Damage to Steel Educational Facilities in the 2011 East Japan Earthquake: Part 2 Damage to Minor Structural Components and Damage due to the Tsunami

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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. In this paper, the damage to roof braces, non-structural components and foundation as well as the damage due to the tsunami are discussed. The typical types of damage observed are introduced along with their distribution of occurrence

Keywords: the 2011 East Japan Earthquake, steel buildings, roof braces, non-structural components, tsunami

1. INTRODUCTION

The 2011 East Japan Earthquake caused extensive damage along the Pacific coast of Japan. 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 damage to major structural components (diagonal braces and column bases) due to earthquake ground motion is reported in Part 1 (Y. Matsumoto et al, 2012). The damage to the other structural components and non-structural components due to the earthquake ground motion and the damage due to the tsunami are discussed in this paper. For details on the method of survey, see Part 1.

2. DAMAGE TO ROOF BRACES

In this section, the damage due to ground motion of 125 gymnasiums is discussed. Since the damage to the roof structure of other buildings such as classroom buildings was slight, they are omitted in this section. The roof structure of a typical elementary or secondary school gymnasium is shown in Figure 2.1. Several 2-dimensional rigid frames are built in parallel and connected using beams and roof braces. This type of structure accounts for 83% of the total gymnasiums investigated, and the damage to the roof structure was mainly observed in this type.

Another typical roof structure observed is the 3-dimensional truss shown in Figure 2.2. This group includes the structure, which is composed of several plane truss frames linked diagonally. In general, the 3-dimensional truss roof has sufficient stiffness and strength to withstand damage from severe earthquakes.

As mentioned in Part 1 (Y. Matsumoto, et al, 2012), the buildings investigated were categorized into 3 groups: “Post 1981,” “Retrofitted”, and “Non-retrofitted”. The number of gymnasiums in each group for each structure is shown in Figure 2.3. The gymnasium whose roof structure couldn’t be identified because of suspended ceilings are categorized as “others”. The retrofit standard of school buildings revised in 1996 requires that the in-plane strength of the roof be ensured. Most of the gymnasiums in the survey are believed to have been retrofitted after this revision.

Figure 2.4 shows the number of buildings grouped according to the shape of the brace section. The round bar with a turnbuckle (turnbuckle brace) was used in 63% of the total buildings, and the angle section was used in 15%. Most of the gymnasiums in the “multiple types” group use a combination of the turnbuckle brace and the angle section brace.

Figure 2.1. Roof structure (consisting of 2-dimensional frames)

Figure 2.2. 3-dimensional truss roof

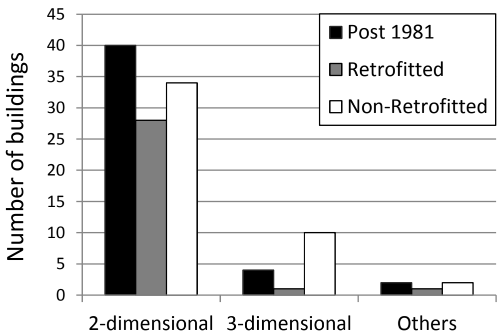


Figure 2.3. Structure type of the roof

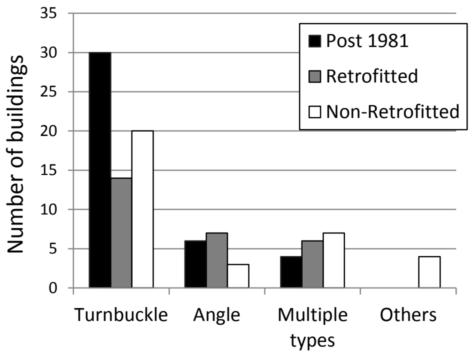


Figure 2.4. Section shape of the roof braces

In the evaluation method introduced in Part 1, only the damage rank of the columns, beams, diagonal braces, column bases, and foundation are defined, and the criteria to rank roof braces is missing. This is because the guideline for post-earthquake damage evaluation issued by the Japan Building Disaster Prevention Association (2001), which is the base of the method of evaluation used in this paper, does not define criteria. Thus in this paper, the damage rank of the roof braces is defined as follows.

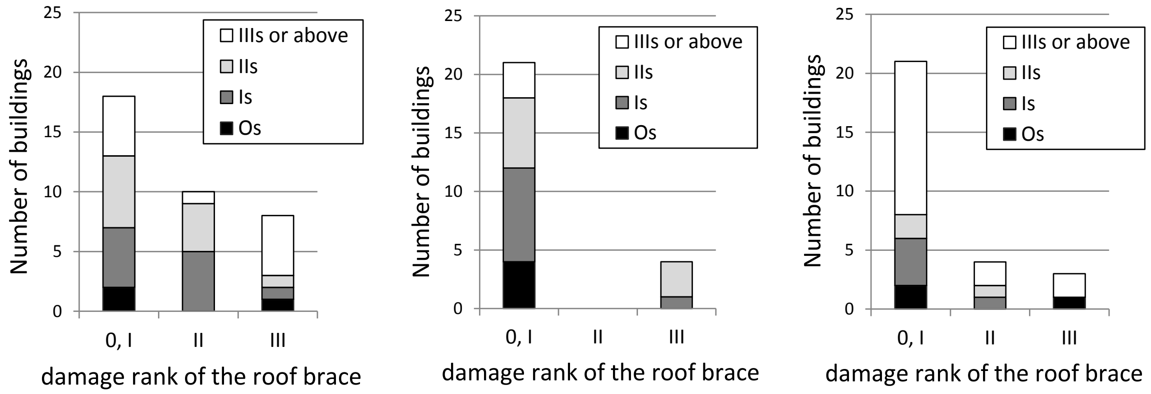
Rank O: None of the roof braces are damaged.

Rank I: Some braces are damaged, but the majority of the braces have not yielded so that the roof is able to maintain its original in-plane stiffness.

Rank II: Most of the braces have yielded such that the in-plane stiffness of the roof has decreased.

Rank III: Several braces have fractured and buckled resulting in a considerable decrease of the in-plane stiffness of the roof.

Figure 2.5 shows the distribution of the damage rank of the roof braces with respect to each group. The bar corresponding to each roof brace damage rank is shaded according to the damage rank of the horizontal force resisting system. The damage rank of the horizontal force resisting system is defined as the maximum damage rank among the column bases, the diagonal braces, the beams, and the columns. In the “Post 1981” group, the roof bracing damage ranks O and I account for 48% and rank II for 30%. The percentage of rank II damage is higher than in other groups. In the “Retrofitted” group, the roof bracing damage ranks O and I account for 82% and damage rank II wasn’t observed. The damage rank III accounts for 18%, and the roof braces which existed before the retrofit fractured in these buildings. Because the buildings of the “Retrofitted” group are believed to have been retrofitted according to the updated retrofit standard, the roof braces conceivably had sufficient strength, which resulted in slight less damage compared to the “Post 1981” group. In the “Non-retrofitted” group, the damage ranks O and I account for 77%. This percentage is similar to that of the “Retrofitted” group. However, 63% of the buildings with roof damage ranks O and I in the “Non-retrofitted” group have a horizontal force resisting system damage rank of IVs or Vs. This may imply that the damage to the roof structure was reduced only because the shear force applied to the roof structure was conceivably lower than that of the other groups due to an early failure of the horizontal force resisting system.



Post1981 Retrofitted Non-retrofitted

Figure 2.5. Damage distribution of the roof braces

Figure 2.6. Elongation of turnbuckle braces

Figure 2.7. Elongation and buckling of angle braces

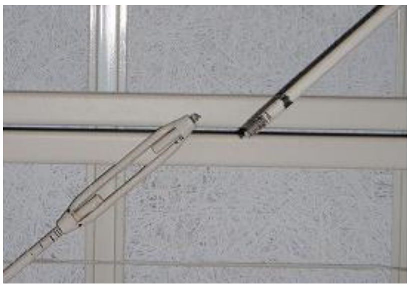


Figure 2.8. Fracture at the screw of a turnbuckle brace

Figure 2.9. Pull out fracture of a turnbuckle brace

Figure 2.10. Fracture at the weld of a turnbuckle brace

Figure 2.6 shows the elongation of a turnbuckle brace, and Figure 2.7 the elongation and buckling of an angle section brace. The turnbuckle braces fractured in most cases and angle section braces fractured in only one “Post 1981” building. Typical fracture modes observed in turnbuckle braces are shown in Figures 2.8, 2.9, and 2.10.

In general, the roof with a 3-dimensional structure has sufficient stiffness and strength to withstand damage from severe earthquakes. Only one gymnasium in the “Retrofitted” group has a damage rank above I. Its roof structure is composed of several arch-shaped trusses crossing each other diagonally as shown in Figure 2.11. The buckling of several truss components was observed as shown in Figure 2.12. The cause of the damage is still under investigation, but the damage of the buildings near the site lead one to believe that the seismic input exceeded the demanded level.

Figure 2.11. Roof structure

Figure 2.12. Buckling of the truss element

3. DAMAGE TO NON-STRUCTURAL COMPONENTS

In this section, the damage to non-structural components due to ground motion in 173 buildings is discussed. The damage rank of the non-structural components, such as the exterior/interior walls, the ceiling, and the openings, are determined based on the criteria given by the guideline for post-earthquake damage evaluation, issued by the Japan Building Disaster Prevention Association (2001). This is shown in Table 3.1. A damage rank of Iw includes the case where there is no damage. Figure 3.1 shows the damage rank distribution of the various non-structural components.

The vulnerability of suspended ceilings has been mentioned for a long time. Since suspended ceilings are fairly heavy, the inertial force under earthquake acceleration is large. When the connections, which suspend the ceilings, are not strong enough, the ceilings have a danger of falling. The damage observed in the survey reinforces this claim. In Figure 3.1, the ceilings which had a rank IIw or higher damage were those suspended. From Figure 3.2, which shows the damage rank with respect to whether or not the ceiling is suspended, one clearly sees that little or no damage occurs if the ceiling is not suspended. The majority of buildings without a suspended ceiling are gymnasiums. Such a gymnasium is shown in Figure 2.11. On the other hand, 5 of the 8 buildings with a rank IIIw or IVw damage are gymnasiums with suspended ceilings, which imply that suspended ceilings in gymnasiums can be vulnerable to strong ground motions. Figure 3.5 shows the complete fall of the ceiling of a gymnasium which suffered a rank 7 earthquake based on the Japanese Meteorological Agency seismic intensity scale. Figure 3.6 shows partial falling of ceiling boards in a classroom.

The types of damage observed in the exterior walls depend strongly on the material and method of construction. These were organized into 4 groups: “sidings” (metal siding, plastic siding), “boards” (asbestos cement board, plaster board, calcium silicate board), “AAC/EPC” (Autoclaved Aerated Concrete(AAC) panel, Extruded Cement Panel (ECP)), and “metal lath and mortar”. The distribution of the damage rank organized into the 4 groups is shown in Figure 3.3. “Metal lath and mortar” and “panels” combined make up most of the severe rank IVw damage. “Metal lath and mortar” exterior walls are extremely vulnerable to damage, since they have a lower deformation capacity compared to the steel structure, and may completely fall off as in Figure 3.7. The same can be said about exterior walls using AAC panels fixed to the structure without a mechanism to allow deformation. On the other hand, “sidings” have a high deformation capacity and generally had slight or no damage. Even in the worst case, as shown in Figure 3.8, there is only some out of plane deformation. Figure 3.4 shows the year of construction of the buildings with respect to the type of exterior wall. The use of metal lath and mortar was popular in the 1960s and 70s, but because of the reason stated above, its usage has declined. The use of boards has also declined and they seem to have been replaced by siding.

The damage to the interior of most steel buildings has been slight, as can be read from Figure 3.1. The types of damage that occurred were cracking and falling off of mortared walls as in Figure 3.9 and peeling or falling of boards from boarded walls as in Figure 3.10.

The majority of the damage observed in the openings was due to the window glass shattering, as in Figure 3.11, or the window panel falling off, as in Figure 3.12. Many of the shattered windows had glass panes secured to the metal frame using hardening putty, which transfer the deformation of the window directly into the glass.

Table 3.1. Criteria to evaluate the damage rank of non-structural components

Damage rank	Non-structural component		
	Exterior/Interior wall	Ceiling	Openings
Iw*	Small cracks at the corners	Slight buckling	Slight difficulty in opening and closing, small cracks
IIw	Slight gaps in the joints Slight detachment	Partial detachment	Fracture in many corners Difficulty in opening and closing
IIIw	Cracks along the entire surface Partial detachment Out of plane deformation	Detachment across the entire surface	Fracture in most corners Impossible to open and close
IVw	Large detachment	Extreme detachment across the entire surface	Extreme fracture

* Iw includes the case where there is no damage

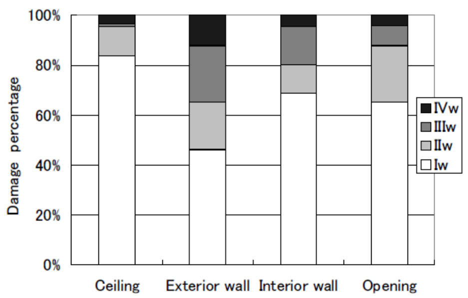


Figure 3.1. Damage distribution of non-structural components

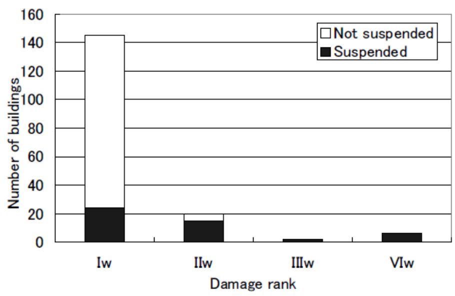


Figure 3.2. Damage to the ceiling with regards to the existence of a suspended ceiling

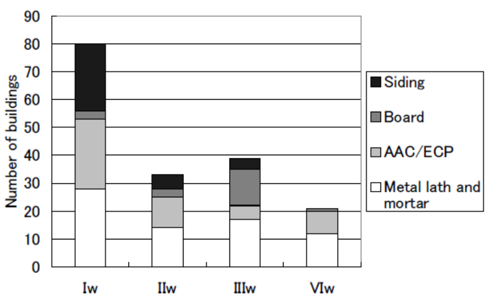


Figure 3.3. Damage to the exterior wall with regard to their type

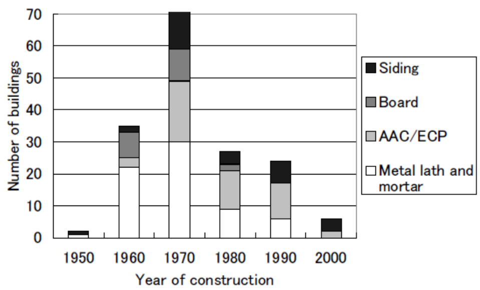


Figure 3.4. Distribution of the types of exterior walls grouped by the year of construction

Figure 3.5. Fallen ceiling in a gymnasium

Figure 3.6. Fallen ceiling in a classroom

Figure 3.7. Complete fallen metal lath and mortar wall

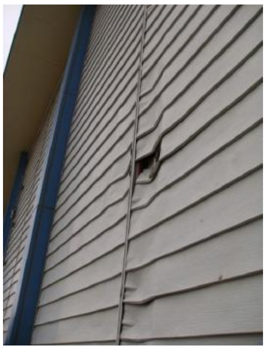


Figure 3.8. Out of plane deformation of the metal siding

Figure 3.9. Mortar falling off of mortared interior walls

Figure 3.10. Board falling off the interior wall

Figure 3.11. Shattering of glass windows

Figure 3.12. Fallen window panel

4. DAMAGE TO FOUNDATIONS

In this section, the damage due to ground motion of 173 buildings is discussed. Except for the areas that experienced the tsunami, apparent soil liquefaction wasn't observed. However, land subsidence or landslide was observed at many sites. The foundation type was unidentified in about 50% of the total buildings. Of the remaining 50%, pile foundations constitute 54%, spread footings 33%

Figure 4.1 shows the distribution of the damage rank of the entire building, with the ones with a damaged foundation shaded in grey. 40% of the buildings had damaged foundations. 23% of the buildings ranked as "slight damage" and 57% of the buildings ranked as "major damage" had damaged foundations. The more severe the damage rank is the higher the ratio of foundation damage.

The cause of the damage to the foundation was categorized into 2 groups. One is landslide of sloped sites and the other is subsidence of flat sites. The former caused about 80% of the damage in the building's ranked as "moderate damage" or above. The latter was observed around a river or a pond.

Figure 4.2 shows a building damaged by a landslide. The pile of this building has fractured, as shown in Figure 4.3, and the whole building has tilted. Uneven settlement can cause damage to the structure above the foundation. Such examples are shown in Figures 4.4 and 4.5. The former shows the tilt of the column caused by landslide of the sloped site. The latter shows the tilt of a foundation caused by subsidence of the flat site, resulting in cracks in the outer wall.

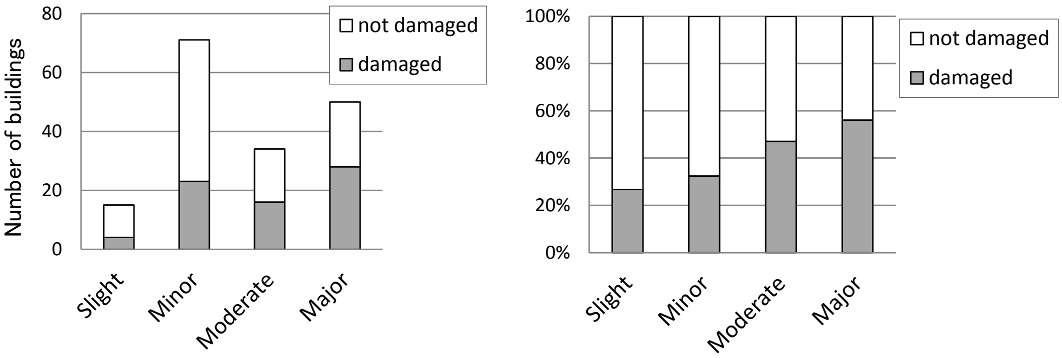


Figure 4.1. Distribution of foundation damage

Figure 4.2. Damage due to a landslide

Figure 4.3. Fracture of a pile at the top

Figure 4.4. Tilt of a column

Figure 4.5. Tilt of a foundation

5. DAMAGE DUE TO TSUNAMI

In this section, the damage due to the tsunami of 43 buildings is discussed. These buildings include 20 gymnasiums, 13 classroom buildings, and some storehouses. 86% of the total buildings are of the S-type structure. Figure 5.1 shows the location of the damaged buildings. They are all located within 2 km of water. Figure 5.2 shows the relationship between the inundation height and the distance from the coast. The inundation height decreases according to the distance.

The buildings that experienced tsunami were damaged not only from the water pressure but also from collision with debris. Figure 5.3 shows the distribution of the damage rank of the buildings. In more than 50% of the total buildings, damage was observed only in the non-structural components.

Figure 5.4 shows the relation between the maximum damage rank of the structural components and the inundation height. Excluding the buildings that experienced fire or soil liquefaction, the damage rank increases proportionally with respect to the inundation height. Severe damage ranked as IIIs or above was observed only in buildings which experienced an inundation height of 5m or higher. Figure 5.5 shows the relation between the maximum damage rank of the non-structural components and the inundation height. Severe damage ranked as IIIw or above was observed even when the inundation height was less than 4m.

Figure 5.6 shows damage of the exterior walls. Although the structure was not severely damaged, the exterior walls were torn and swept away. Figure 5.7 shows a set of diagonal braces bent out of plane. The braces were pushed in the out of plane direction by the exterior wall, which was broken and swept away. Figure 5.8 shows a gymnasium whose structure was damaged. The entire building was pushed by the water pressure in the direction of the arrow and the concrete at the column base failed laterally, as shown in Figure 5.9.

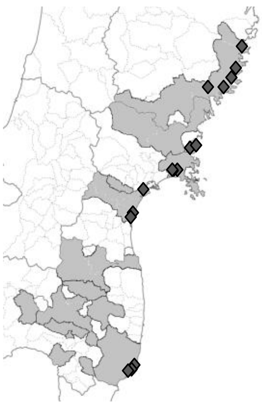


Figure 5.1. Location of the damage buildings

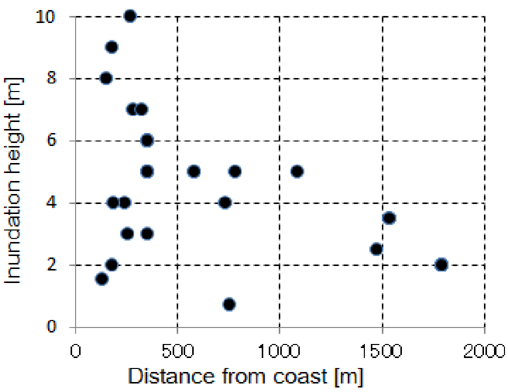


Figure 5.2. Relationship between the distance from the coast and the inundation height

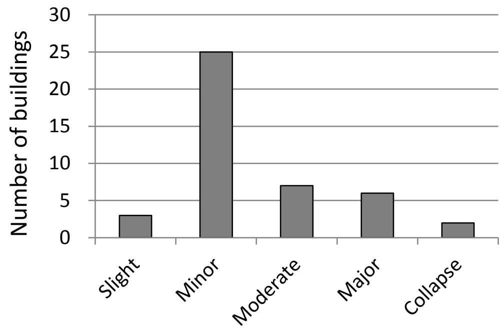


Figure 5.3. Distribution of the damage rank

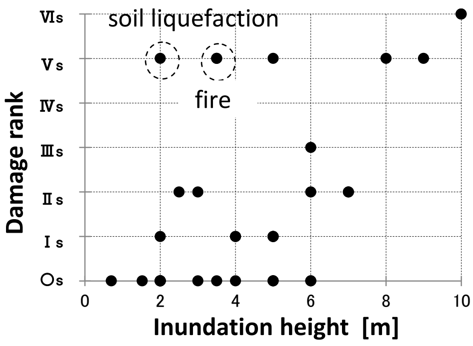


Figure 5.4. Relationship between the maximum damage rank of the structural components and the inundation height

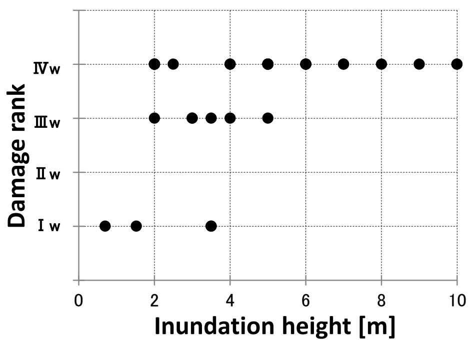


Figure 5.5. Relationship between the maximum damage rank of the non-structural components and the inundation height

Figure 5.6. Damage of the exterior wall

Figure 5.7. Out of plane bending of diagonal braces

Figure 5.8. Major structural damage due to the tsunami

Figure 5.19. Damage at the column base

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 following conclusions can be made.

1) The degree of damage to the roof braces of gymnasiums was related to the year of construction and whether or not retrofit was conducted. In the “Post 1981” group, the percentage of elongated braces was higher than in the other groups. In the “Retrofitted” group, the damage of the roof braces was slight in general. In the “Non-retrofitted” group, the damage to the roof structure was reduced because the shear force applied to the roof structure was conceivably lower than that of the other groups due to an early failure of the horizontal force resisting system.
2) The ceilings of gymnasiums that were not suspended suffered little or no damage, but some of those that were suspended had a damage rank of IIIw of IVw when subjected to severe ground motions. The damage of exterior walls greatly depends on the type of material and construction method. Metal lath with mortar walls received the most damage due to lack of deformation capacity.
3) 40% of the buildings had their foundations damaged due to the ground motion. Landslide or land subsidence caused severe damage to the foundation as well as the structure above.
4) The damage due to the tsunami in the structural components was closely related to the inundation height. In most cases, the non-structural components were more severely damaged compared to the structural components.

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REFERENCES

Matsumoto, Y., Yamada, S., Koyama, T., Iyama, J., Kishiki, S., Shimada, Y., Asada, H. and Ikenaga, M. (2012). Damage of Steel buildings due to the 2011 East Japan Earthquake, Part 1: Outline of the Reconnaissance and Damage to Major Structural Components, 15*th WCEE*

The Japan Building Disaster Prevention Association. (2001). Guideline for Post-Earthquake Damage Evaluation and Rehabilitation Technique (in Japanese), the Japan Building Disaster Prevention Association