



NUMERICAL STUDY ON DAMAGE OF STEEL CHORD MEMBER IN SPACE TRUSS ROOF UNDER EARTHQUAKE

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Abstract

School gymnasiums in Japan have functions for not only sport facilities as own usage but also shelters under disasters such as earthquake. However, many gymnasiums suffered serious damage by the 2016 Kumamoto earthquake and were not able to be used as shelters continuously. For example, brace buckling and breaking, wall falling, roof bearing breaking and roof member falling were occurred. According to the damage survey of the Kumamoto earthquake that occurred in April 2016, it was found that there were many gymnasiums that were not used due to visible damage such as falling secondary structural elements. The seismic response analysis of it was conducted to find the cause of such damage. Analytical gymnasium is real structure suffered the 2016 Kumamoto earthquake in Japan. Although the construction site is about 4.5 km away from the epicentre of earthquake whose moment magnitude is 7.0 and the gymnasium was shaken very strongly. The gymnasium is covered by a steel space truss roof because the span of the roof is rather long. There was a breaking of the chord member in the space truss among various damage. This gymnasium has three floors above ground, the arena is on the third floor and the main frame is constituted by cantilever RC columns and walls. The roof is a space truss consisting of circular steel tubes. Some truss members buckled and the truss joints were broken. The profile of the roof is arched shape, and the damage occurred on the longitudinal direction. The previous study referred that roof members were damaged by roof surface responses and displacement of the roof bearing. However, it is considered that the truss members are not damaged only by the response of the roof surface and out-of-plane responses of the cantilevered RC columns and the walls, and this is because the parallel cantilevered RC columns and walls have displacement difference. More specifically, out-of-plane responses of the cantilevered RC columns and the walls at both sides of the arena occurs on both sides during their vibration, and the chord truss members are compressed or pulled. Therefore, in this study, in order to investigate out-of-plane responses of the cantilevered RC columns and the walls, the gymnasium stated above was mechanically modeled for the non-linear dynamic analysis program. The seismic response analysis was conducted, and the results were examined. The modeling was performed to follow the Japanese structural design standards.

Keywords: Steel space truss; Chord member; Dynamic analysis; Damage; Gymnasium roof



1. Introduction

Gymnasia are supposed to be used as shelters for neighbors after great earthquakes in Japan. However, a large number of gymnasia suffered serious damage and were unable to be used as shelters in recent great earthquakes. Especially, gymnasium constructed by reinforced concrete frame (RC frame). The reason of abandonment using of the building a shelter was not the only damage of main structural members but also that of secondary members or equipment. Such a damage was observed in not only aged gymnasia but also ones designed recently [1], which means that new design has been required strongly.

In the Kumamoto Earthquake in April 2016, structural damage occurred in many gymnasia, and they could not be used as a shelter. In September and December 2016, seven construction companies and the authors surveyed the local gymnasia, and the damage status were recorded. This paper focuses on one high school gymnasium in Kumamoto city, which is one of the subjects of the survey. The gymnasium is covered by a steel space truss roof because the span of the roof is rather long. There was a breaking of the chord member in the space truss among various damage. Some truss members buckled and the truss joints were broken. The previous study [2] states that roof members were damaged by roof surface responses and displacement of the roof bearing. We report the damage situations of that gymnasium and analyze the earthquake response and consider the cause of damage.

2. Analytical frame

Target for structural analysis in this research is a high school gymnasium renovated in 1997 in Kumamoto City and suffered the 2016 Kumamoto earthquake in Japan. The construction site is about 4.5km away from the epicenter of earthquake whose moment magnitude is 7.0 and the gymnasium was shaken very strongly. The gymnasium is constructed of RC frame substructure and steel roof whose bearing is exposed column-base type.

Fig.1 shows the gymnasium frame model removing the foundation beams, concrete slabs and walls. Span and longitudinal directions are EW (X) and NS (Y) directions respectively. This gymnasium has three floors above ground, the arena is on the third floor. The steel roof is over the arena area which is from X2-line to X8-line in Fig.1, and there are lower RC frames in west and north ends. West one is composed of RC frame and north one is composed of RC columns and steel roof. The steel roof is space truss roof composed of 6 kinds of circular steel tubes. Fig.2 shows the framing on Y1-line and X2-line. Tables 1-3 summarizes the cross sectional information of RC columns, RC beams, and plane truss members. Fig.3 shows the details roof bearings details at end of ball joint. Roof bearing S2 has 100mm-wide loose hole in the north-south direction and S3 has 40mm-wide loose hole in the west-east direction and S4 has 60mm-wide loose hole in the west-east direction. Table 4 shows the material properties of structural members.

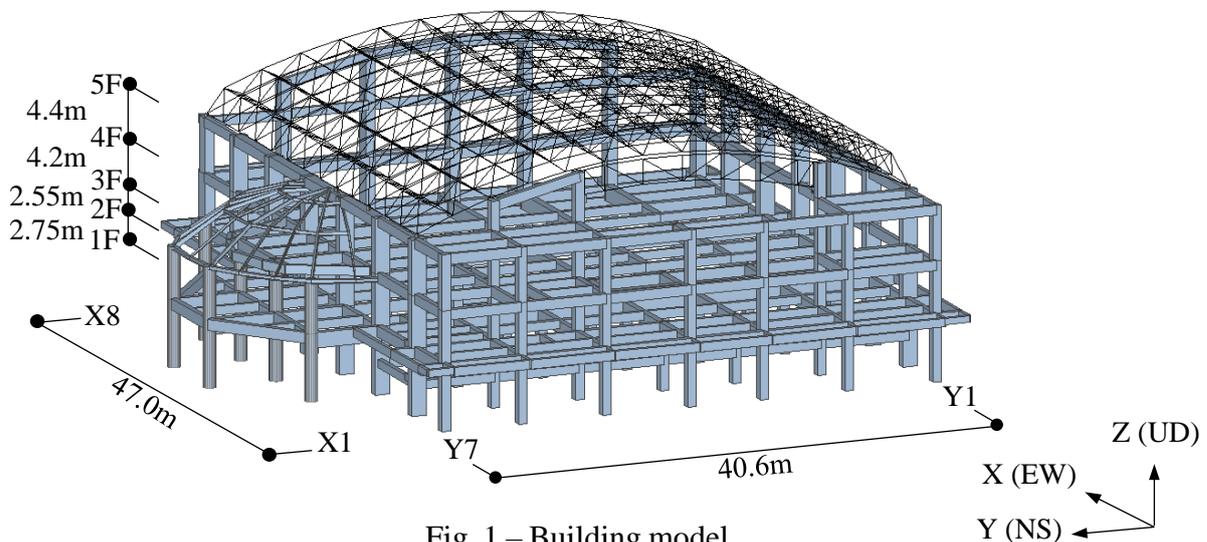


Fig. 1 – Building model

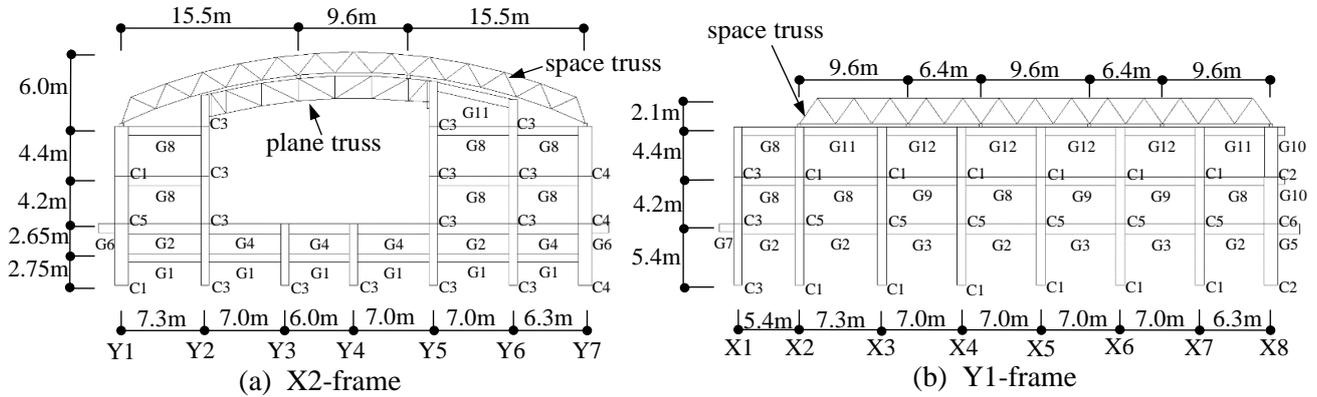


Fig. 2 - Framing elevation

Table 1 - Dimension of RC column

Label	Section (mm)	Top of rebars	Bottom of rebars
C1	800x1200	16-D25	"
C2	1200x800	16-D25	" (note)
C3	700x700	8-D25	" $\frac{16}{D} - \frac{D}{25}$
C4	800x1200	16-D25	" (a) (b) (c)
C5	800x1200	16-D25	20-D25 (a) Number of rebars
C6	1200x800	16-D25	32-D25 (b) Rebar type

(c) Nominal diameter (mm)

Table 2 - Section of RC beam

Label	Section (mm)	Reinforcement(end)		Reinforcement(middle)	
		Top	bottom	Top	bottom
G1	400x550	4-D22	4-D22	4-D22	6-D22
G2	400x900	3-D25	3-D25	"	"
G3	500x 900	6-D25	4-D25	4-D22	4-D25
G4	450x900	6-D25	4-D25	3-D25	5-D25
G5	450x900	5-D25	3-D25	"	"
G6	400x800	5-D22	3-D22	"	"
G7	350x700	3-D22	3-D22	"	"
G8	400x800	3-D25	3-D25	"	"
G9	690x800	5-D25	3-D25	3-D25	3-D25
G10	350x700	5-D22	3-D22	"	"
G11	400x800	4-D25	3-D25	3-D25	3-D25
G12	800x800	4-D25	3-D25	3-D25	3-D25
B1	350x700	4-D19	3-D19	3-D19	5-D19
B2	350x700	4-D19	3-D19	3-D19	4-D19

(note)

H - 400 x 200 x 8 x 13

(a) (b) (c) (d)

(a) Depth

(b) Breadth

(c) Thickness of web plate

(d) Thickness of flange plate

Table 3 - Section of plane truss member

Label	Section (mm)
Chord member	H-400x200x8x13
Bundle member	H-400x320x8x13
Web member	2L-75x75x6

(note)

2L - 75 x 75 x 6

(a) (b) (c) (d)

(a) 2-angle steel

(b) Height

(c) Width

(d) Thickness



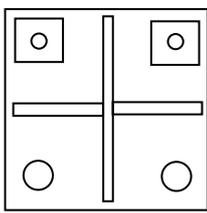
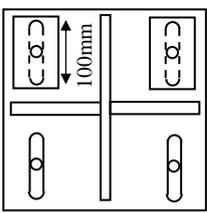
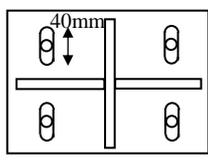
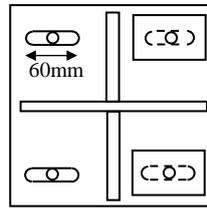
Label	S1	S2	S3	S4
Column end (mm)	 450x450	 450x450	 300x400	 450x450
Anchor rod (mm)	M36 L=900	M27 L=600	M24 L=150	M27 L=600

Fig. 3 - Detail of roof bearing

Table 4 - Material properties

Material property	Strength (N/mm ²)
Compression strength of concrete	21
Yield strength of main rebar	345
Yield stress of hoop of RC member	295
Yield strength of steel member	235

3. Damage situation

The site of this gymnasium was shaken by twice strong earthquakes. The authors conducted surveys on the gymnasium in September and December 2016. So that they observed several buckling of truss members around the X8-line, breaking of truss members near the center of X8-line, sliding of roof bearing, and roof member falling as shown in Fig.4. Buckling of the space truss members around X8-line was caused by sliding of roof bearing which is roller bearing. Fig.5 shows each damage at the space truss roof and the roof bearing. From breaking of joint part in the space truss member as shown in Fig.5-(d), it turns out that the falling of the roof member is caused by breaking of the screw part.

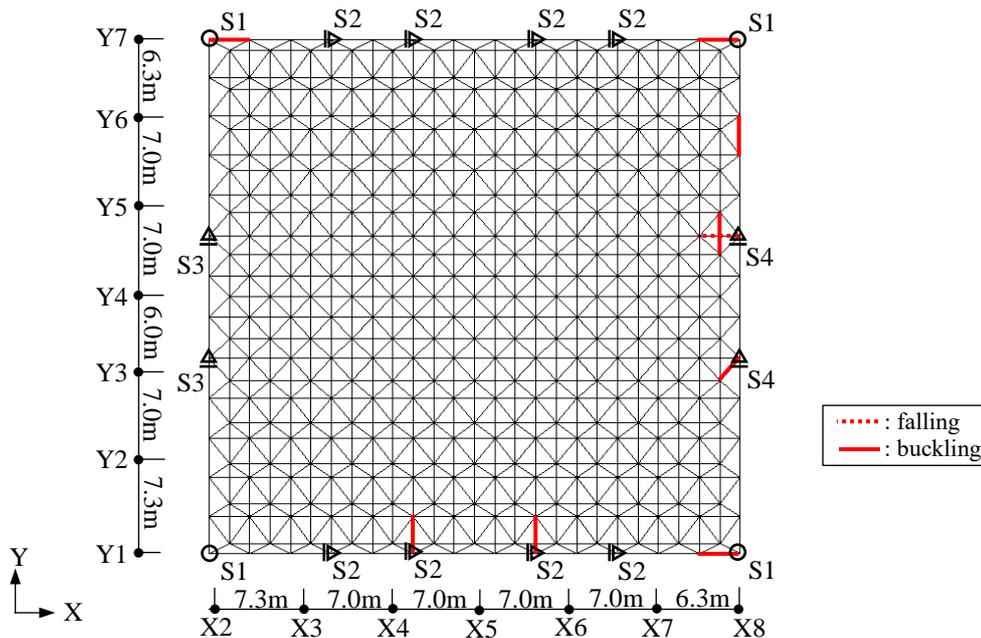


Fig. 4 - Damage location



(a) buckling



(b) falling



(c) sliding



(d) falling down

Fig. 5 – Damage details

4. Analytical result

Seismic response analysis of the gymnasium has been calculated by using 3-D inelastic response analysis program (SEIN La DANS). The structural element for an RC column has the elasto-plastic multi springs at its top and bottom end, and the model of an RC beam has the elasto-plastic hinges, whose restoring force model is assumed to be Takeda model [3]. The model a of steel member has elasto-plastic hinges at its both ends. The restoring force model of the element is assumed to be bi-linear model.

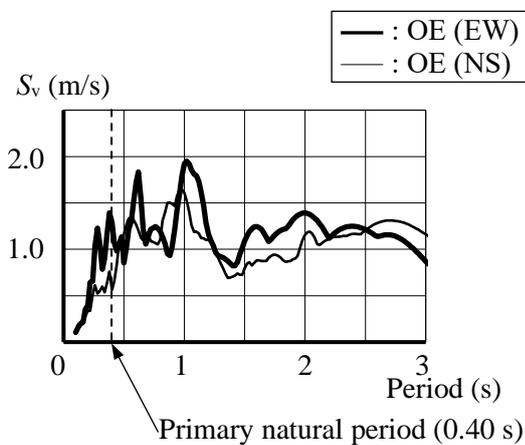


Fig. 6 – Velocity response spectra

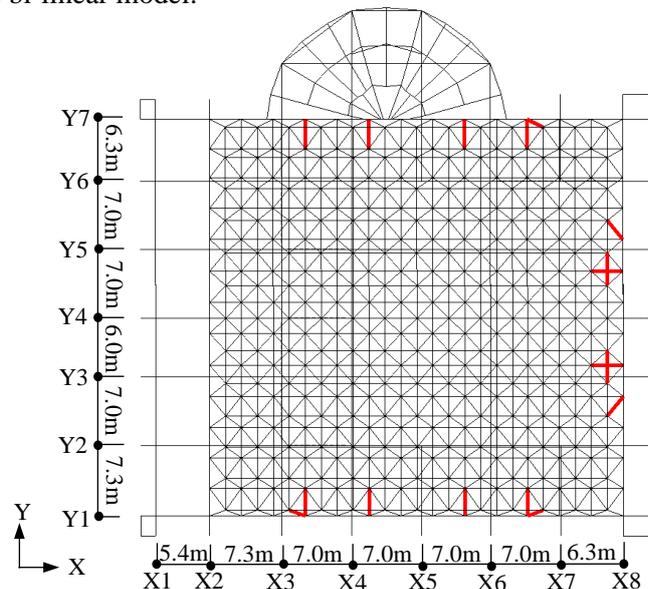


Fig. 7 – Yielded members



Newmark - β method ($\beta = 1/4$) is used as the numerical integration scheme for the dynamic response analysis. Its time increment is 0.002 s in this study. The characteristic of damping is assigned to Rayleigh damping in which the damping factors of the first mode (h_1) and the second mode (h_2) are assumed to be $h_1 = 0.03$ and $h_2 = 0.03$. OE wave was chosen to calculate the seismic response of the real gymnasium. The wave was recorded at the site that is nearest from the place of the analytical gymnasium in the 2016 Kumamoto earthquake. The velocity response spectra of input ground motions and the primary natural period of analytical gymnasium are shown in Fig.6.

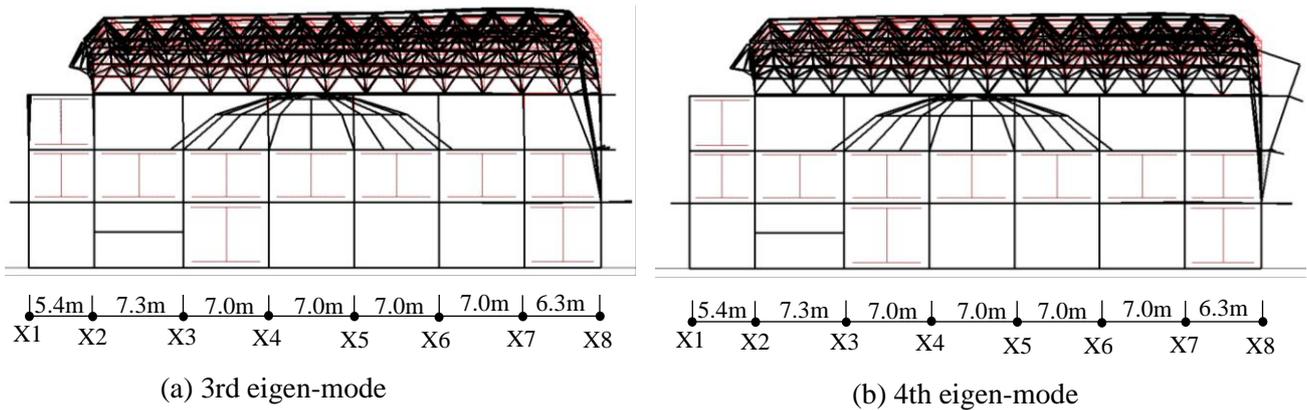


Fig. 8 – Eigen-mode

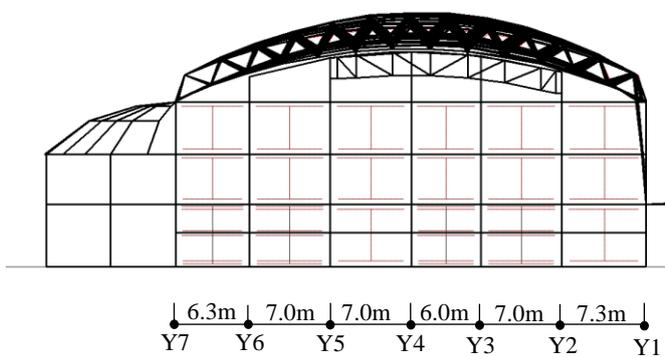


Fig. 9 – 5th eigen-mode

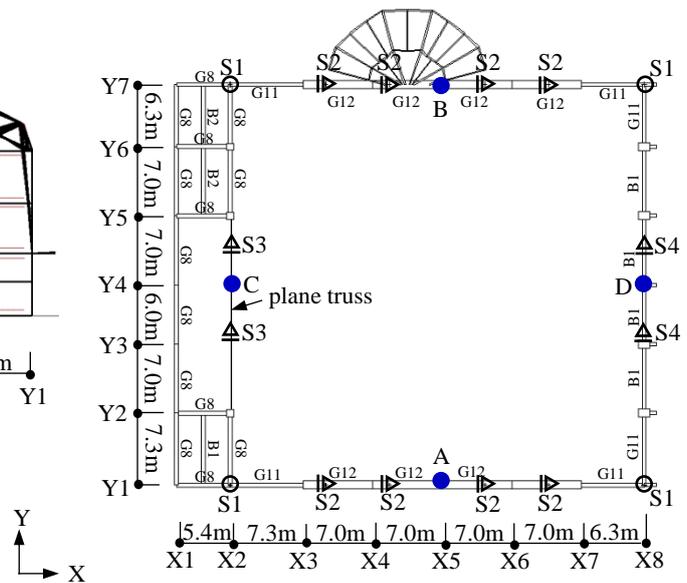


Fig. 10 – Beam framing plan of top story substructure

Fig.7 shows yielded members of the space truss obtained from calculation. The yielded members from the result and the members observed are the same. Consequently, it seems to be reliable that the seismic analysis was well done. Fig.8 shows 3rd and 4th eigen-modes of the frame viewed from Y axis. Also, Fig.9, shows 5th eigen-mode viewed from X axis. The deformed frame was drawn with thick lines. It can be recognized that out-of-plane deformation of the walls at on X2-line and X8-line occurs under the earthquake. It suggests that those modes derive the yielding of the truss members around X8-line. In addition, it can be also seen that there is out-of-plane deformation of wall on Y1-line as shown in Fig.9. The out-of-plane deformation on Y1-line was smaller than that on Y7-line. The fact that there was a low RC frame on Y7-line only, made the difference. From those eigen-modes, those modes have caused the yielding or buckling of the members in the space truss around Y1-line and Y7-line.

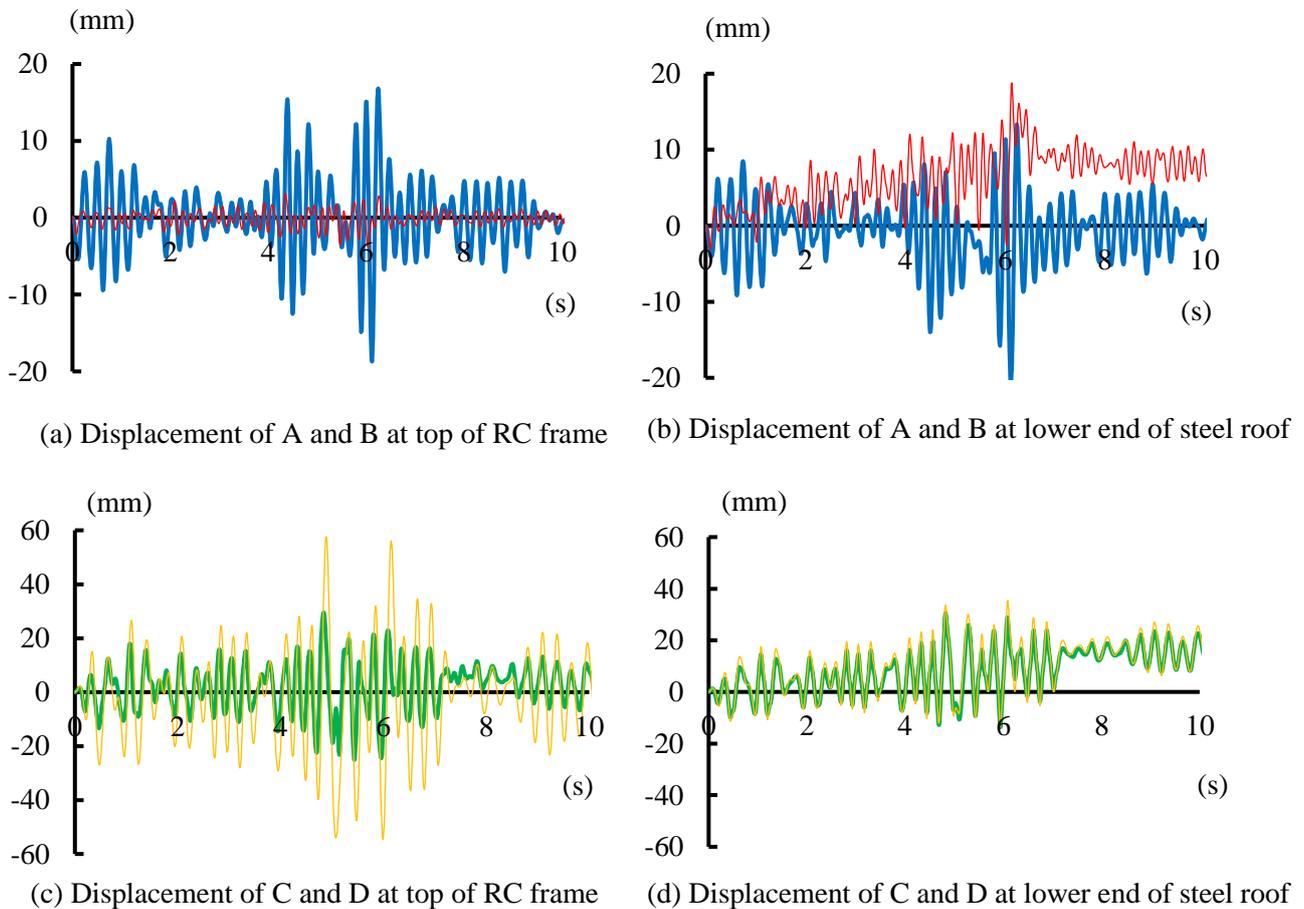


Fig. 11 – Displacement of opposite nodes

Fig.10 shows the representative positions of A, B, C and D in the space truss for examining the out-of-plane displacement under the earthquake. Fig.11 shows for recognizing the relative lateral displacement between A and B as well as C and D along the time line. A and B are the truss nodes that exist opposite point mutually in the plan. The history of the displacements of the opposite points insists that the truss chord members were under tensile or compressive stress. Eventually, some chord members broke or buckled because of exceeding their loading capacity.

Compared with (a) and (b) of Fig.11, the response of (b) is larger than (a). On the other hand, compared with (c) and (d), there is more difference between thick line and thin line than (d) because displacement of D at top of RC frame is larger. Then, calculation of the difference of lateral displacements between at the top of RC column and the bottom of the steel roof at each point was attempted. As a result, the maximum differences are 7mm, 19mm, 19mm, and 56mm, respectively. The maximum difference is over 50mm at the point D., It means that the difference exceeds the allowed length of loose hole. In addition, the calculated the difference between thick line and thin line in each graph, the maximum displacement is 7mm, 39mm, 50mm, and 7mm, respectively. In (b) and (c) of Fig.11, it reveals the maximum displacement of opposite node becomes large. It can be said that this out-of-plane deformation caused the pulling or pushing the space truss roof. From that those result, it is found that the out-of-plane response is one of reason that space truss is damaged.



5. Conclusion

In the 2016 Kumamoto earthquake, there were many gymnasiums that could not be used as shelters, because there were occurred structural damage. This research dealt with the damage situations of a school gymnasium that suffered the very strong earthquake, and by 3-D structural analysis of the building, the reason of yield of the space truss member was considered. As a result, it was clarified that some truss members yielded or buckled by exceeded tensile force or axial force respectively.

6. Acknowledgement

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7. Reference

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