for industrial constructions suffer heavy damages of walls, ceilings, finishing panels and non-structural elements. In some cases the failure of these non-structural components produces the failure of structural elements and even the collapse of the structure. In the case of reinforced concrete buildings in general resist the tsunami without collapse, however the non-structural elements like panels and ceilings were severely damaged. However, in some cases low rise RC buildings were tilted by the tsunami action. In this report, the characteristics of the damages and behavior of RC buildings during the tsunami action is discussed based on the field survey of the damages in selected cities located on the coast of the affected zone. The analysis has permitted to understand the behavior of this kind of building and has also permitted to establish recommendations for their use to take refuge from tsunami in places where natural topography makes impossible to reach hilltops or other safer places.

2. CHARACTERISTICS OF THE EARTHQUAKE AND TSUNAMI

The Great East Japan Earthquake that occurred on March 11, 2011 (at 14:46) was an inter-plate earthquake which occurred on the boundary between the Pacific Ocean plate and the Continental plate (called American plate). This earthquake is also known as the 2011 off the Pacific Coast of Tohoku Earthquake or the 2011 Tohoku-Pacific Earthquake. The magnitude of the earthquake was reported as being 9.0, which is the highest magnitude ever recorded in Japan.

2.1. Tsunami source

The Japanese Meteorological Agency (JMA) has reported an analysis of the tsunami source and its generation mechanism, based on the observed data (2011). The result of this analysis can be observed in Figure 1. In total, data of 19 observation stations were used for the analysis. The observation points include the coast from Hokkaido (north of Japan) to Kanto region. From the arrival time observed in each stations and by means of an inverse analysis the tsunami source is estimated. As can be observed in Figure 1, the source ranges from off the coast of Iwate prefecture to off the coast of Ibaraki prefecture which represents about 500 km of length and also the width of the source is estimated to be as 200 km.

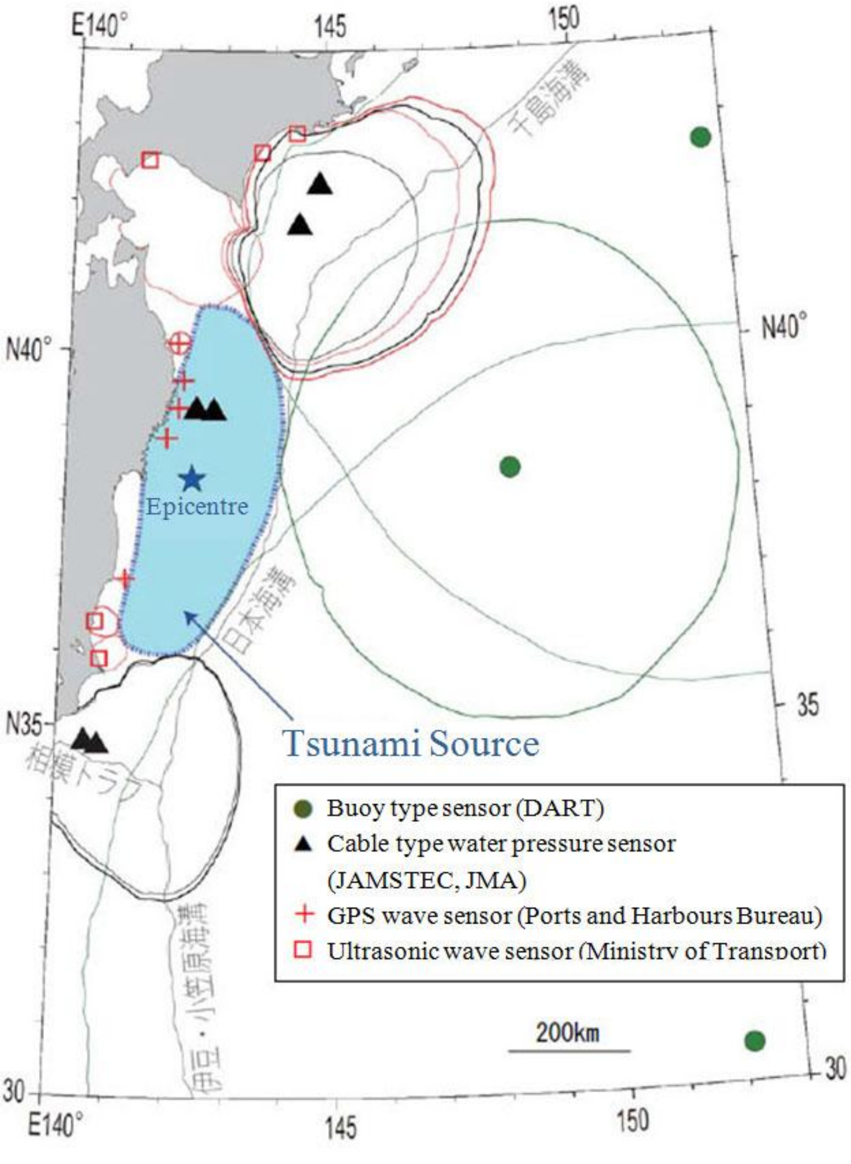

Figure 1. Tsunami source

The validity of the estimation of the tsunami source area is verified by comparing it with the distribution of the aftershocks. According to the Japanese Meteorological Agency the distribution of these aftershocks (with magnitude larger than 5) is as shown in Figure 2 (reported by Shimizu Corporation, 2011). It can be observed from the distribution that the plane of the rupture or fault extends to about 500 km in the North-South direction (length) and about 200 km in the East-West direction (width). Before the main shock an earthquake of magnitude 7.3 occurred in off-shore of Sanriku region on March 9 (see Figure 2). In the same day of the main event (March 11, 2011) 33 aftershocks were observed and their frequency decrease with the days. Events with magnitude 7 or larger are summarized in Table 1. From the aftershocks, two events that occurred on April 7 and April 11 were of magnitude 7 and 7.1 respectively. These magnitudes lead to emit the warning of tsunami occurrence. On the other hand, two large inland earthquakes occurred after the main shock. One occurred on March 12 in the northern part of Nagano Prefecture and was of magnitude 6.7. The other one was the earthquake of March 15 in the eastern part of Shizuoka Prefecture and it had a magnitude of 6.4. Also an event of magnitude 6.4 in the north part of Akita prefecture that falls out of the zone of aftershocks was observed. These events produced seismic intensities larger than 5 in the Japanese scale of earthquake intensity.Use upper and lower case letters. Leave one blank line above a sub-heading and one blank line between sub-heading and the first line of the text.

Table 1. Main shock and events of large magnitude (larger than 7)

Event	Date & time	Epicenter	Depth	Magnitude
Foreshock	03/09, 11:45	38º19.7'N, 143º16.7'E	8 km	Mj 7.3
Main	03/11, 14:46	38º06.2'N, 142º51.6'E	24 km	*Mw 9.0
Aftershocks	03/11, 15:08	39º50.3'N, 142º46.8'E	32 km	Mj 7.4
	03/11, 15:15	36º06.5'N, 141º15.9'E	43 km	Mj 7.7
	03/11, 15:25	37º50.2'N, 144º53.6'E	34 km	Mj 7.5
	04/07, 23:32	38º12.2'N, 141º55.2'E	66 km	Mj 7.1
	04/11, 17:16	36º56.7'N, 140º40.3'E	6 km	Mj 7.0

Mj: Magnitude by Japan Meteorological Agency,
*Mw: Moment Magnitude

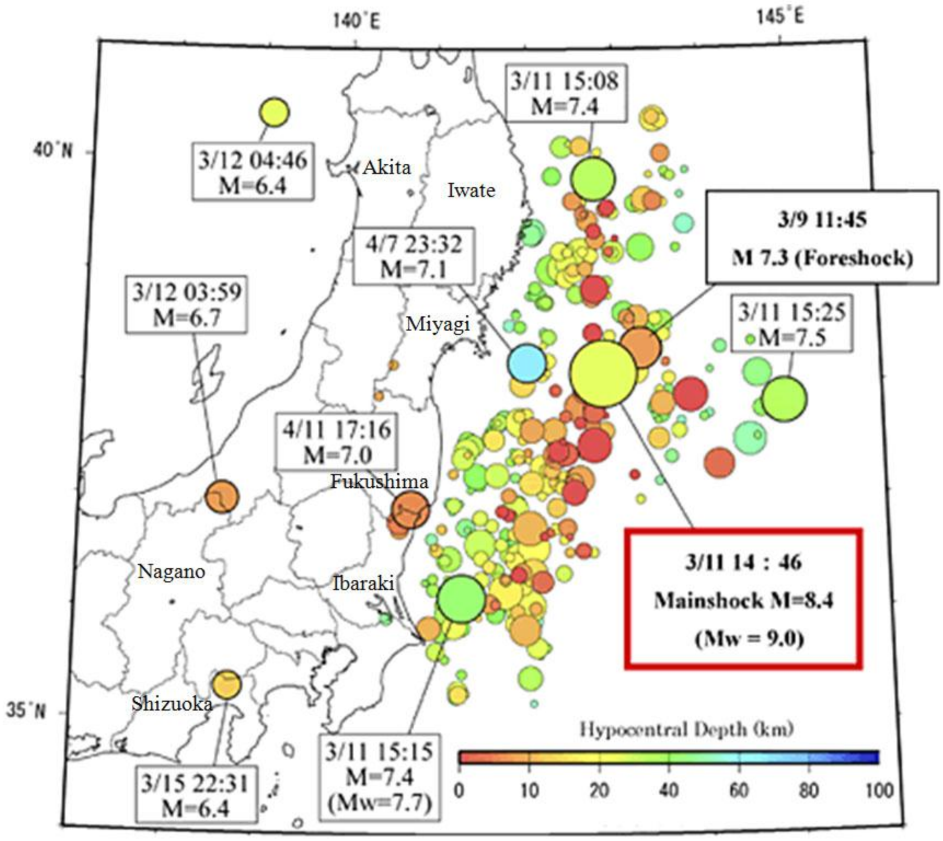

Figure 2. Distribution of epicenters

Comparing Figure 2 which is the distribution of aftershock epicenters and Figure 1 which is the tsunami source region obtained by inverse analysis of tsunami observed data, it can be said that there is a good agreement between both Figures. These results show that the earthquake of March 11, 2011 with epicenter at 129 km west of Sendai city has implied a rupture of a large geological fault which ranges from off the coast of Iwate prefecture to off the coast of Ibaraki prefecture, and therefore this event originated a great tsunami that affect cities located at the Pacific Ocean coast of the Tohoku region.

The tsunami affected a wide area along the Pacific Ocean coastline from Hokkaido to the Kanto area. Tsunami waves were observed not only in the Hokkaido, Tohoku and Kanto regions, but also far regions like Tokai, Shikoku and Kyushu regions. In Iwate prefecture and the northern area of Miyagi prefecture, the inundation height and the run-up height of tsunami exceeded 20m. In Figure 3, the distribution of the inundation height and run-up height is observed as is reported by the field survey carried out by Report of the Coastal Engineering Committee of the Japanese Society of Civil Engineers (2011). Small circles represent the inundation height which is the height between the water surface at the observation point and the original or normal sea level. The triangles represent the run-up height which is the maximum topographical level reached by the tsunami in reference to the normal sea level. Since both heights are referred to the normal sea level (cero level), it does not mean that these heights are strictly related to the damages on structures. Instead of these heights, the inundation depth which is the height between the water surface at the observation point and the ground level at that point could be a better value to refer the damages of building. The inundation depth is more directly related to the water pressure which is the cause of the damages on the buildings. The inundation depth varies according to the topographical shape of the ground surface and during the field survey could be estimated from the marks of the tsunami that remains on taller building.

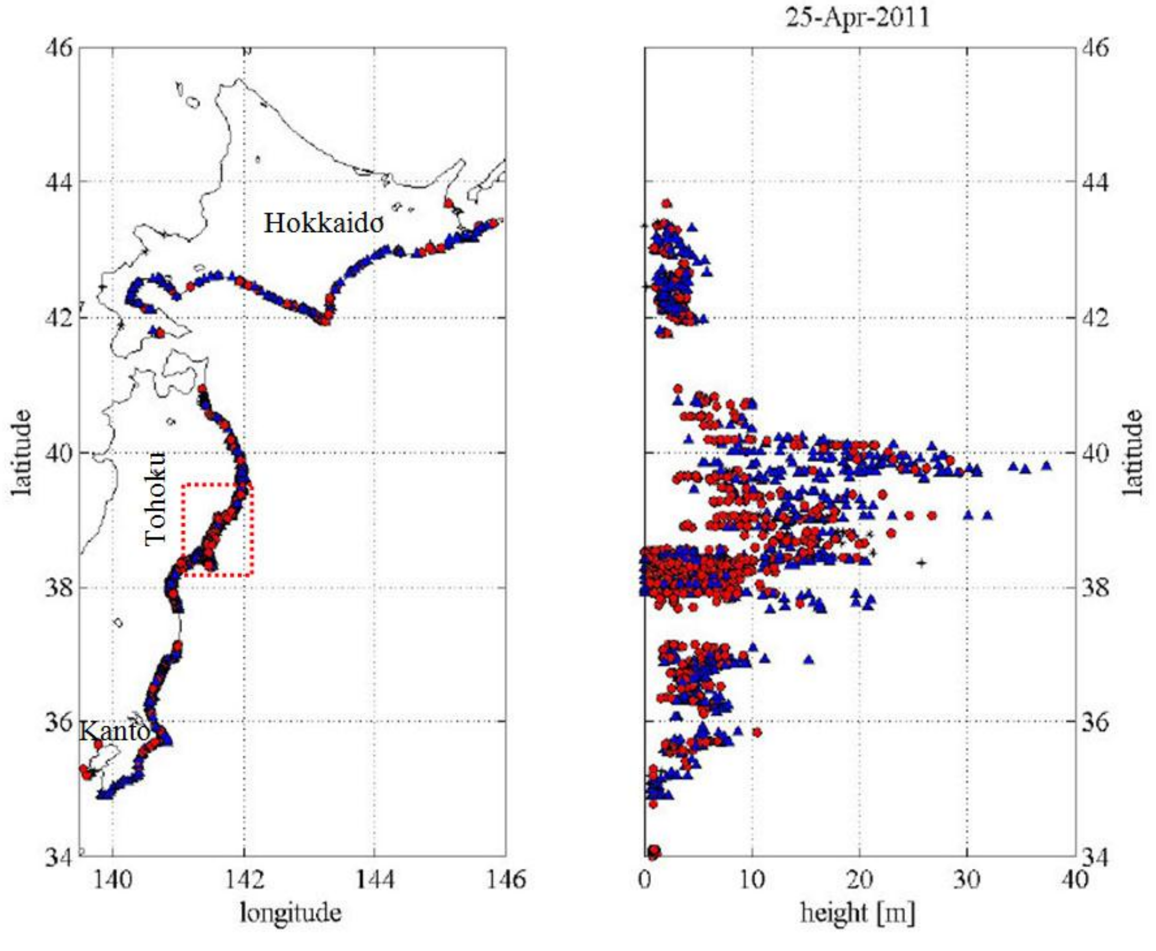

Figure 3. Inundation height and run-up heights

3. DAMAGES DUE TO TSUNAMI

The damages on building structures that were produced by the tsunami are described in this section and in special the damages that occurred on reinforced concrete structures. However it is necessary to mention that damages are not limited only to building structures. Tsunami affected also many infrastructures like ports, embankments, roads, railroads, oil tanks, and in its more dramatic damage affected the nuclear power plant of Fukushima. Environmental damages are also reported like the chlorination of agricultural soils, sedimentation of debris near ports, transportation of old industrial and mine residues from the sea bottom to the ground surface, etc.

3.1. Selected Area

The sites that were selected for the present survey are shown in Figure 4. This zone is also marked in Figure 3 by a dashed rectangle. Cities of Ofunato, Rikuzentakata, Kesennuma, Ishinomaki and Onagawa were visited to perform the corresponding survey. Figure 4 shows that the shape of the coast line is intricate with coast lines that converge forming shapes like river deltas that facilitated the run-up of the tsunami.

Figure 4. Zone of survey (Google map)

3.2. Damages on buildings

To compare the damages of reinforced concrete, also damages on wooden structures and steel structures as described as references. In general the wooden structures collapse when were attacked by the tsunami. The steel structures remain stand up however, the finishing walls, ceilings and other non-structural elements fails and in some cases these fails originate the fail of the main structure. The reinforced concrete structures presented better behaviour and were the structures that in general remain in their original location without structural damages. This can be explained by the high lateral stiffness of the reinforced concrete buildings in comparison to steel structures and wooden structures. The wooden structures have the smaller lateral stiffness and in general were washed up when the tsunami reached or covered the first floor. The relation between the damages and the earthquake resistant characteristics of these three types of structures are summarized in Table 2.

Table 2: Relation of earthquake resistant forces and damages due to Tsunami

Type of structure	Earthquake resistant force for design	Level of Tsunami damages
Wooden structure	Low	High
Steel structure	Medium	Medium
Reinforced concrete	High	Low

3.2.1. Damages on wooden houses

From damage surveys reported by other authors, it is recognized that in general the wooden houses collapse or present damages due to the tsunami action when the inundation depth is larger than 2 meters. As is presented in Figure 5, the damages on wooden houses are divided into three zones according to the inundation depth. Zone A correspond to a places where the inundation depth is smaller than 2 meters and structural damages are not observed, that is the wooden houses are safe in this case. Zone B correspond to a zone where the inundation zone ranges from 2 to 4 meters, and depending on the structural shape and/or condition of the structural elements, the houses can suffer from light damages to severe damages. From the field observation it can be said that when the water level cover the first floor of the wooden house the structures collapse not only due to the lateral force of the water but also due to the water pressure on the ceiling of the first floor causing floating of the upper floors. Zone C correspond to a zone where the inundation depth is large that 4 meters and total collapse of the structure is expected to occur.

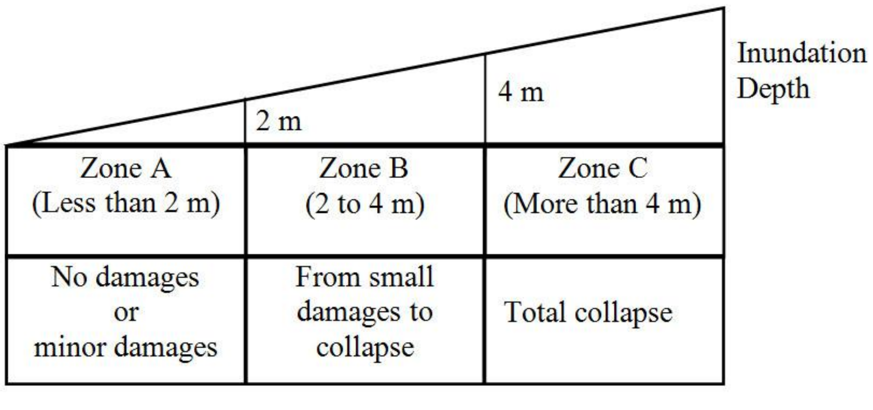

Figure 5. Inundation depth and damages on wooden houses

Figure 6 shows some typical damages on wooden houses that were produced by the tsunami. In Figure 6(a) it can be observed that wooden houses were completely destroyed by the tsunami action. It can be also observed that houses located on high sites are not affected. In Figure 6(b) the first floor was destroyed by the tsunami and the upper part of the house was transported and then left by the tsunami on a different place from their original location. In the case of Figure 6(c) the tsunami destroyed the first floor and also produced the overturning of the remaining upper floor.

Figure 6. Damages on wooden houses

3.2.2. Damages on steel structures

Steel structures are used in general for industrial facilities and office buildings. Most of the buildings are framed structures and structural elements like beams and columns are slender elements. Floors and walls are made of light panels and the lateral stiffness is appropriately designed to resist the earthquake force. However during the tsunami attack the water pressure acting on panels or in general in elements of large area generated large lateral forces that destroyed that non-structural elements and in some cases the failure of these elements lead to the failure and even to the collapse of the main structure.

Damages on Steel structures can be observed in Figure 7. When the inundation depth reaches only the first floor the structure remains almost intact however the wall panels of the first floor suffer some damages as can be observed in Figure 7(a). In Figures 7(b) the inundation depth reached the second floor and wall panels and ceiling are destroyed. In this case the structure remained stand up however some local failure of the structural elements were observed. Figure 7(c) shows a total collapse of steel structures. In this case the building was completely covered by the water.

Figure 7. Damages on steel structures

3.2.3. Damages on RC structures

Many reinforced concrete structures resisted the tsunami action without collapse as can be observed in Figure 8. Figure 8(a) is the building of a local bank located at Funato city, and it can be observed from the damages of the windows and the damage of the advertisement panel of the left corner of the building that the tsunami reach the third floor. In Figure 8(b) it is also inferred that the tsunami covered the 2-story building by observing that the windows glasses were destroyed and now are replaced by wood panels. Figure 8(c) is an apartment building located at Rikusentakata city and from the damages of the balconies it is inferred that the tsunami reaches the fourth floor. Detailed of the damages of the balconies can be observed in Figure 8(d), where the panels of the balconies of the fifth floor are intact while the panels of the lower floors are completed destroyed.

Figure 9 shows the condition of a hotel building located very near the shoreline in Rikuzentakata city. The building resists the tsunami attack however the lower floors suffered the destruction of the non-structural elements and also, as it is observed in the Figure 9(a), the damage of a reinforced concrete wall due to the lateral water pressure. In this building it was also observed that the cover concrete of structural elements of columns was spall-out probably due to a combination of earthquake vibration action and posterior tsunami as can be observed in Figure 9(b).

Figure 8. RC buildings after tsunami attack

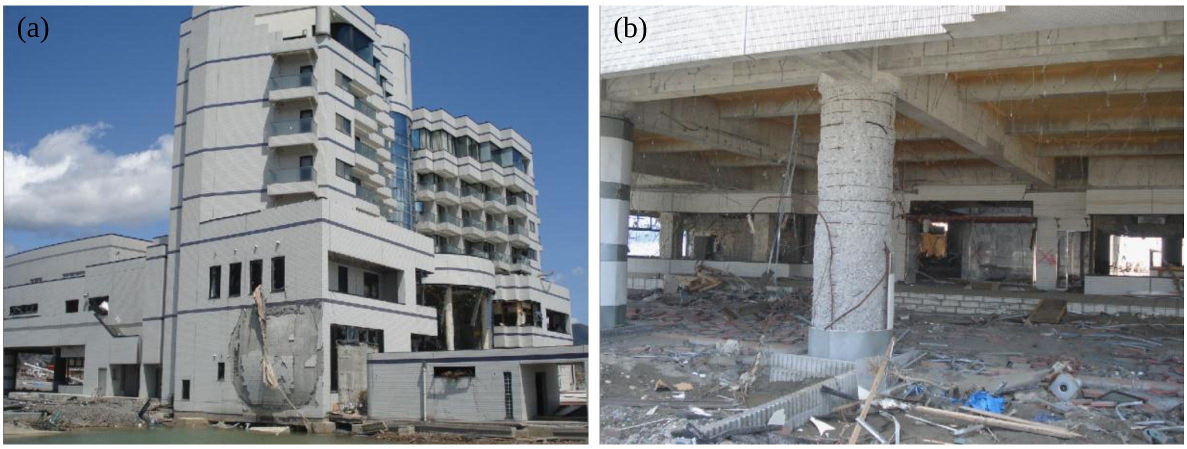

Figure 9. Condition of RC Building (hotel) near shoreline

In general reinforced concrete buildings did not collapse however under certain conditions the tsunami attack caused the overturning and even the translation of building from its original location. This was reported by a survey team of the Tohoku Branch of the Architectural Institute of Japan (March 29, 2011) and verification survey was carried out by the authors. These damages occurred at Onagawa town and the affected buildings were buildings with weak foundation, and with shape like boxes that do not permit the transit of the water and facilitate the action of the floating force. In Figure 10 damages of these buildings are shown.

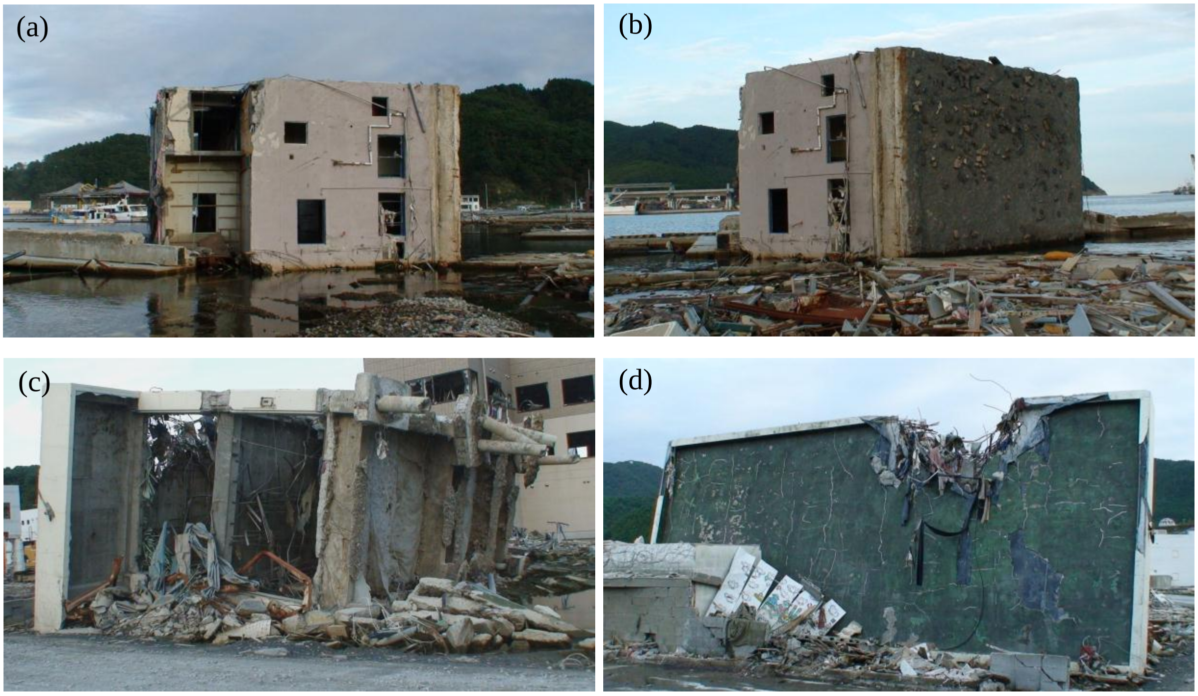

Figure 10. Damages on RC structures

Figures 10(a) shows an overturned 3-story building with a shape of box and few openings. This building was competed covered by the tsunami water and as it is shown in Figure 10(b) it has a sallow slab foundation that together with the shape of the building facilitates the action of the floating forces. Figure 10(c) shows the overturning of a 2-story building with exposition of the pile foundation. The use of piles for lower rise buildings indicates the poor quality of the foundation ground. On the other hand in the Figure 10(d) it can be observed that the building has suffered the impact of a body (probably a ship) that could originate the overturning of the building.

4. CONCLUSIONS

Behaviour of reinforced concrete building during the tsunami action originated by the Great East Japan Earthquake on March 11, 2011 was discussed by comparing their damages with those of other type of constructions. Reinforced concrete buildings in general resist the tsunami without collapse however when constructions present shallow or weak foundation and building shapes induce the action of the floating force, overturning of the building was observed. In the case of not collapsed buildings severe damages on non-structural elements like panels and ceilings were observed.

If reinforced concrete buildings are intended to be used as refuge, buildings of more than four floors or more than 15 meters are recommend. It is also important to check the condition of the foundation of the structures that are designated as refuge since the failure of the foundation could originate the overturning of the building. Additionally, this selected building must be verified to resist some impact forces or in any case must be located in places where the impact of displaced ships or other building can be avoided.

The survey has permitted to understand the behavior of reinforced concrete buildings under tsunami attack and it can be state that these kind of buildings could be used to take refuge from tsunami in places where natural topography make impossible to reach hilltops or other safer places.

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