CHAPTER 5

RC buildings performance under the 2011 great East Japan Tsunami

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Abstract

The Great East Japan Earthquake on 11 March, 2011 is the most powerful known earthquake that has hit Japan with a magnitude 9.0 and with epicentre located at 129 km of Sendai city (off the coast). The earthquake triggered a destructive tsunami with run-up height of up to 40 m that mainly affect cities located on the Pacific Ocean coast of the Tohoku region (north-east region of Japan). Reinforced concrete buildings in general resist the tsunami without collapse; however, the non-structural elements such as panels and ceilings were severely damaged. In this report, the characteristics of the damages and behaviour of RC buildings during the tsunami action are discussed based on the field damage survey in selected cities located on the coast of the affected zone. The analysis made us understand the behaviour of the kind of buildings under tsunami attack, and has also permitted us 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.

Keywords: East Japan Earthquake, RC buildings, seismic damage, tsunami

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 known earthquake that has hit Japan with its epicentre located at 129 km of Sendai city of north-east region of Japan. The earthquake triggered a destructive tsunami with run up height of up to 40 m. The tsunami affects cities mainly located on the Pacific Ocean coast of Iwate, Miyagi and Fukushima prefectures in the Tohoku region, and also Ibaraki prefecture in the 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 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. Reinforced concrete (RC) buildings in general did resist the tsunami without collapse; however, the non-structural elements such as panels and ceilings were severely damaged. However, in some cases low-rise RC buildings were tilted by the tsunami action. In this chapter, the characteristics of the damages and behaviour 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 made us understand the behaviour of the kind of buildings under tsunami attack and has also permitted us 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 11 March, 11 2011 (at 14:46) was an inter-plate earthquake that 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 Mw 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 [1]. The result of this analysis can be observed in Fig. 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 Fig. 1, the source ranges from off the coast of Iwate prefecture to off the coast of Ibaraki prefecture that represents about 500 km of length and also the width of the source is estimated to be 200 km.

The validity of the estimation of the tsunami source area is verified by comparing it with the distribution of the aftershocks. The distribution of these aftershocks (with magnitude larger than 5), According to the Japanese Meteorological Agency, is shown in Fig. 2 (reported by Shimizu Corporation) [2]. 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 the Sanriku region on March 9 (see Fig. 2). On the same day of the main event (11 March, 2011), 33 aftershocks were observed and their frequency decreased as days followed. Events with magnitude 7 or larger are summarized in Table 1. From the aftershocks, two events that occurred on 7th April and 11th April were of magnitude 7 and 7.1, respectively. These magnitudes led to emit the warning of tsunami occurrence. On the other hand, two large inland earthquakes occurred after the main shock. One occurred on 12th March in the northern part of Nagano Prefecture and was of magnitude 6.7. The other one was the earthquake of 15 March in the eastern part of Shizuoka Prefecture and it had a magnitude of 6.4. Also, an event of
Figure 2: Distribution of epicentres.

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

<table>
<thead>
<tr>
<th>Event</th>
<th>Date and time</th>
<th>Epicentre</th>
<th>Depth (km)</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreshock</td>
<td>03/09, 11:45</td>
<td>38°19.7′N, 143°16.7′E</td>
<td>8</td>
<td>Mj 7.3</td>
</tr>
<tr>
<td>Main</td>
<td>03/11, 14:46</td>
<td>38°06.2′N, 142°51.6′E</td>
<td>24</td>
<td>*Mw 9.0</td>
</tr>
<tr>
<td>Aftershocks</td>
<td>03/11, 15:08</td>
<td>39°50.3′N, 142°46.8′E</td>
<td>32</td>
<td>Mj 7.4</td>
</tr>
<tr>
<td></td>
<td>03/11, 15:15</td>
<td>36°06.5′N, 141°15.9′E</td>
<td>43</td>
<td>Mj 7.7</td>
</tr>
<tr>
<td></td>
<td>03/11, 15:25</td>
<td>37°50.2′N, 144°53.6′E</td>
<td>34</td>
<td>Mj 7.5</td>
</tr>
<tr>
<td></td>
<td>04/07, 23:32</td>
<td>38°12.2′N, 141°55.2′E</td>
<td>66</td>
<td>Mj 7.1</td>
</tr>
<tr>
<td></td>
<td>04/11, 17:16</td>
<td>36°56.7′N, 140°40.3′E</td>
<td>6</td>
<td>Mj 7.0</td>
</tr>
</tbody>
</table>

Abbreviations: Mj: Magnitude by Japan Meteorological Agency; *Mw: Moment Magnitude.
magnitude 6.4 in the northern part of Akita prefecture that falls out of the zone of aftershocks was observed. These events produced seismic intensities larger than 5 on the Japanese scale of earthquake intensity.

Comparing Fig. 2 that is the distribution of aftershock epicentres and Fig. 1 that 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 11 March, 2011 with epicentre at 129 km west of the Sendai city has implied a rupture of a large geological fault that ranges from off the coast of Iwate prefecture to off the coast of Ibaraki prefecture, and therefore this event originated a great tsunami that affected 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 such as 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 20 m. In Fig. 3, the distribution of the inundation height and run-up height is observed as is reported by the field survey carried out by the Building Research Institute, Ministry of Construction of Japan [3]. The small circles represent the inundation height that is the height between the water surface at the observation

Figure 3: Inundation height and run-up heights.
point and the original or normal sea level. The triangles represent the run-up height that 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 that 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 that is the cause of the damages on 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.

3 Damages due to tsunami

The damages, on building structures, that were produced by the tsunami are described in this section, specially the damages that occurred on reinforced concrete (RC) structures. However, it is necessary to mention that damages are not limited only to building structures. Tsunami also affected many infrastructures such as ports, embankments, roads, railroads, oil tanks and in its more dramatic damage affected the nuclear power plant of Fukushima. Environmental damages are also reported such as 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 this survey are shown in Fig. 4. This zone is also marked in Fig. 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 facilitate the run-up of tsunami. In the case of Ishinomaki city, as the location shows in the lower left corner of the figure, the coast line is straight; however, the large portion of the city is located parallel to this coast line and therefore the inundation area was large in comparison with other cities. On the other hand, high ground level in the Ishinomaki city is located far away of the coast line. Figure 5 is a detailed aerial photograph published by the Geospatial Information Authority of Japan (GSI) [4], where a portion of the Ishinomaki port after the tsunami can be located.

In Fig. 6, a portion of Ofunato city is shown. It is clear from the figure that only large building remains in the inundated zone while small building like wooden houses were washed up. These buildings were steel structures and RC structures that resist the lateral forces originated by the inundation of the tsunami. In the left part of Fig. 6, some intact constructions can be observed. These building are located on a high ground level that was not reached by the tsunami.
Figure 4: Zone of survey (Google map).

Figure 5: Details of the Ishinomaki city port affected by the tsunami.
Figure 6: Aerial photograph of Ofunato city after the tsunami.

In Fig. 7, a portion of the aerial photograph of Rikuzentaka city can be observed. Near the coast line only few buildings existed after the tsunami attack. The behaviour of the buildings located in the left part, which was a hotel, and the buildings of the lower right side that correspond to apartment buildings is described in the following section. It can be observed that the tsunami first destroyed a sea wall and then the sea water reached the road that can be observed as a straight line from the left to the lower right corner. On the right-upper corner by observing the colour of the vegetation the limit of the inundation area can be inferred. This place corresponds to a high ground level where a school building is located. These school facilities are now used as a shelter zone.

Figure 8 shows the condition of Onagawa town after the tsunami damage. In this aerial view it is possible to clearly identify the zones of high ground level by observing the condition of the vegetation. As can be observed in the figure, the area between the sea line and high ground level is narrow, and therefore the tsunami reached high inundation depths. This high level of water and poor soil condition originated the overturning of some RC buildings that is described in the following section.

Table 2 shows the extension of the inundated area and the number of family units in selected cities of this survey. The number of affected families and the extension of the inundated area are larger for Ishinomaki city. The extension of the inundation area was large due to the location of ports on lower ground along the coast line. On the other hand, Onagawa city is the zone with the smallest values; however, the
Figure 7: Aerial view of Rikuzentakata city after the tsunami.

Figure 8: Aerial view of Onagawa city after tsunami inundation.
The number of victims (deaths and disappeared) was of the order of 1000 persons (1/4 of the number of affected families) and in the case of Ishinomaki, victims reached 4000 persons (1/10 of the number of affected families). The high rate of victims of Onagawa city was due to the topographical condition of the location of the city with a very narrow area between the coast line and the surrounding hill. This condition led tsunami reach high inundation depths and it is also supposed that the successive waves of the tsunami produced violent flows of the sea water.

### 3.2 Damages on buildings

Damages on wooden structures and steel structures are described as reference to compare them with damages on RC buildings. 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 fail and in some cases these fails originate the damage of the main structure. The RC 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 RC buildings in comparison to steel structures and wooden structures. The wooden structures have 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 is summarized in Table 3.

#### 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 m. As is presented in Fig. 9, the damages on wooden houses are divided into three zones according to the inundation depth. Zone A corresponds to places where the inundation depth is smaller than 2 m and structural damages are not observed, that is the wooden houses are safe in this case. Zone B corresponds to a zone where the inundation zone ranges from 2 to 4 m, and depending on the structural shape, condition of the structural elements, etc. 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

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**Table 2: Inundated area and affected families in the investigated cities.**

<table>
<thead>
<tr>
<th>Prefecture</th>
<th>City</th>
<th>Inundated area (km²)</th>
<th>Number of affected families</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iwate</td>
<td>Ofunato</td>
<td>8</td>
<td>6,957</td>
</tr>
<tr>
<td></td>
<td>Rikuzentakata</td>
<td>13</td>
<td>5,592</td>
</tr>
<tr>
<td>Miyagi</td>
<td>Kesennuma</td>
<td>18</td>
<td>13,974</td>
</tr>
<tr>
<td></td>
<td>Onagawa</td>
<td>3</td>
<td>3,155</td>
</tr>
<tr>
<td></td>
<td>Ishinomaki</td>
<td>73</td>
<td>42,157</td>
</tr>
</tbody>
</table>
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 corresponds to a zone where the inundation depth is larger than 4 m and total collapse of the structure is expected to occur.

Figure 10 shows some typical damages on wooden houses that were produced by the tsunami. In Fig. 10(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 Figs. 10(b) and (c) the first floor was destroyed by the tsunami and the upper parts of the houses were transported and then left by the tsunami on a different place from their original location. In the case of Fig. 10(d), the tsunami destroyed the first floor and also produced the overturning of the remaining upper floor.

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 such as 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 the large area generated large lateral forces that destroyed that non-structural elements, and in some cases the failure of these elements led to the failure and even to the collapse of the main structure.

Damages on steel structures can be observed in Fig. 11. When the inundation depth reaches only the first floor, the structure remains almost intact; however, the
Figure 10: Damages on wooden houses.

Figure 11: Damages on steel structures.
wall panels of the first floor suffer some damages as can be observed in Fig. 11(a). In Figs. 11(b) and (c) the inundation depth reached the second floor and wall panels and ceiling are destroyed. In this case, the structures remain stand up, however, some local failures of the structural elements were observed. Figure 11(d) shows a total collapse of steel structures. In this case, the building was completely covered by water.

3.2.3 Damages on RC structures

Many reinforced concrete structures resisted the tsunami action without collapse, as can be observed in Fig. 12. Figure 12(a) is the building of a local bank located at the Funato city, and it can be observed from the damage of the windows and the damage of the advertisment panel of the left corner of the building that the tsunami reached the third floor. In Fig. 12(b), it is also inferred that the tsunami covered the two-story building by observing that the windows glasses were destroyed and are now replaced by wood panels. Figure 12(c) is an apartment building located at Rikusentakata city and from the damages of the balconies it is inferred that the tsunami reached the fourth floor. Details of the damages of the balconies can be observed in Fig. 12(d), where the panels of the balconies of the fifth floor are intact while the panels of the lower floors are completely destroyed.

Figure 13 shows the condition of a hotel building located very near the shoreline in the Rikuzentakata city. The building resists the tsunami attack; however, the lower floors suffered the destruction of the non-structural elements and also, as is
observed in Fig. 13(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 Fig. 13(b).

In general, reinforced concrete buildings did not collapse; however, under certain conditions the tsunami action 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 [5] and the verification survey was carried out by the author. These damages occurred at Onagawa town and the affected buildings were those 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 Fig. 14, damages of these buildings are shown.

Figure 14(a) shows an overturned three-story building with a shape of box and few openings. This building was completely covered by the tsunami water, and as is shown in Fig. 14(b) it has a shallow slab foundation that together with the shape of
the building facilitates the action of the floating forces. Figure 14(c) shows the overturning of a two-story building with exposition of the pile foundation. Its use for lower rise buildings indicates the poor quality of the foundation ground. On the other hand in the Fig. 14(d) it can be observed that the building has suffered the impact of something (probably a ship) that could originate the overturning of the building.

4 Conclusions

Behaviour of RC building during the tsunami action originated by the Great East Japan Earthquake on 11 March, 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 non-collapsed buildings severe damages on non-structural elements such as 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 m 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 behaviour 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.

References