Damage to Steel Educational Facilities in the 2011 East Japan Earthquake: Part 1 Outline of the Reconnaissance and Damage to Major Structural Components

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SUMMARY:
On 11 March 2011, the strong ground motion and tsunami caused by the East Japan Earthquake, which occurred off the coast of Miyagi Prefecture, induced extensive damage along the Pacific coast. A series of reconnaissance on steel educational facilities were conducted in Iwate, Miyagi, Fukushima, Ibaraki, Chiba, and Tochigi prefectures from April to June 2011. The buildings were categorized according to the year of construction and date of retrofit, and the damage of each group was examined. In this paper, the outline of the reconnaissance, the method of evaluation, as well as the damage to diagonal braces and column bases are reported.

Keywords: the 2011 East Japan Earthquake, steel buildings, reconnaissance, brace, column base

1. INTRODUCTION

On 11 March 2011, the East Japan Earthquake occurred off the coast of Miyagi Prefecture. The magnitude 9.0 earthquake was one of the largest earthquakes ever recorded in the world, and the strong ground motion and tsunami induced extensive damage along the Pacific coast. In response to the request of the Ministry of Education, Culture, Sports, Science and Technology, a series of reconnaissances were conducted on steel educational facilities in order to assess their damage and plan their rehabilitation policy. The reconnaissances were conducted only on buildings of which the decisions as to whether they should be repaired or rebuilt were difficult to make and also had a survey request submitted. Thus, the reconnaissances do not cover all the school buildings in each region. However, the majority of the severely damaged buildings are believed to have been covered and enable one to make claims on the general trend of the types of damage that have occurred. The damage to major structural components due to earthquake ground motion is reported in this paper. The damage of the other components and damage due to the tsunami are discussed in Part 2 (Koyama et al, 2012).

2. OVERVIEW OF THE RECONNAISSANCE

2.1. Area and period

As shown in Figure 2.1, the surveyed areas include Iwate, Miyagi, Fukushima, Ibaraki, Chiba, and Tochigi prefectures. The period of reconnaissance is from April to June 2011. A total of 216 steel school facilities, which include 147 gymnasiums, were surveyed. According to the ground motion record at the nearest monitoring point of each site, about 90% of the buildings experienced a ground motion with a 6-lower or 6-upper reading on the Japan Meteorological Agency seismic intensity scale.

2.2. Method of evaluation

A visual survey was conducted on each building and the damage was evaluated according to a guideline for post-earthquake damage evaluation (2001) issued by the Japan Building Disaster Prevention Association. The damage to each structural component was ranked from 0s(no damage) to VIs(complete collapse) based on the criteria shown in Table 2.1 with the most severe rank of all components used as the structural damage rank of the entire structure. The damage to each non-structural component was also evaluated from Iw (slight damage) to IVw (major damage) with the most severe rank used as the non-structural damage rank. The overall damage of the entire building was ranked from the combination of structural and non-structural damage rank according to the diagram shown in Table 2.2.

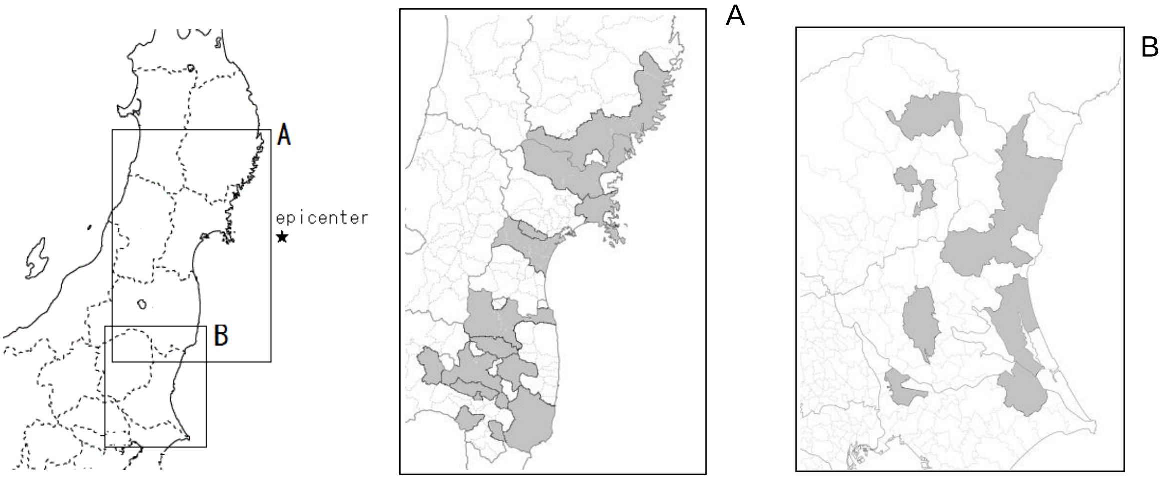


Figure 2.1. Area covered by the reconnaissance

Table 2.1. Criteria to evaluate the damage rank of structural components

Damage rank	Structural component			
	Column base	Diagonal brace	Column, beam, panel zone	Foundation
0s	No damage			
Is	Cracking of concrete	Slight buckling	Slight yielding Tilt 1/300-1/150	Tilt 1/300-1/150
IIs	Elongation of anchor bolts	Slip of friction bolts Yielding of braces	Yielding of the panel zone Tilt 1/150-1/100	Tilt 1/150-1/100
IIIs	Fracture of anchor bolts (less than 20%)	Fracture of braces (less than 20%)	Slight local buckling Tilt 1/100-1/50	Tilt 1/100-1/50
IVs	Fracture of anchor bolts(20-50%)	Fracture of braces (20-50%)	Moderate local buckling Fracture (less than 20%) Tilt 1/50-1/30	Tilt 1/50-1/30
Vs	Fracture of anchor bolts(more than 50 %)	Fracture of braces (more than 50 %)	Severe local buckling Fracture (more than 20%) Tilt more than 1/30	Tilt more than 1/30
VIs	Complete collapse			

Table 2.2. Damage evaluation diagram

<table>
<tr><td></td><td colspan="8">Structural damage rank</td></tr>
<tr><td rowspan="5">Non-structural damage rank</td><td></td><td>0s</td><td>Is</td><td>IIs</td><td>IIIs</td><td>IVs</td><td>Vs</td><td>VIs</td></tr>
<tr><td>Iw</td><td rowspan="2">Slight damage</td><td rowspan="4">Minor damage</td><td rowspan="2"></td><td rowspan="4">Moderate damage</td><td rowspan="2"></td><td rowspan="4">Major damage</td><td rowspan="4">Complete collapse</td></tr>
<tr><td>IIw</td></tr>
<tr><td>IIIw</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>IVw</td></tr>
</table>

3. OUTLINE OF THE DAMAGE

3.1. Classification of the facilities

As mentioned in Section 2.1, gymnasiums account for 70% of the total buildings. Classrooms account for 20%, and the rest include dormitories and storehouses. The structure of a typical gymnasium is shown in Figure 3.1. It is a steel structure (S-type) composed of moment resistant frames in the Y-direction and braced frames in the X-direction. Other common types are shown in Figure 3.2. One is the R-type which is a reinforced concrete frame with a steel roof, and the other is the RS-type whose upper part is a steel frame and lower part is a reinforced concrete frame.

The Building Standard Law of Japan was drastically revised in 1981 and the buildings designed after this revision are conceivably more resilient to severe earthquakes. The distribution of buildings with respect to their year of construction is shown in Figure 3.3. Two-thirds of the buildings were constructed in or before 1981. The years of construction of 20 buildings were not identified. In this paper, the buildings are categorized as follows.

1) Post 1981: 64 buildings
   a) Constructed after 1981
2) Retrofitted: 40 buildings
   a) Constructed in or before 1981, and seismically retrofitted before the earthquake, or
   b) Constructed in or before 1981, and has seismic resistance equivalent to "Post 1981 buildings" according to seismic evaluation.
3) Non-retrofitted: 97 buildings
   a) Constructed in or before 1981 and neither seismic evaluation nor seismic retrofit has been conducted.

3.2. Damage rank distribution

Figure 3.4 shows the distribution of the damage rank in each group. In the "Post 1981" or "Retrofitted" group, the ranks slight damage and minor damage account for 60% of the buildings damaged due to ground motion. Since the percentage of these two groups match, one can confirm the effectiveness of retrofitting. However, some buildings suffered major damage, and the damage rank of the column base was IVs or Vs for most of these buildings. In the "Non-retrofitted" group, major damage accounts for 40% of the buildings damaged due to ground motion.

Figure 3.5 shows the distribution of the structural components ranked as IVs or Vs in the buildings with major damage for each group. The "column base" category in this figure includes the roof-column anchor connection of R-type gymnasiums. In the "Post 1981" group, the most severe damage was observed at the column bases, and second at the diagonal braces. In the "Retrofitted" or "Non-retrofitted" groups, the most severe damage was observed at the diagonal braces, and second at the column bases.

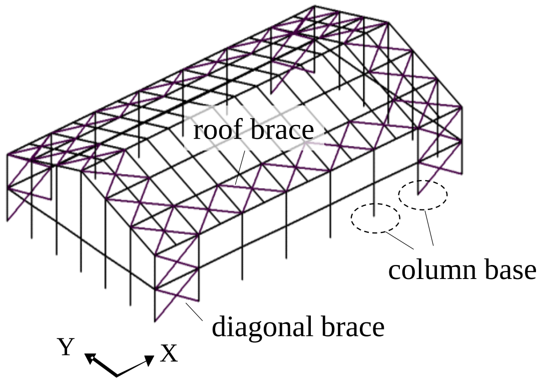


Figure 3.1. Typical structure of a school gymnasium (S-type)

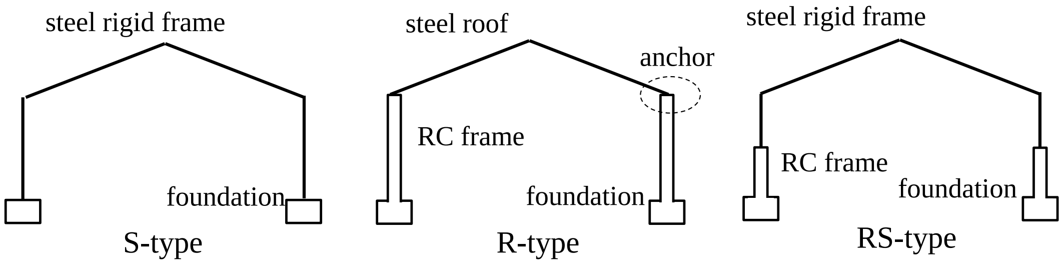


Figure 3.2. Structural frame in the Y-direction

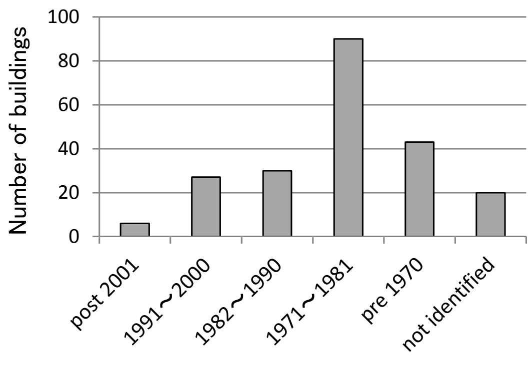


Figure 3.3. Year of construction

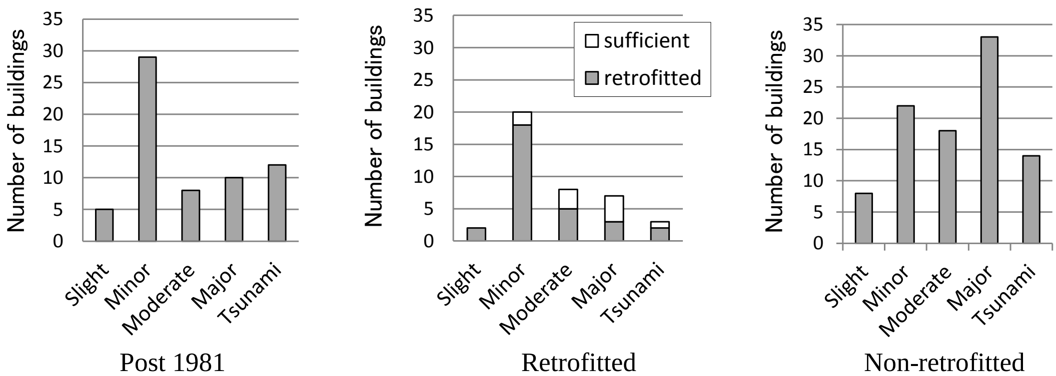


Figure 3.4. Damage rank of the buildings

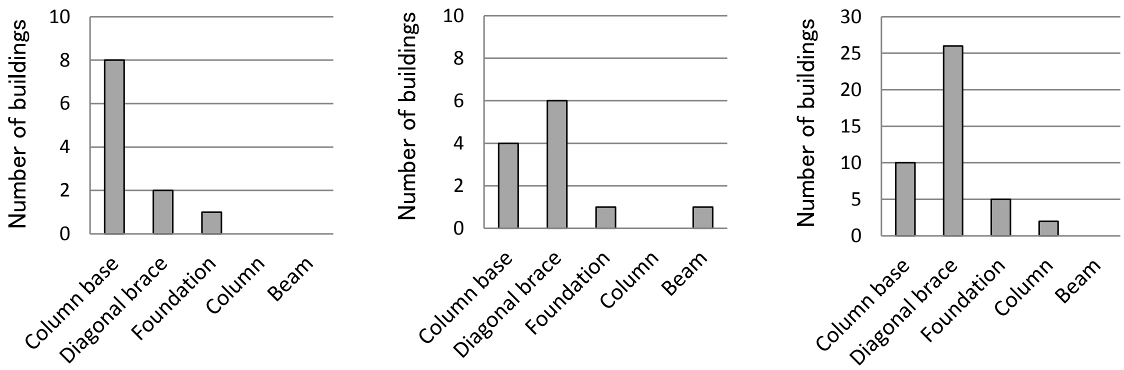


Figure 3.5. Structural components whose damage rank was IVs or Vs of buildings with "major damage"

4. DAMAGE TO DIAGONAL BRACES

In this section, the damage to diagonal braces in 129 buildings caused by the ground motion is discussed. Figure 4.1 shows the number of buildings grouped according to the shape of the brace section. The angle section was used in 60% of the buildings (70% of the gymnasiums) and the round bar with a turnbuckle was used in 30% of the buildings (25% of the gymnasiums). The round bar was mainly used in buildings constructed in or before 1981. Others sections used are tubes and flat bars.

Figure 4.2 shows the distribution of buildings grouped according to the brace section shape and damage rank. As shown in Table 2.1, a damage rank of IIIs or above means that fracture occurred at the section or connection of the brace.

Typical damage observed in angle braces is shown in Figures 4.3, 4.4, and 4.5. Figure 4.3 shows the buckling and yielding of an angle brace, and Figures 4.3 and 4.4 show fracture at the brace connection. In the current Japanese building standard, the brace connection, including the bolt, weld, and gusset plate, is required to have a higher ultimate strength than the yield strength of the brace's effective cross section in order to ensure ductility of the structure. The fracture of the angle brace was exclusively observed in buildings constructed before 1981 and these brace connections conceivably didn't meet the demands of the current building standard.

Typical damage observed in round bars with a turnbuckle is shown in Figures 4.6, 4.7, and 4.8. The brace fractured in 28 out of 44 buildings, and this ratio is higher than in the buildings with angle braces. Although fracture mainly occurred in buildings constructed before 1981, a case worthy of mentioning is the fracture of a turnbuckle in a building constructed in the 1990s, shown in Figure 4.9. At this time, the usage of Japan Industrial Standard turnbuckle braces for buildings was not common practice, and the ductility of turnbuckle braces wasn't always ensured. One can assume that the fractured brace shown in Figure 4.9 did not have sufficient ductility. Similarly, the fracture of a tube-section brace shown in Figure 4.10, which was used in a pre 1981 building whose seismic evaluation deemed it unnecessary to retrofit, is believed to have prematurely fractured due to lack of ductility.

Other types of severe damage observed are the out of plane bending and fracture of the brace joint in Figure 4.11, the fracture of the gusset plate in Figure 4.12, and the fracture of the fillet weld in Figure 4.13. These were observed in buildings constructed before 1981.

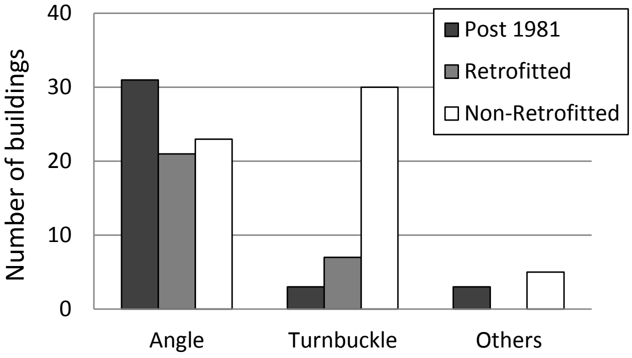
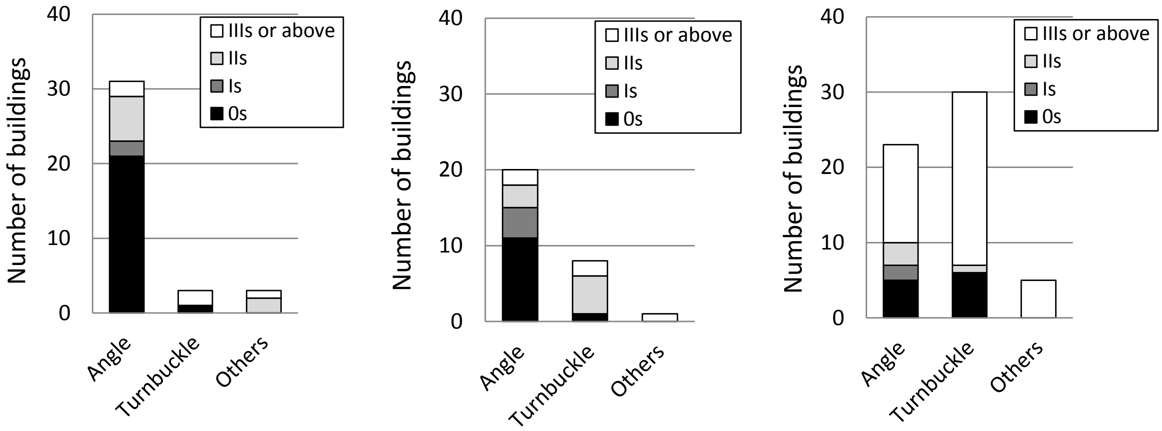


Figure 4.1. Section shapes used in the diagonal braces



Post 1981   Retrofitted   Non-retrofitted

Figure 4.2. Damage rank of the diagonal braces

Figure 4.3. Buckling and yielding

Figure 4.4. Pull out fracture at the end

Figure 4.5. Net section fracture

Figure 4.6. Fracture at the turnbuckle

Figure 4.7. Fracture at the screw

Figure 4.8. Fracture at the bolt

Figure 4.9. Fracture at the turnbuckle

Figure 4.10. Fracture of the tube-section brace

Figure 4.11 Out of plane bending

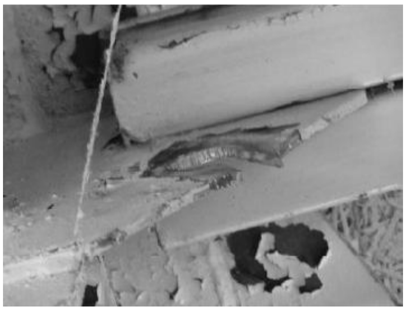


Figure 4.12 Pull out fracture at the gusset plate

Figure 4.13 Fracture at the weld

5. DAMAGE TO COLUMN BASES

In this section, the damage to column bases in 173 buildings caused by the ground motion is discussed. Figure 5.1 shows the number of buildings grouped according to the structure type (S, R, or RS). Figure 5.2 shows the distribution of the damage rank grouped according to the year of construction. A damage rank of IIs includes damage such as the fracture of the concrete shown in Figure 5.3. In this case, one can assume that elongation of the anchor bolt has already occurred. As shown in Table 2.1, a damage rank of IIIs or above means that fracture of the anchor bolts or equivalent damage has occurred. Out of the 120 damaged buildings, the anchor bolts fractured in 27.

As mentioned in Section 2.2, most of the severe damage was observed at the column bases in the "Post 1981" group. Figure 5.4 shows a fractured column base from a "Post 1981" building. Both elongation and fracture of the anchor bolts were observed. Up till the 1995 Kobe earthquake, the column base had been designed as a pinned connection and elongation of the anchor bolt was not always considered in design. Due to the severe damage that occurred in exposed column bases under the earthquake, a provision to prevent premature fracture of the anchor bolts was added to the Ministry of Construction (currently part of the Ministry of Land, Infrastructure, Transport and Tourism) notification No. 1791 and it has been required to follow this provision in practice since. However, it was not till the 2000s that standards for anchor bolts with ensured ductility were decided on and then manufactured. This is why severe damage has occurred to column bases of the "Post 1981" buildings.

Figure 5.5 shows a fractured column base of a building which did not require retrofit by the standards for seismic evaluation. Figures 5.6 and 5.7 show elongation and fracture of the anchor bolts in "Non-retrofitted" buildings. Fracture at the column base was observed in many buildings constructed in or before 1981, as well as in the "Post 1981" group. Although most failed in tension, some failed by torsion of the column caused by an eccentrically connected brace as is shown in Figure 5.8.

Typical damage of an R-type gymnasium was the collapse of the side concrete at the anchor, shown in

Figure 5.9. In one-third of the R-type gymnasiums, the anchor's damage was ranked as IIs, which includes concrete collapse like in this figure. Figure 5.10 shows the sway of the roof base in an R-type gymnasium. In this case, the anchor bolt was bent and fractured because the amount of sway exceeded the clearance between the bolt and base plate.

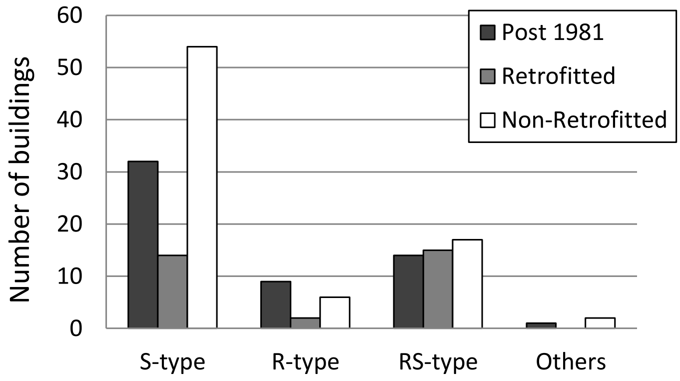
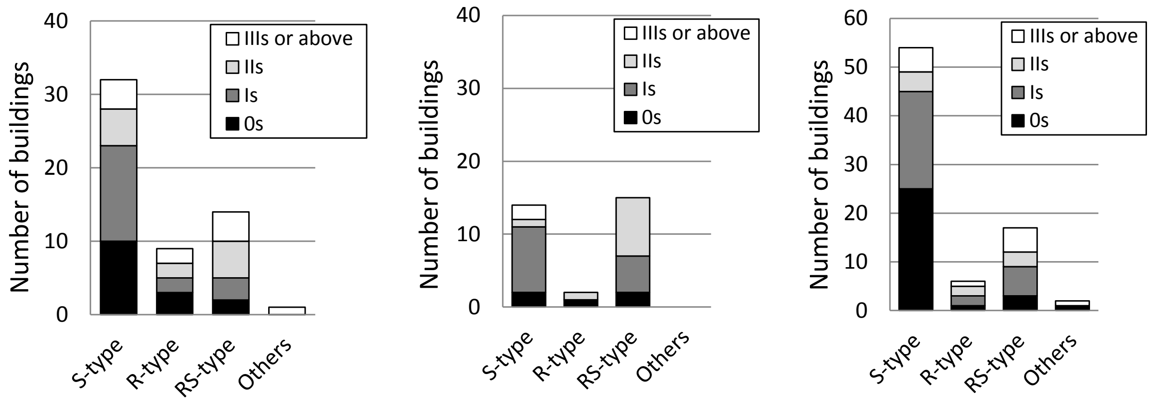


Figure 5.1. Number of buildings



Post 1981 Retrofitted Non-retrofitted

Figure 5.2. Damage rank of the column base

Figure 5.3. Collapse of the concrete

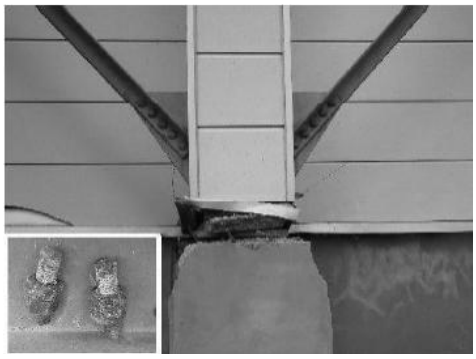


Figure 5.4. Pull out fracture of the anchor bolts

Figure 5.5. Pull out fracture of the anchor bolts

Figure 5.6. Pull out fracture of the anchor bolts

Figure 5.7. Elongation of the anchor bolt

Figure 5.8. Fracture and torsion of the column base

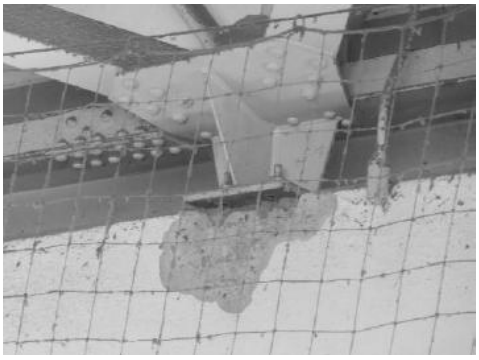


Figure 5.9. Collapse of the concrete (R-type gym)

Figure 5.10. Sway of the roof base(R-type gym)

6. CONCLUSION

The 2011 East Japan Earthquake caused extensive damage along the Pacific coast of Japan. A series of reconnaissances were conducted in 6 prefectures from April to June 2011. The damage to 216 steel school buildings was surveyed and evaluated. The buildings were categorized into “Post 1981,” “Retrofitted” and “Non-retrofitted” groups, and the damage of each group was examined. The following conclusions can be made.

1) In the “Post 1981” group, the percentage of major damage was lower than that of the “Non-retrofitted” group. However, fracture of the diagonal brace or fracture of the column base was observed in several “Post 1981” buildings. It is conceivable that the ductility of these components was not ensured.
2) In the “Retrofitted” group, the percentage of buildings with slight or minor damage was equivalent to the “Post 1981” group, and the effectiveness of retrofit was confirmed.

3) In the ”Non-retrofitted” group, most of the severe damage was observed at the diagonal braces. It seems that the ultimate strength of the brace connection didn’t meet the demand of the current Japanese building standard.

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