ABSTRACT: The 2011 Tohoku Japan earthquake and tsunami caused extensive damage to steel building structures. Large slippage over a large inter-plate fault produced very high tsunami waves that attacked the east coast of Japan. The Committee of Steel Structures of the Architectural Institute of Japan carried out earthquake damage reconnaissance over cities where severe ground shaking was recorded among the prefectures of Miyagi and Fukushima. Tsunami damage reconnaissance was also conducted along the coastlines of Iwate, Miyagi, and Fukushima.

Key Words: 2011 Tohoku Japan earthquake, earthquake damage, tsunami damage, steel building

INTRODUCTION

The Committee of Steel Structures of the Architectural Institute of Japan carried out earthquake damage reconnaissance over the prefectures of Miyagi and Fukushima. Tsunami damage reconnaissance was conducted along the coastlines of the prefectures of Iwate, Miyagi, and Fukushima.

The observed damage to steel buildings are classified into those caused by ground motions and those caused by tsunami. Severe ground motion caused damage to beam-to-column connections, buckling of diagonal braces, cracking and fracture of concrete overlaying the column base, yielding and fracture of anchor bolts, which are the similar damage aspects observed from past earthquakes. Severe nonstructural damage occurred to ceilings and claddings of steel building structures with large open areas, such as gymnasiums and factories. Extensive damage was observed in external finishes composed of mortar over light-gauge metal lath.

A distinctive feature of the Tohoku event is the damage caused by tsunami. In the most extreme
cases, buildings were displaced from their original location and completely destroyed. In other cases, fracture of connections and members caused the building to tilt or collapse. In buildings whose claddings were completely washed away by tsunami, structural damage was minor. The extent of tsunami damage is various significantly depending on the locality of tsunami attack.

**DAMAGE CAUSED BY EARTHQUAKE GROUND MOTION**

The ground motion caused damage to many low- to mid-rise buildings. Judging from the types of members and framing system, the majority of damaged buildings were constructed in older years preceding the major change in the seismic provisions of the Building Standard Law in 1981.

**Damage to structural members**

*Beam-to-column connections*

Brittle fracture of beam-to-column connections, which was observed widely after the 1995 Kobe earthquake, has not been reported from the Tohoku event. Photo 1 shows damage observed in an older structure that employed built-up HSS (hollow structural steel) columns made up of a light W-shape and a pair of cover plates. Such sections were commonly used before cold-formed HSS sections became available.

*Braces and bracing connections*

Brace buckling, net-section fracture, and distortion and fracture of the gusset plates were observed in many brace framed structures (Photos 2-10).

Failure of angle-section braces, which were commonly used in older construction, was typically governed by buckling and fracture initiating at the bolt holes. In contrast, the predominant damage to HSS braces was out-of-plane bending of the gusset plates. Some gusset plates fractured as a result of a large number of repeated bending.

*Column bases*

The majority of investigated buildings were low- to mid-rise, where exposed base plate connections are more commonly used than embedded or encased column base connections. The damage to exposed base plates points out that, unless the anchor bolts fractured, residual story drift and structural damage to the building was minimal. On the other hand, evidence suggests that fracture of anchor bolts led to dislocation of the column and severe residual story drift (Photos 11-18).

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Photo 1 Yielding of an older built-up column (Koriyama)  
Photo 2 Buckling of double-angle brace (Miyagino, Sendai)  
Photo 3 Local buckling in square-HSS brace (Aoba, Sendai)
Photo 10 Out-of-plane deformation of gusset plate caused by compression (Miyagino, Sendai)

Photo 11 Spalling of reinforced concrete encasing a steel column base (Wakabayashi, Sendai)

Photo 12 Elongation of anchor bolts in an exposed base plate (Miyagino, Sendai)

Photo 13 Cracking of asphalt covering a column base (Miyagino, Sendai)

Photo 14 Spalling of concrete covering a column base (Koriyama)

Photo 15 Spalling of reinforced concrete foundation supporting a column base (Koriyama)
Damage to nonstructural elements

Widespread damage was observed in dry-construction elements such as ceilings made up of mortar over metal lath and ALC-panel cladding. Nonstructural damage was observed in buildings of all construction ages (Photos 19-30). Extensive damage was observed in older-type external finishes that place mortar.

Photo 16 Fracture of anchor bolts (Miyagino, Sendai)

Photo 17 Fracture of anchor bolts, spalling of concrete covering a column base (Miyagino, Sendai)

Photo 18 Fracture of anchor bolts, out-of-plane deformation of base plate (Miyagino, Sendai)

Photo 19 Fallen ceiling grid and boards (Fukushima)

Photo 20 Fallen claddings; damaged ceiling boards (Miyagino, Sendai)

Photo 21 Fallen ceiling, partitions damaged by impact (Aoba, Sendai)

Photo 22 Partly fallen ceiling (Koriyama)

Photo 23 Fallen ceiling on the outside of a building (Wakabayashi, Sendai)

Photo 24 Cracking of external finish (Aoba, Sendai)

Photo 25 Failure of metal lath-and-mortar cladding (Miyagino, Sendai)

Photo 26 Fallen cladding (Ishinomaki)

Photo 27 Fallen and twisted cladding (Koriyama)
DAMAGE CAUSED BY TSUNAMI

In areas attacked by high tsunami waves, severe damage was observed such as failure of the column base that led to overturning and dislocation of the building, and extreme distortion of structural members and connections. In instances where the external claddings were washed away, the load produced by tsunami was reduced to cause little damage to the structural system. Tsunami damage is described for different districts in the following.

Port of Ishinomaki (reported inundation height 5 m)

**Office building A (Photos 31-32)**
X-dir.: 5 spans, Y-dir.: 2 spans, Number of stories: 1
X-dir.: moment frame, Y-dir.: moment frame
Columns: square HSS’s, Beams: W-shapes, External finish: ALC panels
Observations: Internal and external finishes washed away. No structural damage.

**Office building B (Photos 33-34)**
X-dir.: 5 spans, Y-dir.: 1 span, Number of stories: 2
X-dir.: braced frame, Y-dir.: moment frame
Columns: W-shapes, Beams: W-shapes, Braces: angles (1F), round bars (2F), External finish: ALC panels
Observations: Extensive structural damage. Foundation exposed due to scouring, braces fractured.

**Port Facility A (Photos 35-37)**
X-dir.: braced frame, Y-dir.: moment frame
Columns: W-shapes, Beams: W-shapes, Braces: round bars, Column base: exposed type
Observations: External cladding partly lost. Residual drift of 1/400 in the north and east directions.

**Port facility B (Photos 38-39)**
X-dir.: braced frame, Y-dir.: moment frame
Columns: W-shapes, Beams: W-shapes, Braces: angles, Column base: exposed type
Observations: Two spans closest to the shore collapsed. Fracture of anchor bolt
Onagawa (reported inundation height 15 m)

Building A (Photos 40-41)
X-dir.: 3 spans, Y-dir.: 1 span, Number of stories: 3
Y-dir.: moment frame
Columns: W-shapes, Beams: W-shapes, External finish: corrugated metal sheets
Observations: Building tilted after foundation scouring.

Building B (Photos 42-43)
Number of stories: 3 (partially 4)
X-dir.: moment frame, Y-dir.: moment frame
Columns: square HSS’s, Beams: W-shapes, External finish: ALC panels
Observations: Building dislocated about 15 meters and lain sideways after all piles failed due to pullout.

Building C (Photos 44-45)
Columns: square HSS’s, Beams: W-shapes
Observations: Collapsed after extensive connection failure.

Building D (Photos 46-48)
X-dir.: moment frame, Y-dir.: moment frame
Columns: older built-up square HSS’s, Beams: W-shapes, Column bases: exposed type
Observations: Internal and external finishes washed away, damage in column bases.

**Building E (Figures 49-51)**
Columns: Square HSS’s, Beams: W-shapes, Column bases: exposed type  

**Warehouse A (Photos 52-54)**
Use: Refrigeration  
X-dir.: braced frame, Y-dir.: moment frame  
Shiogama (Reported inundation height: 4 m)

*Warehouse B (Photos 55-56)*
Columns: W-shapes, Beams: W-shapes, Braces: round bars, Column bases: exposed type, External finish: slate tiles over metal lath
Observations: Foundation subsided due to tsunami and liquefaction.

Miyagino, Sendai (Reported inundation height: 8 m)

*Office Building C (Photos 57-59)*
Columns: square HSS’s, Beams: W-shapes, Column bases: exposed type
Observations: Underground piping exposed after scouring.

*Office Building D (Photos 60-61)*
X-dir.: moment frame, Y-dir.: moment frame
Columns: Square HSS’s, Beams: W-shapes, Column bases: exposed type
Observations: First floor cladding washed away. No structural damage.
Minami-Sanriku (Reported inundation height: 13 to 15 m)

Office Building E (Photos 62-63)
X-dir.: moment frame, Y-dir.: moment frame
Observations: Evidence of beam yielding. No residual drift.

Store A (Photos 64-65)
X-dir.: moment frame, Y-dir.: moment frame

Factory A (Photos 66-67)
X-dir.: moment frame, Y-dir.: moment frame
Observations: Chord member of roof truss buckled presumably due to impact of debris. Part of structure demolished and cleaned by the time of visit.

Gymnasium A (Photos 68-70)
X-dir.: moment frame, Y-dir.: moment frame
Observations: Wall closest to shore line was pulled toward the shore. Roof truss buckled and collapsed. Anchor bolts in column base fractured. Bolts joining roof truss members fractured. Adjacent 3-story R/C school building completely subsided during tsunami attack.
Kesennuma (Reported inundation height: 4 to 10 m)

**Warehouse C (Kawaguchi District) (Photos 71-72)**
X-dir.: moment frame, Y-dir.: X-braced frame
Observations: Collapsed and severely deformed.

**Store B (Photos 73-74)**
X-dir.: moment frame, Y-dir.: moment frame

**Hotel A (Niihama District) (Photos 75-76)**
X-dir.: moment frame, Y-dir.: moment frame
Observations: Second story collapsed after weld fracture between through-diaphragm plate and column.

**Store C (Photos 77-79)**
Single story
X-dir.: moment frame, Y-dir.: moment frame
Observations: Plastic hinging and fracture at top and bottom of column. Residual drift of 1/5 in Y-direction.

**Factory B (Photos 80-81)**
X-dir.: unknown, Y-dir.: moment frame
Observations: Residual deformation of 1/10 in lower segment with cracking of concrete encasing the column bases, yielding of panel zone, and local buckling of beam flanges.

**Factory C (Photos 82-83)**
X-dir.: inverted V-braced frame, Y-dir.: moment frame
Observations: Buckling and fracture of braces, bending of column base plates.
**Factory D (Photos 84-85)**

X-dir.: braced frame, Y-dir.: gable frame

Observations: Collapsed in Y-direction. Yielding in column bases and panel zones and gable frame beams

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Photo 71 Warehouse C: external view.

Photo 72 Warehouse C: deformed columns and beams.

Photo 73 Store B: external view.

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Photo 74 Store B: fractured beam-to-column

Photo 75 Traditional hotel A: external view.

Photo 76 Traditional hotel A: close-up view of collapsed second story.

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Photo 77 Store C: external view.

Photo 78 Store C: distorted columns.

Photo 79 Store C: plastic deformation at top of first-story column.

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Photo 80 Factory B: external view.

Photo 81 Factory B: yielding in beam-to-column connection.

Photo 82 Factory C: external view.
Rikuzen-Takada (Reported inundation height 12 to 16 m)

**Store D (Photos 86-87)**
X-dir.: moment frame, Y-dir.: moment frame
Observations: No residual drift. Torsional deformation of beams in frame facing the shore line.

**Store E (Photos 88-89)**
X-dir.: moment frame, Y-dir.: moment frame
Observations: Residual drift of 1/200. Damage to second-floor concrete slab. Suspected cause is lifting force produced by air pocket in the first story.

**Factory E (Photos 90-92)**
X-dir.: X-braced frame, Y-dir.: moment frame

**Gymnasium B (Photos 93-94)**
X-dir.: X-braced frame, Y-dir.: gable frame
Observations: First story collapsed in X-direction. Building displaced in X-direction by 20 m.

**Gymnasium C (Photos 95-97)**
X-dir.: X-braced frame, Y-dir.: moment frame, roof: space truss
Observations: Severe deformation of frame facing the shore line. Buckling of X-braces. Buckling of chord members in roof truss.
Kuji (Reported inundation height at Kuji Port: 8 to 9 m)

*Warehouse D (Photos 98-99)*
X-dir.: moment frame, Y-dir.: moment frame
Columns: W-Shapes, Beams: W-Shapes
Observations: No structural damage. Internal and external finish washed away.

*Factory F (Photos 100-101)*
X-dir.: moment frame, Y-dir.: X-braced frame
Columns and beams: Built-up W-Shapes, Braces: round bars, External finish: corrugated metal sheets
Observations: Evidence of debris impact on shore side wall.

*Factory G (Photos 102-103)*
X-dir.: 1 span, Y-dir.: 3 spans, Number of stories: 2
X-dir.: moment frame, Y-dir.: moment frame
Columns: square HSS’s, Beams: W-shapes, External finish: corrugated metal sheets
Observations: Internal and external finishes washed away. No residual drift.
Miyako (Reported Inundation height at Taro Port: 13.4m)

**Hotel B (Photos 104-105)**
X-dir.: 1 span, Y-dir.: 6 spans, Number of stories: 6
X-dir.: moment frame, Y-dir.: moment frame
Columns: Square HSS’s, Beams: W-shapes, Column base: concrete encased, External finish: ALC panels
Observations: Internal and external finish washed away in first to third stories. Little residual drift.

**Ice Making Factory A (Photos 106)**
X-dir.: 1 span, Y-dir.: 2 spans, Number of stories: 4
Columns: square HSS’s (concrete-encased in first story), Beams: W-shapes, External finish: extruded cement panels
Observations: Internal and external finishes washed away in first to third stories. Little residual drift.

Kamaishi

**Office Building F (Photos 107-108)**
X-dir.: 4 spans, Y-dir.: 2 spans, Number of stories: 2
X-dir.: moment frame, Y-dir.: moment frame
Columns: Square HSS’s, Beams: W-shapes, Column bases: exposed type, External finish: extruded cement panels
Observations: Internal and external finishes washed away. Little residual drift. Foundation exposed after scouring.

**Ohfunato**

**Factory H (Photos 109-110)**
X-dir.: 2 spans, Y-dir.: 3 spans, Number of stories: 2
Columns: older built-up square HSS’s (1F), W-shapes (2F), Beams: W-shapes, Column bases: exposed type, External finish: slate tiles
Observations: Internal and external finishes washed away. First story deformed towards shoreline. Round bar braces fractured.

**Damage caused by ground deformation and fire**

In areas with poor soil conditions, ground deformation caused structural damage. In some cases the foundation mounted on piles was undamaged but the surrounding soil subsided. Liquefaction caused differential subsidence that tilted the building. (Photos 111-113)

Damage in some buildings was exacerbated by fire that initiated after the earthquake and tsunami. The cause of fire is unknown. (Photos 114-116)
SUMMARY

Preliminary observations are summarized as follows:
1) The ground motion caused limited structural damage to steel buildings constructed after major revision in the seismic provisions of the Building Standard Law was implemented in 1981. However, older buildings constructed prior to 1981 saw notable damage caused by ground motion. Nonstructural damage to internal and external finishes and ceilings was extensive regardless of construction age.
2) A large proportion of industrial and commercial facilities in the tsunami affected area were constructed in steel. Extensive damage was observed in these steel buildings.
3) In areas attacked by violent tsunami, some steel buildings saw limited structural damage because their internal and external finishes were immediately washed away. Many buildings were damaged by debris impact.
4) In areas attacked by less violent tsunami, steel buildings saw varying degrees of nonstructural damage depending on the tsunami water height. However, the majority of buildings saw limited structural damage.

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