CATEGORIZATION OF DAMAGE TO BUILDINGS CAUSED BY THE 3.11 TSUNAMI

Hiroshi Fukuyama, Hiroto kato, Tadashi ishihara, Seitaro Tajiri, Masanori Tani
Building Research Institute (BRI), Tsukuba, Japan

Yasuo Okuda and Toshikazu Kabeyasawa
National Institute for Land and Infrastructure Management (NILIM), Ministry of Land, Infrastructure and Transport (MLIT), Tsukuba, Japan

Abstract

The objective of our field investigation is to understand an overview of building damaged by Tsunami, to obtain basic data and information required to evaluate mechanisms for causing damage to the buildings and to contribute to tsunami load and tsunami-resistant designs for buildings such as tsunami evacuation building, by means of collecting building damage cases by tsunami, classifying the damage patterns for different structural categories, and calculating tsunami force acting on buildings and the buildings' strength to the force and making a comparison between the calculate values. The NILIM and the BRI jointly created a tsunami damage investigation team that consists of 27 members, for field investigation. The joint team collected national and international standards and codes concerning tsunami evacuation buildings and tsunami loads and surveyed about 100 buildings and structures in three site investigations. This paper describes the damage patterns of buildings damaged by tsunami based on the preliminary report on the relevant investigation.

Introduction

Great Tsunami was observed in a widespread coastal area in Tohoku by 2011 Tohoku Earthquake. The measured inundation depth of tsunami exceeded 10 m in several areas, and not only wooden houses but also reinforced concrete buildings or steel buildings collapsed or overturned by tsunami loads in those areas.

In April 2011, Building Research Institute and National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism jointly created a tsunami damage investigation team, and surveyed about 100 buildings and structures in three site investigations in Miyagi and Iwate Prefectures.

In June 2011, Building Research Institute join a committee on the structural design of tsunami evacuation buildings (Leader: Prof. Y. Nakano, the University of Tokyo) under Japanese building code revision promotion project, which mainly focuses on appropriate design tsunami loads for tsunami evacuation building. The revision and verification of the calculation method are based on those observed tsunami damage on reinforced concrete and steel buildings by 2011 Great Tohoku Earthquake. This paper introduces the damage patterns of reinforced concrete and steel building structures affected by tsunami in the preliminary investigations.

Building Damage by 3.11 Tsunami

The BRI and the NILIM of MLIT jointly carried out site investigation for building damages affected by tsunami in 6 cities for Iwate prefecture (Miyako, Yamada, Otsuchi, Kamaishi, Ofunato, and Rikuzen-Takata), and 9 cities for Miyagi prefecture (Kesennuma, Minami-sanriku, Onagawa, Ishinomaki, Sendai, Natori, Iwanuma, Watari, and Yamamoto)

Detail investigation results of individual buildings are described in the preliminary report of above Institutes. In this paper, the damage pattern of reinforced concrete buildings and steel buildings are classified based on the investigation result. The collapse, overturning, drift, debris impact, and scouring are common to both of structures.

Reinforce Concrete Building Structures: The large part of the reinforced concrete building subjected to tsunami seems to be no damage on structural frames without obvious concrete cracks on surface. The nonstructural concrete panels are also survived in most of those buildings, while the windows and doors are totally broken. The damage pattern of buildings damaged by tsunami is classified as follows.

(1) Pancake Collapse: This reinforced concrete building is completely collapsed due to tsunami loads in transvers direction as shown in Figure 1. The structure is two story moment resisting frame, which has 6 bays in longitudinal direction, and 1 bay in transverse direction. The bending failure at the bottom of 1st story columns indicates that base shear induced by tsunami exceeded lateral load carrying capacity of the 1st story in this building. The round steel bar was used for the reinforcement of elements and it seems to be constructed before the present Japanese building code requirements. Collapse of whole building structure has not been observed in 3-story or higher buildings in the past investigations.

Figure 1. Pancake collapse of a two-story building

(2) 1st story collapse: A case where column capitals and bases on the 1st floor in a building were subject to bending failure and subsequently to story collapse was seen in two-story buildings (Figure 2). These buildings have a column-to-beam frame. The first floor has a relatively small number of walls, but many concrete block walls are placed on the second floor. The first and second floors of the building in Picture 1 are used as a shop and dwelling, respectively. The relevant buildings are estimated to have structural characteristics of low strength and rigidity on the first floor. Due to that an opening on the second floor is not large, it is assumed that the second floor suffered a large tsunami wave pressure and a shear force acting on the first floor exceeded the same floor' lateral load-bearing capacity, resulting in the collapse of the building.

Story collapse of a first floor has not been observed in 3-story or higher buildings in the past investigations. In 3-story buildings, in general, reinforced concrete walls are often used for a first floor. For this reason, the first floor's strength is considered to have been larger in these buildings, and it is difficult to refuse the possibility of collapse in 3-story or higher moment resisting frame by tsunami loads.

Figure 2. 1st story collapse of a two-story building

Figure 3. Survived three-story building

(3) Overturning and Movement: Overturning was observed in 4-story or lower buildings. In all overturned buildings, a maximum inundation depth exceeded their height. Overturning types that were observed include building that felt sidelong and building that was turned upside down. Most of overturned buildings are of spread foundation (Figure 4). In one of overturned buildings on pile foundation, piles were pulled out (Figure 5).

An overturning case was often seen in 4-story or lower buildings with the relatively small openings. However, there are many cases where 4-story or lower buildings with large openings were not overturned. Consequently, a size of an opening on an exterior wall is considered to have greatly affected overturning. Some cases are that there were tsunami traces at heights of the upper end of openings on the top floor in the inside of the buildings whose height were exceeded by maximum inundation depths (Figure 6). It is considered that air has been accumulated in an area to the ceiling above the upper end. Overturning is believed to occur when an overturning moment by tsunami wave force exceeds overturning strength by a dead load of a building (considering the effect of buoyancy as required). Even a slight horizontal tsunami force may overturn a building, in which a distance from an opening's upper end on each floor to a ceiling is long, when buoyancy significantly acts on the building.

Most of overturned buildings were moved from their original positions. It is estimated that large buoyancy acted on the buildings. The overturned four-story building moved 70 m from its original positions without dragged traces on the ground. One of the buildings climbed over a concrete block fence on an adjoining land (about 2 m) without destroying the fence (Figure 7). The building seems to have floated up by buoyancy.

Figure 4. Overturned building with mat foundation

Figure 5. Overturned building with pile foundation

Figure 6. Tsunami traces

Figure 7. Building climbed over a concrete block fence

(4) Tilting and Drifting by scouring: When tsunami acted on a building, a strong stream was generated around the corner of the building, resulting in many large holes on the ground that was bored by scouring (Figure 8). One building on spread foundation fell into a hole bored by scouring (Figure 9)

Figure 8. Large holes on the ground by scouring

Figure 9. Two-story building tilted by scouring

(5) Sliding: A buildings on spread foundation moved 70 m by a combination of lateral tsunami loads and scouring of footings (Figure 10).

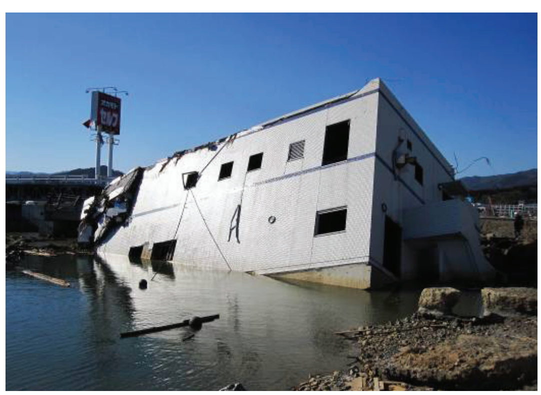

Figure 10. Sliding of two-story building with scoured spread foundation

(6) Fracture of wall (fracture of opening): When tsunami acts on openings in a building and opposite openings are smaller than the affected openings, a stream flowing from the affected openings is concentrated on the opposite small openings. In one observed case related to this event, a stream generated by tsunami provided a large pressure to a reinforced concrete non-structural wall around small opposite openings in buildings. The pressure enlarged the concrete wall to the outside and fractured the wall reinforcement. A case where such wall reinforcement was fractured is often seen in wall members with single layer bar arrangement (Figure 11).

In one case of a damaged building (Figure 12), a 300 mm-thick shear wall with double layer bar arrangement and a support span of more than 10 m and without no 2-story floor was bent inside by a tsunami wave pressure. However, a shear wall in an area (Figure 12, Back of the building), where there is a floor on the second story and a support span is not long in the same building, was not bent. A tsunami wave force that acts on a building will be reduced if the building's opening becomes larger. However, a size of outlet openings should be also taken into consideration in order to flow out of the building in design.

Figure 11. Fracture of non-structural RC walls

Figure 12. Out-of-plane fracture of RC shear wall

(7) Debris Impact: Variant debris such as wooden logs (Figure 13), cars, shipping containers, and ships are attacked on the buildings. In most of those buildings, non-structural members such as window, ceiling materials and veranda are broken. The obvious damage to structural frames was not observed, but in one case, a multi-story wall in an apartment house was probably bored by debris impact (Figure 14).

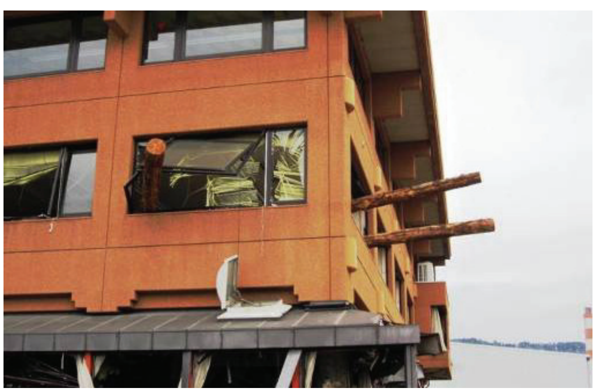

Figure 13. Debris (Wooden Log)

Figure 14. Precast concrete wall opening generated by debris impact

Steel Building Structures: Considerable number of steel building structures survived for a loss of the exterior walls before the large tsunami pressure affect to the buildings. On the other hand, collapse, overturning, movement, and wash out of the steel buildings are often observed in the past investigation, in which the buildings seem to suffer a large tsunami wave pressure. The damage patterns of steel buildings are classified in following 8 items. Damage patterns of No.1~5 causes loss of evacuee directly, and the rest does not always cause loss of evacuee, if they could escape upper floor higher than inundation depth. Overall building frames are washed out in damage pattern of No.1 and No.2, while the building frame existed around original position in damage pattern of No.3 and No.4.

(1) Movement and washout by fracture of exposed column base: A typical case of building movement and washout is that a building moved and flew due to the fracture of anchor bolts and/or base plates at steel exposed column bases and the fracture of a weld between the column and the base plate (Figure 16). In most cases, a foundation and some column bases were left in a site (Figure 16), but the body of a building was moved beyond the site and missing.

Figure 15. Steel building overturned by fracture of column base anchor bolts

Figure 16. A building washed out due to the fracture of anchor bolts and/or base plates

(2) Movement and washout by fracture of capital connection: Damage cases that were seen relatively often include that a capital connection on a first or second floor in a building was fractured and the building was moved and washed away. When a clad or embedded column base has a large strength, this type of fracture is considered to occur.

In one case, a foundation in a building, and several columns on a first floor (or up to a second floor) were left on a site, and the columns fell in the same direction as if the building's trace had been indicated (Figure 17). In most cases, a weld between a diaphragm with upper flange and 1st-floor column was fractured and a section of the column was exposed. In one building, flanges of 2nd-floor

H-shaped beams were torn (Figure 18).

Figure 17. 1st-story columns falling in the same direction *Figure 18. Fracture of the flanges of beams*

(3) Overturning: Overturning of steel building structures is classified into two cases; (a) overturning of overall frame with base foundation, (b) overturning with partially collapse of 1st story. The Former type of overturning was observed in a four- story building with pulling out of piles in Onagawa (Figure 19). A large part of exterior ALC panels survived in the building. The distance from slab on the upper floor to the upper end of openings is about 800 mm. The buoyant force on each floor will be 0.8 ton/m^2 supposing water inflow completely inside of the building, which is almost equal to the self-weight of the buildings.

It seems that the overturning of the building will cause easily, though the weight of base foundation and the piles resist to overturning.

The latter type of overturning generates due to a pull out and buckling of 1st story columns. (Figure 20)

Figure 19. Overturned four story steel building *Figure 20. Overturned building with a pull out and buckling of 1st story columns*

(4) Large residual deformation: Slight tilting was often observed in steel constructions with only a skeleton left (Figure 21).

(5) Full fracture and washout of cladding and internal finishing materials: Cladding materials such as ALC panel were almost fully fractured and washed away, and a steel frame as a skeleton was left. This case was often seen (Figure 22). Due to early washout of the cladding materials, an external force that acts on the skeleton became small. This is considered to contribute to the residual building. In the residual building, slight tilting of the skeleton, member deformation on a face affected by tsunami, or members locally damaged possibly by debris impact, was observed.

Figure 21. Residual deformation in3-story steel building   *Figure 22. Residual 2-story steel building*

(6) Local deformation in structural frames and nonstructural elements: Columns, braces and nonstructural elements are deformed locally by tsunami wave pressure or debris impact force.

Figure 23. Local deformation of columns   *Figure 24. Local deformation of nonstructural elements*

Conclusion

This paper for this investigation classified the damage patterns for different structural categories and briefly discussed the factors that had caused various types of damage. Based on the results of the relevant investigation, The Ministry of Land, Infrastructure, Transport and Tourism has given new bulletin about a structural requirement on tsunami evacuation buildings "Establishment on safety building construction method against assumed tsunami in the tsunami inundation estimation".

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