The Japan Tohuku Tsunami of March, 2011

Part I: Preliminary Observations of Effects on Buildings

By Gary Chock, S.E.

Japan has a long history of experiencing great earthquakes, and it is the country with the highest frequency of tsunami attack in the world. On March 11, 2011, the Great East Japan Earthquake of moment magnitude 9.0 generated a tsunami of unprecedented height and spatial extent along the coast of the main island of Honshu. There is great interest in the United States in studying the effects of the Tohoku Tsunami due to the analogous threat posed by the Cascadia subduction zone to the Pacific Northwest, which in 1700 generated a tsunamigenic earthquake also estimated to be magnitude 9. Inundation of the Washington, Oregon and Northern California coastlines would occur within 30 minutes of an earthquake under this scenario.

The author was the team leader of the ASCE Tsunami Reconnaissance Team that visited the Tohoku coast in mid-April, roughly one month after the earthquake, and in the course of two weeks was able to examine nearly all towns and cities with significant damage due to the tsunami. The ASCE website carried a daily blog of this trip, which focused on studying tsunami effects to buildings, bridges, and coastal protective structures within the inundation zone. In this article, we present some of our observations relevant to structural engineers.

By now, most readers are likely familiar with the scenes of widespread destruction, stretching up to several miles inland. It is now estimated from aerial and satellite photography that about 200 square miles of land was inundated, including several major coastal cities and numerous ports. As of May 16, 2011, the Japanese government had estimated that 126,800 buildings (mostly residences) had fully or partially collapsed, essentially all due to the tsunami; the earthquake occurred about 100 miles offshore in the northeast Pacific with attenuation of ground shaking to Modified Mercalli Intensities of VII or less in most of Honshu. The cost of the damage and economic losses has been estimated at over $309 billion, which would make it the most expensive natural disaster in history. The list of fatalities and missing persons now totals about 24,000.

The primary affected area was the Tohoku coastline of the main island of Honshu. This area can be geographically subdivided into the Sanriku coast of the three prefectures of Miyagi, Iwate and Aomori, which has a sawtooth coastline with numerous estuaries and coastal valleys, and the middle coastline from the city of Sendai in southern Miyagi leading southward towards Fukushima prefecture, where the coastline has broader low-lying plains. Along the Sanriku coast, in most instances the tsunami occurred as a long-period, high-amplitude surge. Along the coastal plain south of Sendai, the offshore bathymetry caused the tsunami to break into a series of bores, which were seen racing inland on worldwide television networks as live videos taken from Japanese news helicopters.

Figure 1: Overturned Cold Storage Building in Onagawa.

Fluid and impact loads, and scouring from tsunami inundation, pose a significant risk to coastal buildings and infrastructure. The Tohoku Tsunami presented all loading and effects, including:

- **Hydrostatic Forces:** buoyant forces, additional loads on elevated floors, unbalanced lateral forces
- **Hydrodynamic Forces:** lateral and uplift pressures of tsunami bore and surge flow
- **Debris Damming and Debris Impact Forces:** external and internal debris accumulation and striking
- **Scour Effects:** shear of cyclic inflow and outflow, and transient liquefaction due to de-pressurization

Any of these effects alone, or in combination with the others, was observed to be sufficient to cause structural failures of low- to mid-rise building components of any structural material. Building performance was not guaranteed simply by generic choice of structural material and structural system. Lateral strength and individual element resistance to impact did matter.

In general, collapse of light-frame residential construction occurs in most cases in areas subject to about a story height or more of inundation. Along the Tohoku coast, tsunami water height was in the range of 15 feet to 60+ feet; therefore, complete collapses of residential light-frame construction occurred in nearly 100% of all affected areas extending to the edge of the inundation limit. In commercial and industrial areas, low-rise building collapses occurred in the approximate range of 75% to 95%. We found building sites scrubbed down to their foundations, numerous debris piles of large structural steel, masonry, and concrete building structural elements

Figure 2: Overturned Steel-Framed Office Building in Onagawa.

Figure 3: Onogawa Reinforced Concrete Building Frame Structure with Shear Wall Blow-outs.

Figure 4: Otsuchi Town Three-Story Steel Moment-Resisting Frame with 15-foot tall Enwrapping Debris Load.

Figure 5: Otsuchi Town Collapsed Three-Story Steel Moment Resisting Frame with Debris Load.

Figure 6: Ian Robertson of the ASCE Tsunami Reconnaissance Team Examines the Results of a Tsunami Bore-Projectile Car Impact on a Structural Precast Bearing Wall Apartment Building in Yuriage, Natori.

and wood framing, as well as building successes and failures still on their original sites. Through the following straightforward examples, tsunami effects on buildings are illustrated.

The harbor town of Onagawa, east of Sendai City, experienced a tsunami surge of approximately 60 feet that overtopped nearly all buildings in the area except those on a central hillside. Among the failed structures, we found more than a half-dozen overturned and displaced buildings on their side, structurally complete from foundation to roof. These buildings were either floated by hydrostatic forces and carried away or overturned by hydrodynamic forces of the tsunami inflow or outflow, or a combination of both effects.

One illustration is a two-story reinforced concrete cold storage building (*Figure 1*), which had the refrigerated storage on the ground floor and the refrigeration equipment on the second floor. Due to this function, the building consisted of a closed concrete shell except for doors and a few windows of its administrative room, and ventilation. The building was lifted by hydrostatic buoyancy off its pile foundation, which did not have tensile capacity, and carried over a low wall before being deposited about 50 feet inland from its original location. This building was approximately 30 feet by 70 feet in plan, and 40 feet tall.

Other overturned concrete and steel buildings were sufficiently open to relieve hydrostatic uplift, but were still toppled by hydrodynamic forces of the incoming or returning flow. A four-story structural steel moment-resisting frame (*Figure 2*) lost many of its lightweight precast concrete cladding panels and had numerous window openings. Nevertheless, the building's spun-cast precast piles were sheared off or extracted from the ground, and the office building was displaced by about 50 feet. Skid gouge marks were found on the pavement leading back to its original location.

In many communities, buildings experienced wall failure due to hydrodynamic forces. The simplest cases of this effect were buildings that had three-sided, enclosed spaces that became pressurized by flow stagnation. Flexural yielding led to a catenary membrane condition followed by overall punching shear of the body of the wall. The reinforced concrete building frame system shown in *Figure 3* had its shear walls blown outward by the flow returning to the ocean, entering through the door visible on the far side.

Rather than remaining a pristine fluid, tsunamis quickly become massively laden with debris from failed building components, street infrastructure, and natural material stripping. Moreover, this debris load increases with each passing cycle of inflow and outflow. Buildings have contents that act as internal debris loading elements subject to hydrodynamic forces when a tsunami's flow enters the structure; such debris then transmits hydrodynamic load to the structure even when the exterior enclosure has opened to allow water to flow through.

Even relatively open buildings, or those with breakaway cladding, can be re-loaded with debris that wraps around structural framing and recreates bluff body effective projected areas. The three-story steel moment-resisting frame building shown in *Figure 4* with a 15-foot tall debris pile is an illustration. Note the roof decking material bent around the corner. This building frame in Otsuchi Town was essentially undamaged in a 30-foot inundation height, due to a robust structural design that in effect did not rely on breakaway cladding. Note evidence of tsunami inundation at the height of damaged cladding and top floor windows and balcony soffit.

The three-story steel-moment-resisting frame shown in *Figure 5* had significant debris wrapping. The frame collapsed due to yielding of the top and bottom of all first story columns, then was transported by the incoming flow and crushed and compacted sideways against the three-story reinforced concrete building in the background. Thus, the steel building frame, itself laden by debris, became a large-scale debris load on the adjacent structure.

In addition to building components and even whole buildings, tsunami debris flows include discrete masses such as floating vehicles (*Figure 6*), logs and trees, rolling boulders, large and small concrete fragments, boats and ships, shipping containers, and fuel and oil storage containers. These projectiles can impact building exterior walls and structural columns. Vertical load-carrying structural elements without enhanced local protection or redundant alternative load paths are more susceptible to such impacts and possible partial collapses.

A building foundation may also be undermined by erosion; this was observed to occur at the corners of some buildings, especially (but not exclusively) those with larger plan dimensions and solid or unbreached wall enclosures. Flow accelerating around, between, or over any bluff body obstructions generates a scouring of the surface soil; we found cases of scour pockets up to 9 feet deep.

The ASCE Tsunami Reconnaissance Team is now preparing an extensive report on its observations and findings that will include numerical analysis of various example case studies. In a future issue of STRUCTURE® magazine, we will give a summary of this report along with some conclusions leading towards general recommendations that structural engineers should consider when designing for tsunami effects.▪

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