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EARTHQUAKE AND TSUNAMI DAMAGE ON STEEL BUILDINGS CAUSED BY THE 2011 TOHOKU JAPAN EARTHQUAKE

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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).

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)

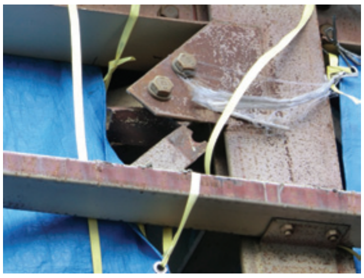

Photo 4 Net section fracture of single-angle brace (Miyagino, Sendai)

Photo 5 Bending of middle gusset plate in an X-brace (Miyagino, Sendai)

Photo 6 Fracture of gusset plate-to-column weld and spalling of concrete covering an exposed base plate (Ishinomaki)

Photo 7 Out-of-plane deformation of gusset plate (Miyagino, Sendai)

Photo 8 Yielding of column web near bracing connection (Koriyama)

Photo 9 Out-of-plane deformation and fracture of gusset plates (Miyagino, 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)

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)

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 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)

Photo 28 Damage to cladding covering a column (Wakabayashi, Sendai)

Photo 29 Damaged cladding in a mechanical penthouse (Koriyama)

Photo 30 Damaged cladding (Sukagawa)

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

Photo 31 Office building A: External view.

Photo 32 Office building A: inside view.

Photo 33 Office building B: external view showing noticeable residual drift.

Photo 34 Office building B: net section fracture of a single-angle brace.

Photo 35 Port facility A: external view.

Photo 36 Port facility A: inside view.

Photo 37 Port facility A: column base rusted presumably due to seawater proximity.

Photo 38 Port facility B: external view.

Photo 39 Port facility B: fractured 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
Observations: Collapsed. Fracture of beam-to-column connections, anchor bolts, and horizontal braces.

Warehouse A (Photos 52-54)
Use: Refrigeration
X-dir.: braced frame, Y-dir.: moment frame
Observations: Residual drift exceeding 1/20. East frame collapsed.


Photo 40 Building A: external view showing large tilt.


Photo 41 Building A: foundation scour.


Photo 42 Building B: building collapsed towards left.


Photo 43 Building B: view of foundation showing fracture piles.


Photo 44 Building C: external view.


Photo 45 Building C: failed connection.


Photo 46 Building D: external view.


Photo 47 Building D: column base lifted and anchor bolts deformed.

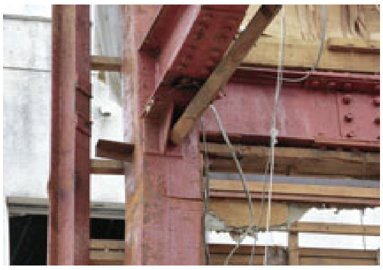
Photo 48 Building D: beam-to-column connections at corner


Photo 49 Building E: external view.


Photo 50 Building E: beam-to-column connection.


Photo 51 Building E: column base.


Photo 52 Warehouse A: external view.


Photo 53 Warehouse A: damage to column base.


Photo 54 Warehouse A: inside view.

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.


Photo 55 Warehouse B: external view; right end subsided.


Photo 56 Warehouse B: view of front side; far-right end subsided.

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.


Photo 57 Office building C: external view.


Photo 58 Office building C: severe damage to cladding.


Photo 59 Office building C: under-ground piping exposed after scouring.

Photo 60 Office building D: cladding washed away in first story; minimal structural damage.

Photo 61 Office building D: nonstructural damage in first story.

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
Observations: Evidence of beam yielding. Residual drift of 1/200 in first story. Cracking of concrete wrapping the column base.

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.

Photo 62 Office building E: majority of nonstructural elements washed away; minor structural damage.

Photo 63 Office building E: yielding of beam near beam-to-column connection.

Photo 64 Store A: external view.


Photo 65 Store A: slight yielding of beam near beam-to-column connection.


Photo 66 Factory A: external view.


Photo 67 Factory A: buckled chord members in roof truss.


Photo 68 Elementary school gymnasium A: external view.


Photo 69 Elementary school gymnasium A: damaged column base.


Photo 70 Elementary school gymnasium A: severely damaged roof.

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
Observations: Severe damage caused by impact of debris. Damage concentrated in single-story segment. (Residual drift of 1/160 in Y-direction. Anchor bolts fractured. Fracture in beam-to-column connections. Ceiling braces fractured.) No damage in two-story segment.

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


Photo 71 Warehouse C: external view.


Photo 72 Warehouse C: deformed columns and beams.


Photo 73 Store B: external view.

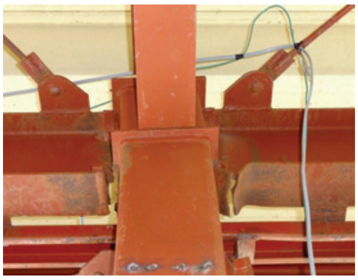
Photo 74 Store B: fractured beam-to-column


Photo 75 Traditional hotel A: external view.


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


Photo 77 Store C: external view.


Photo 78 Store C: distorted columns.


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


Photo 80 Factory B: external view.


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


Photo 82 Factory C: external view.

Photo 83 Factory C: net section fracture of a single-angle brace at the column base.

Photo 84 Factory D: building leaning towards right.

Photo 85 Factory D: yielding of joint region.

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
Observations: Lateral-torsional buckling of beam. Yielding of column base. Severe deformation of column panel zones.

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.

Photo 86 Store D: damage to cladding.

Photo 87 Store D: torsional deformation of beam.

Photo 88 Store E: damage to cladding.


Photo 89 Store E: deformed metal floor slab.


Photo 90 Factory E: cladding washed away.


Photo 91 Factory E: local flange buckling of column near base.


Photo 92 Factory E: large deformation of column panel zone.


Photo 93 High-school gymnasium B: external view of collapsed building.


Photo 94 High-school gymnasium B: building displaced by 20 m.


Photo 95 Gymnasium C: external view.


Photo 96 Gymnasium C: severely distorted columns.


Photo 97 Gymnasium C: distorted roof trusses.

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.

Photo 98 Warehouse D: nonstructural elements washed away.

Photo 99 Warehouse D: minimal structural damage; no residual drift.

Photo 100 Factory F: cladding remained.

Photo 101 Factory F: damage to concrete encasing column base.

Photo 102 Factory G: external view.

Photo 103 Factory G: little structural damage.

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.

Photo 104 Hotel B: external view.

Photo 105 Hotel B: interior damage seen at first story.

Photo 106 Ice making factory A: exterior view.

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.


Photo 107 Office building F: exterior view.


Photo 108 Office building F: 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.


Photo 109 Factory H: external view.


Photo 110 Factory H: first story leaning towards inland.

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)


Photo 111 Shopping complex: ground subsided near footing foundation. (Rifu)


Photo 112 Office building: Two right-end spans subsided due to liquefaction. (Iwanuma)


Photo 113 Subsided corner of same building shown in Photo 112 (Iwanuma)

Photo 114 Warehouse (Miyagino, Sendai)

Photo 115 Building (Miyagino, Sendai)

Photo 116 Delivery station (Natori)

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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