A study of the seismic effects on a portal frame having a hole at the beam-column connection

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Abstract

This paper presents the results of the study on thin walled steel portal frames, which are used in Japan as basic structural frames for motorway viaducts. A serious problem found in many such frames is fatigue cracks developed at the beam to column connection. To act as a measure against the fatigue failure, in some cases a hole is provided at the beam –column connection of the frames. In this study, dynamic analysis using real earthquake data from 3 different earthquakes have been carried out to examine the influence of such a hole on the global behavior of the frame and also on the local buckling around the location of the hole. Non-linear, large displacement analysis was performed using the FEM program MSC. Marc. The hole radius has been varied and used as a parameter of study. The results showed significant effect of the hole on local buckling and global behavior, specifically when the radius of the hole was larger than 100 mm.

***Keywords**:* Fatigue strength; Hole; buckling strength; Portal frame; Dynamic analysis

1. Introduction

Steel portal frames are commonly used for viaduct motorways in Japan. Many fatigue cracks were found in the beam-column connection of these frames [1-3]. Among the problems that are faced regarding the design and maintenance of steel frames, one is the development of such fatigue cracks. Different case studies and researches on the cause, mechanism and effect of fatigue cracks have been carried out [4-9]. Once the cracks are formed, they propagate and may lead to brittle fracture causing structural failure. The structural failure may occur solely under regular service conditions or under the effect of an earthquake. Different remedial measures are taken for preventing the development of fatigue cracks and for retrofitting once the cracks are formed. Both experimental and numerical studies have been carried out to understand the behavior of steel box sectioned columns and also to find out effective retrofitting methods for fatigue cracks [10-12]. In order to prevent the development of fatigue crack and also as a fatigue retrofitting method, Tanabe et al [13] have proposed to arrange a hole at the beam-column connection as illustrated in Fig.1. Here, a "Large core" [14] is drilled with a view to removing the high stress intensity zone, fatigue cracks and other flaws. The primary objective of this paper is to present the influence of this hole on the global behavior of the structure and on the local displacement behavior around the hole.

Fig. 1

The Japanese highway bridge design code (Japanese Specifications for Highway Bridges, JSHB) [15] did not specifically describe such situation of fatigue cracks or specific method for fatigue design, as the load variation was considered small. But the code did mention to pay special attention for the design of corner of intersection as there the direction of force changes suddenly, and particularly when the steel structure is a thin-walled structure, which makes the force-transfer mechanism quite complicated. The code specified it as desirable to assess the effect of the dominant issues in designing the corner of an intersection through finite element analysis, experimentation etc. Fatigue design recommendations in JSSC (Japanese Society of Steel Construction) [16] considered the effect of fatigue based on the static behavior. Generally, it did not consider the seismic behavior of the structure.

Fatigue crack is initiated from weld defects, notch or stress concentrated parts in joints and propagate. Residual stress also has influence on the development of fatigue crack [14,17]. The problem is that the common sense of static design does not apply for the fatigue design. Also evaluation of fatigue-damaged part based on stress analysis is sometimes hard to apply. So, more detailed analyses and studies are required to understand such cases properly.

Many studies have been carried out on the seismic behavior of steel box columns, mainly in Japan after the Kobe earthquake in 1995, for example by Morishita et al. [18], Hanbin et al. [19]. However, almost all of such studies have dealt with steel columns standing alone. Very few studies were made on the column of the portal frame structure.

Nakajima et al. [20] studied the seismic behavior of a portal frame structure under the effect of earthquake. The target of that study was the "complete" portal frame, and the hole to prevent from the fatigue crack was not considered. Silva et al. [21] performed non-linear dynamic analysis of semi rigid, low rise portal frames. The FEM model in that study included geometric non-linearity. The study indicated that geometric non-linearity could significantly affect the dynamic behavior of the frame. Sakano and Wahab [22] carried out extremely low cycle (ECL) fatigue experiments and 3-dimensional elasto-plastic finite element analysis of steel pier beam-column joints. They have studied the effect of web-corner fillet on the ECL “fatigue crack initiation life” of box sectioned beam-column joints. Shimizu [23] conducted study on the strength of the corner zone of steel frames regarding the influence of the hole. He varied the core radius, plate thickness and considered cases with stiffeners and without stiffeners. The study showed that the hole decreased the strength of the column up to 9% when compression stress had arisen near the hole. It also showed that the coring method was appropriate to prevent the development of the fatigue cracks when the core had been arranged at the tension zone. However, when the zone had been subjected to compression, or the alternative stress of tension and compression, the displacement strength of the column needed to be taken into account. Shimizu [23] took the static load into account; but the effects on the seismic performance of the frame cannot be understood from a static analysis. And in order to ensure the continued safe operation of such heavy-duty structures, it is necessary to carry out detailed study on predictive models under complex loading conditions. This requires evaluation of the effect of real loading spectra. Tanabe et al. [24] studied the influence of the hole at the beam-column connection on the fatigue strength of portal frames. In their study they examined the effect of seismic loads. Kawashima and Unjoh [25] studied the effect of earthquake on highway bridges and have described its impact on the modification of seismic design specifications. They specifically focused on the Hyogo-ken-Nanbutsu earthquake (Kobe Earthquake). It was found that horizontal seismic force caused local displacement at the webs and flanges of rectangular steel columns in steel bridge piers. It caused the corner welds to split. The decks were subsided by the loss of the vertical strength of columns.

To accurately predict the behavior of a bridge during an earthquake, including the nonlinear effects of structural members, dynamic analysis is necessary. Hence, in this study dynamic analysis was carried out to find the seismic behavior of the structure under real earthquake loads. Here, three earthquakes having different characteristics were used to study the variation of the effects on the same structure. Different combinations of east-west (EW), north-south (NS) and up-down (UD) components of the earthquakes were studied. The radius of the hole was varied to observe its effect on the seismic behavior.

2. Analysis conditions and numerical model

2.1 Earthquake data

Earthquake data from the Niigata Chuetsu earthquake (2004), the Noto earthquake (2007) and the Iwate, Miyagi earthquake (2008) have been used here in this study. Each of the earthquakes had different characteristics. From the Fourier spectrum in Fig. 2, it is seen that Iwate earthquake (EW component) is a high frequency earthquake having its major wave components in the range of 2.5 to 4.5 Hz. On the other hand, the EW component of Chuetsu earthquake has its major wave-components in the frequency range of 0.6 to 0.9 Hz. The Fourier spectrum of Noto earthquake (EW component) is similar to that of Chuetsu earthquake (EW component) with a dominating frequency of 0.5 to 0.6 Hz. The model that was used in the study had a natural frequency of 1.7 Hz. So, depending on the natural frequency of the structure and the frequency of the earthquake, the effects could vary. Again, the EW component of Iwate earthquake has a peak acceleration of 6.5 m/s^2 whereas Chuetsu earthquake’s EW component and Noto earthquakes EW component has a peak acceleration of 12.5 m/s^2 and 4 m/s^2 respectively. So, each of the earthquakes are different in their characteristics.

Fig. 2

The earthquake data that were used had three components: the east-west component (EW), the north-south component (NS) and the up-down component (UD). The EW component was the most dominating component in all the three earthquakes. From the Iwate earthquake data and the Noto earthquake data all the three components were applied. But for the case of the Niigata Chuetsu earthquake, only the EW and NS component were used as the earthquake load.

In order to ensure the safety of steel bridge piers against earthquake, their inelastic response up to collapse needs to be predicted accurately [26]. In this study, the effects of the hole at different stages of the earthquake during the collapse of the structure were examined. Under the actual earthquake load the structure did not undergo total collapse. To study the structural behavior during total collapse of the structure, different multiplying factors were used for the earthquake loads. In case of Iwate earthquake the multiplying factor was 6, which means 6 times the load of the original earthquake components was applied in all the three directions. For Niigata Chuetsu earthquake, two times the EW and NS components of the earthquake was considered for the same reason of observing total collapse. And in case of Noto earthquake the multiplying factor was 4. Table 1 shows some characteristic properties of the earthquake data used in this study. In the table, the peak acceleration is shown considering the multiplying factors used for the analysis. ‘Frequency’ indicates the dominant frequency component of the earthquake found from Fourier analysis. The frequency in each case is quite different. In all the cases, the east-west (EW) component of the earthquake was applied along the direction of the beam axis.

Table 1

Fig. 3 shows the directions of load application on the portal frame structure. The EW component was applied parallel to the beam and the NS component was applied in the direction perpendicular to the beam. In case of the Iwate earthquake and the Noto earthquake, the UD component was applied in the vertical direction.

Fig. 3

2.2 Numerical model

The finite element program package MSC. Mark was used here for the numerical analysis. Elasto-plastic large deflection analysis was carried out. The model used for the analysis was a typical steel portal frame with a height of 12 meter. The box columns and beams had a cross section of 2m × 2m. The steel plates were 20 mm thick. The material properties were: modulus of elasticity, E = 200 GPa, Poisson's ratio = 0.3 and yield stress = 315 MPa. A hole was arranged at the beam-column connection and the radius was varied to see its effect on the structure. The arrangement of the hole is illustrated in Fig. 4. From the figure it can be seen that the core is common to both the beam and column. The core with the same radius is present both in the Y-Z plane (web plate) and the X-Y plane (column flange).

Fig. 4

Three different cases were studied: without any hole (r = 0 mm), with 100 mm radius hole (r = 100 mm) and with 150 mm radius hole (r = 150 mm). These are the typical hole radiuses used in the portal frames of metropolitan expressway in Tokyo.

2.4 Analysis conditions

In addition to the self-weight of the structure, a superstructure weight of 1400 ton was applied. In the analysis, the bases of the columns were completely fixed. The displacement and rotation of the nodes connecting the ground were set to zero. On the remaining part of the structure, no restriction was considered. This was same to the practical structure. In the study damping was considered by an equivalent Rayleigh Damping in the form of

$$[C] = \alpha [M] + \beta [K] \quad (1)$$

Here, [C] = damping matrix of the physical system; [M] = mass matrix of the physical system; [K] = stiffness matrix of the system; α and β are pre-defined constants.

The duration of analysis was 15 seconds.

2.4 FEM mesh discretization

Depending upon the type of structural component, purpose of analysis, ease of modeling and desired accuracy the element type is chosen. For this investigation mostly rectangular thin shell elements were used for the FEM modeling. In some places triangular thin shell elements were also utilized for the convenience of modeling. As the corner zone of the beam-column connection was a special place of interest and also because of the complex load transfer mechanism, a gradually finer mesh size was used there. Fig. 4 (b) shows the FEM model and the arrangement of the hole for the corner zone. The whole portal frame was modeled for analysis.

3. Results

3.1 General

The analysis results can be presented in two categories. One is the effect of the hole on the global displacement at the top of the frame as shown in Fig. 5a. The other is the local displacement near the corner zone of the beam-column connection as shown in Fig. 5b.

3.2 Global displacement at the top of the frame

The Japanese design code specified the limiting horizontal displacement at the top as 1% of the height of the structure. Here horizontal displacement at a specific time is measured as the horizontal difference between the initial position of the top corner and its position at that time as shown in Fig. 5a. The location of the top and bottom plate of the beam and also the out of plate displacement on a vertical plate is shown in Fig. 5b. The time history of the global horizontal displacement parallel to the beam for the Iwate earthquake, the Niigata Chuetsu earthquake and the Noto earthquake are shown in Fig. 6, Fig. 7 and Fig. 8

respectively. Fig. 6 shows that there was almost no effect on the displacement behavior when the radius of the hole was 100 mm. But for 150 mm radius hole the curve started to shift after 6 sec. For the frame with no hole and with 100 mm hole, the residual displacement was about 1300 mm and for the frame with 150 mm hole the residual displacement was about 1580 mm. This difference could be observed from Fig. 6 at the x-axis range of 8 to 15 sec. Thus the increase in the residual displacement was found to be about 22%.

Fig. 5a

Fig. 5b

Fig. 7, similar to Fig. 6, shows the time history of global displacement at the top of the structure, this time for the Chuetsu earthquake. In this case, unlike the previous case, there was somewhat reduction in the residual displacement when the radius of the hole was 100 mm. But again for 150 mm radius the increase in residual displacement was quite significant. In the case where there was no hole in the structure, the residual displacement was about 250 mm. But in the case with 150 mm hole, the residual displacement increased up to 320 mm. The change in the residual displacement was almost –10% (decrease) for 100 mm hole and 30% (increase) for 150 mm hole. The maximum horizontal displacement was also different in the three cases. The 100 mm hole seemed to decrease the value to some extent. In the case with no hole the maximum displacement was about 370 mm where it increased to 450 mm for the case of 150 mm hole. Fig. 7 shows that the displacement behavior up to 4 second was same for all the three cases of no hole, 100 mm hole and 150 mm hole. After 4 second the structure with 150 mm hole started to go under larger displacement and this continued till the end. Although the pattern of the displacement response was similar in all the three cases, the hole certainly affected significantly the extent of displacement.

Fig 6

Fig 7

Fig 8

Fig. 8 shows the response of the structure subjected to the Noto earthquake. In this case the three earthquake components were used in the similar manner to the Iwate earthquake and with a multiplying factor of 4 as mentioned earlier in “Analysis conditions and the numerical model” section. There was about 14% increase in the maximum displacement (Fig. 8, near 10.5 sec) when the hole radius was 100 mm and the amount of increase reaches 50% when the hole radius was 150 mm. The permanent horizontal displacement was 175 mm when there was no hole. The introduction of a 100 mm hole made the permanent deformation to increase to 208 mm. When the hole radius was 150 mm, the permanent deformation was even more increased to 267 mm. The increase in permanent displacement was 19% and 53% for the case of 100 mm hole and 150 mm hole respectively. The affect of 150 mm hole seemed to be quite high.

3.3 Effect of hole radius on local displacement near the corner zone

Along with the study of the horizontal displacement of the structure, the local displacement near the corner zone, where the hole is provided was also studied. Stress concentration occured at the beam-column connection, which caused the steel plates near that zone to undergo out of plane displacement. The pattern of the local displacement was very similar to the displacement behavior at the top of the structure. This indicated a relation between the local displacement and the displacement of the total structure. The time history curves for the local displacement near the hole for the different cases of the Iwate earthquake, the Niigata Chuetsu earthquake and the Noto earthquake are presented in Fig. 9, Fig. 10 and Fig. 11 respectively.

Fig. 9 is the time history curve for the out of plane displacement at the bottom plate of the beam just below the hole (Fig. 5b). This is for the Iwate earthquake. The figure shows that the two cases of without hole and with 100 mm hole were almost same. But the 150 mm hole definitely increased the amount of out of plane displacement. The residual displacement was 342 mm when there was no hole and it was 402 mm when the hole radius was 150 mm. The increase in displacement was about 18%.

Fig 9

Fig 10

Fig 11

Fig. 10 shows the out of plane displacement for the Chuetsu earthquake. The displacement location was on the top plate of the beam near the beam-column connection (Fig. 5b). The pattern of the time history was identical to the top displacement of the whole structure (Fig. 7). In both cases there was an abrupt change in displacement near 4 second, which indicated that the local displacement failure initiated the sudden increase in top displacement of the structure. When there was no hole, the residual out of plane deformation was 144 mm and the introduction of 150 mm hole increased it to 167 mm. So, the 150 mm hole increased the residual deformation by 16%.

In case of the Noto earthquake the displacement occurred more on the bottom plate of the beam near the beam-column connection. The displacement was more affected by 150 mm hole during 7 to 10 second period as shown in Fig. 11. The difference in amount of displacement between the cases of no hole and 150 mm hole was most significant near 10 second. The displacement values were 72 mm for the frame with no hole and 104 mm for the frame with 150 mm hole; which showed an increase in displacement of almost 45%. The residual displacement seemed to have very little effect in this case of the Noto earthquake.

Table 2 shows the effect of the hole radius on the cases of 3 different earthquakes. In the table the values in the parentheses are the percentage of increase in the displacement compared to the displacement in the case without hole.

Table 2

From the table it is clear that the hole affected the structure, both on its global and local behavior. The important observation was how the radius of the hole affected these behaviors. It was found that the introduction of 100 mm hole had very small affect on the structure’s global or local behavior and in some cases the displacement was even reduced. The only exception was the global displacement in the case of the Noto earthquake. On the other hand, the 150 mm hole largely affected both the local and global displacement in all the analyzed cases. The increase in displacement ranged from 16%-53%, which was quite high and indicated the requirement of limiting the size of the hole.

The gradual effect of the hole radius on the local displacement pattern could be observed from Fig. 12. The figure shows the displacement of the top plate adjacent to the hole or the beam-column connection as indicated in Fig. 5b, for the case of the Niigata Chuetsu earthquake.

Fig. 12

The hole radius being changed from 100 mm to 150 mm induced an increase in out of plane displacement at the left side of the plate, where the hole was situated. This made an overall increase in the local displacement and thus accelerated the local failure.

4. Remarks

In this study, effects of hole radius on the behavior of the thin walled box portal frame structure were studied under different earthquake loads with varying magnitude and frequency. The duration of the load application was same. If we look at the response behavior of the structures under the earthquake loads, it can be seen that they were quite different in each case. In case of the Iwate earthquake (Fig. 6), the structure remained quite stable up to 3.5 second and starting from 6 second until 8 second there was an abrupt change in displacement. During any small segment of time, the sway amplitude remained around 200 mm. In case of the Chuetsu earthquake, the structure was quite stable up to 4 second. But just at 4 second, there was a very sudden change in displacement, which was a bit similar to the case of the Iwate earthquake, but occurred, in a much shorter time. In case of the Noto earthquake the sway amplitude gradually increased and after 10.5 second held constant amplitude.

The vibration frequency of the structure in case of the Iwate earthquake and the Chuetsu earthquake was found to be 1.8 Hz whereas; it was 1.4 Hz in case of Noto earthquake. It should be noted that the natural frequency of the structure was 1.68 Hz in the first mode, which was sway in the direction parallel to the beam. And this was the direction, which was considered for global horizontal displacement calculation.

Now, among the different factors that influence the response and collapse of a structure, some are the ground characteristics, structure type and earthquake characteristics. In this study the material properties, boundary conditions of the structure were constant. The difference in the characteristics of the earthquakes, which has been discussed in the “Analysis conditions and the numerical model” section was the reason for the variation in the structural response.

Among the three cases that were stated in this paper, the Noto earthquake showed the most prominent effect of hole radius on the response of the structure. All of global residual displacement, maximum displacement and local out of plane displacement experienced about 50% increase as a result of using a 150 mm hole. Compared to the east-west components of the other two earthquakes, this case had the lowest peak acceleration value of 1520 gal (including multiplying factor). On the other hand, the east-west component of the Iwate earthquake and the Chuetsu earthquake had a peak acceleration of 4140 gal and 3350 gal respectively (including multiplying factor). But in these cases the effect of 150 mm hole was not same as the case of Noto earthquake. The 150 mm hole produced an average increase of about 20% in global residual displacement, maximum displacement and local out of plane displacement.

The use of 100 mm hole did not have the same effect as the 150 mm hole did. It did not change the global behavior of the structure under the Iwate earthquake and on most other cases it reduced the global and local displacement. There might be several reasons for such different behavior. The study of the local displacement pattern showed that the initial introduction of the 100 mm hole reduced the rigidity at the beam-column joint and thus helped absorb more energy. In the case of no hole, the plate near the beam-column joint experienced stress concentration. But the introduction of the 100 mm hole removed those stress concentrated zones and thus caused the plate near the beam column joint to undergo a much uniform deformation. On the other hand, the 150 mm hole, although had removed the stress concentrated zone, caused a significant reduction on the section strength. The 100 mm hole definitely reduced the sectional strength to some extent, but its effect was definitely suppressed by the advantage of the stress concentrated zone being removed. The local deformation pattern of the same section of the three cases of without hole, with 100 mm hole and with 150 mm hole showed that the local failure was accelerated by the increase of hole radius to 150 mm.

The local displacement behavior also affected the global behavior of the structure. The horizontal displacement at the top of the structure was influenced by the local failure of steel plate near the beam-column connection. As we can see by comparing Fig. 6 with Fig. 9 and Fig. 7 with Fig. 10 that their displacement pattern with respect to time were quite similar. In case of Iwate earthquake it can be seen from Fig. 6 that the increase in horizontal displacement occurs between 7 and 8 second. Similarly the increase in local displacement occurred between 7 and 8 second (Fig. 9). The same behavior could be observed in case of the Niigata Chuetsu earthquake from Fig. 7 and Fig. 10. In case of the Noto earthquake the similarity was not quit obvious, but the sudden increase in local displacement at 5 second (Fig. 11) definitely increased the sway amplitude (Fig. 8).

5. Conclusion

Dynamic analysis of a commonly used bridge portal frame was carried out to find the effect of hole radius on the structural behavior. The hole is used at the beam-column connection of portal frames of viaduct bridges as a remedy against the fatigue failure. The frame was studied under the effect of three different earthquake loads and in each case there were three different types; one without a hole at the beam-column connection and the other two with varying hole radius. It was found that the presence of the hole did have an effect on the structural behavior both globally and locally. Specially, for this study, when the hole radius was greater that 100 mm, the effect was found to be more prominent. So, the radius of the hole needed to be paid attention to. Specifically, from the study of this paper, following were the findings that need to be considered while dealing with the fatigue problem using the coring (hole) method.

- The 100 mm hole was found to have quite small effect on the structural behavior. But the 150 mm hole affected both the global and local behavior.
- It was found that the 150 mm radius hole caused about 20% to 50% increase in the top horizontal displacement in different cases.
- The local displacement was also affected in a similar manner to the global behavior and it was observed that the local displacement and the global behavior were

interrelated.

- The displacement behaviors of the structures were different depending on the characteristics of the earthquake loads.
- The coring or hole method may be used for increasing the fatigue strength, but the hole radius should be kept under the limit above which the sectional strength is compromised significantly.

As the local displacement and the global behavior of the structure was found to affect each other, the buckling strength of steel plates, especially in case of thin walled bridge piers must be kept in mind. Joint sections in thin walled structures like the one here in the beam-column connection are prone to buckling failure due to the complicated stress transfer mechanism and the development of stress concentration. But the presence of a comparatively large hole may aid into the buckling failure rather than serving its main purpose of removing stress concentrated zones. And the local buckling failure will induce large sway of the whole structure leading to structural failure. So, the results of this paper indicated that special attention should be paid on the buckling strength while designing the joint section and determining the hole (core) radius.

But the coring method can be used as an effective remedy in removing the stress concentrated zones to increase fatigue strength as long as the radius of the hole is kept under the limit, in this case which was found to be 100 mm. Hence, the radius of the hole must be considered while designing such joints to increase fatigue strength.

This limiting radius of the hole may vary on different cases. Also, the effect of the hole radius may depend a lot on the type of structure, use of stiffeners, the thickness of the plates and also on the properties of the material. So, different other individual cases should be studied with other commonly used frames and also using earthquake data of varying characteristics. Dynamic analysis should be carried out as done here in this study to accurately predict the behavior of the structures.

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Figures and Tables

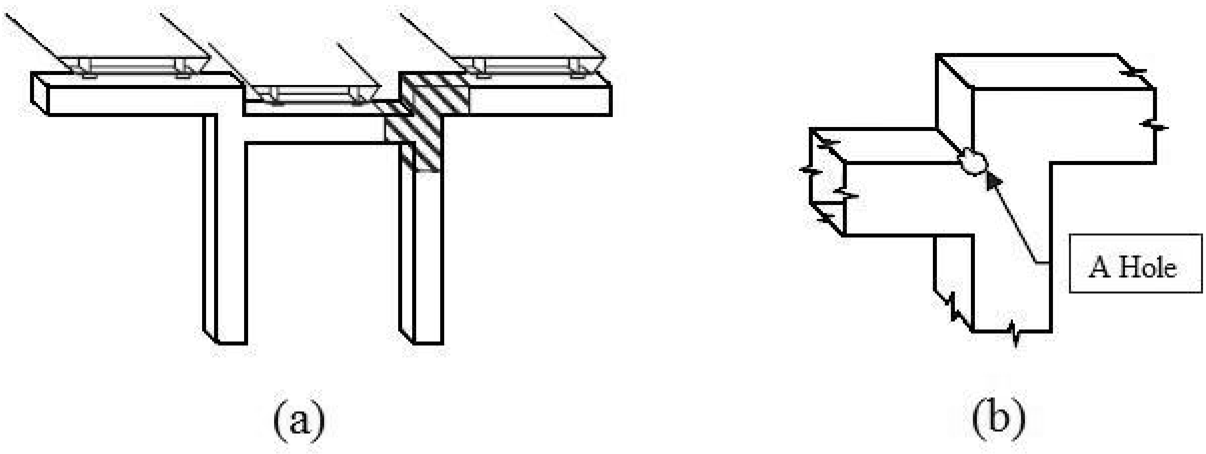
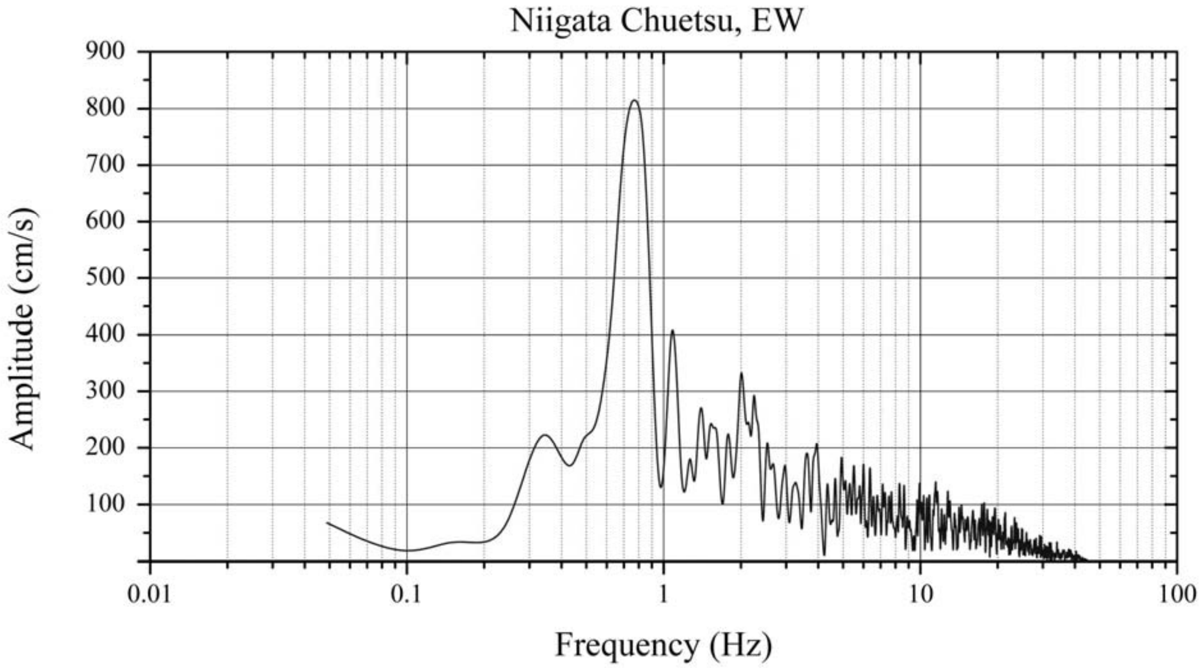


Fig. 1. (a) Portal frame used as a pier for motorway viaduct and (b) arrangement of hole at the beam-column connection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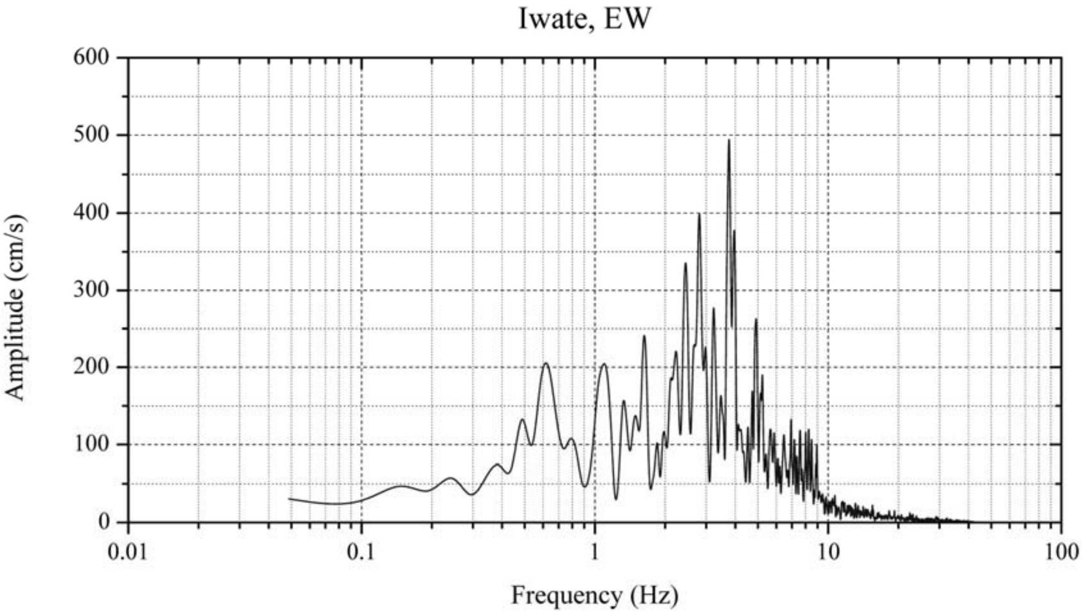
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Frequency (Hz)

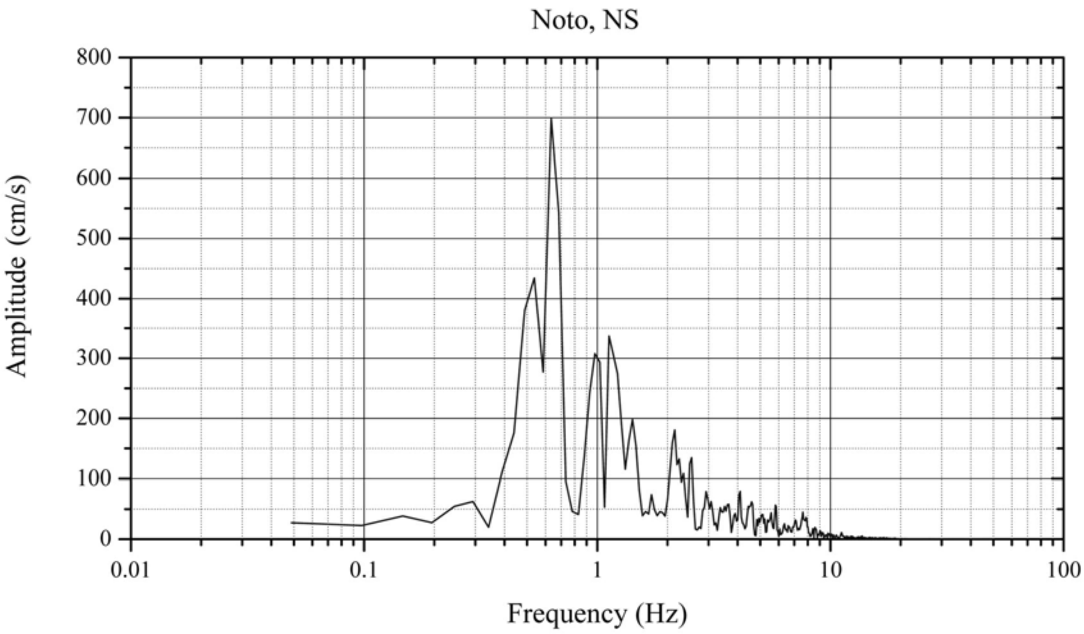


Fig. 2. Seismic load, EW component. (a) Ground acceleration (left) and fourier spectrum (right) of Iwate earthquake, (b) ground acceleration (left) and fourier spectrum (right) of Niigata Chuetsu earthquake, (c) ground acceleration (left) and fourier spectrum (right) of Noto earthquake.

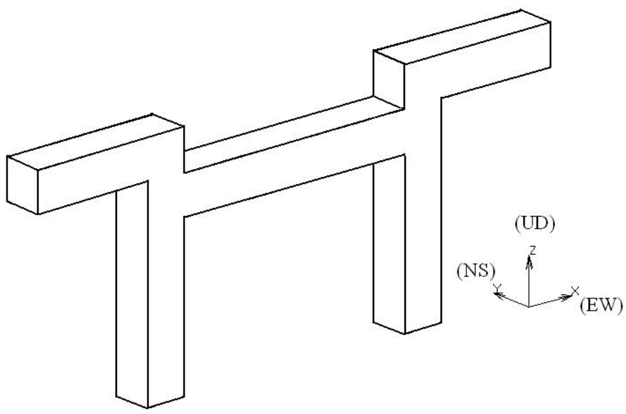
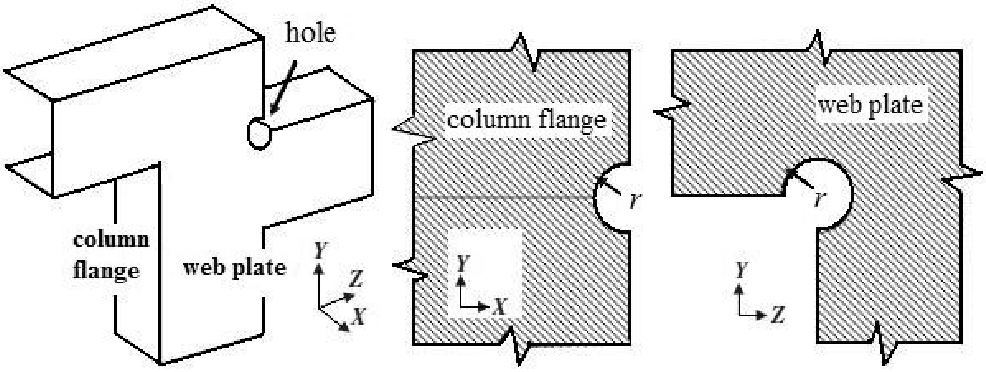
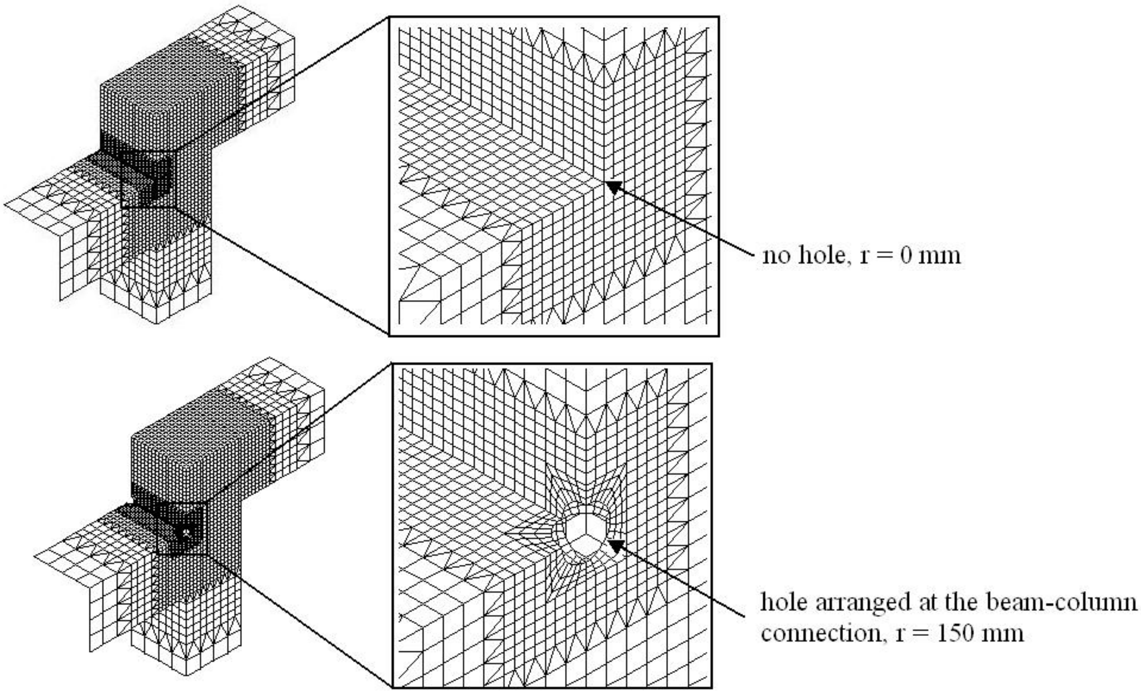


Fig. 3: Application of earthquake load components



(a)



(b)

Fig. 4: (a) Arrangement of the hole, (b) FEM model for hole arrangement at the beam-column connection

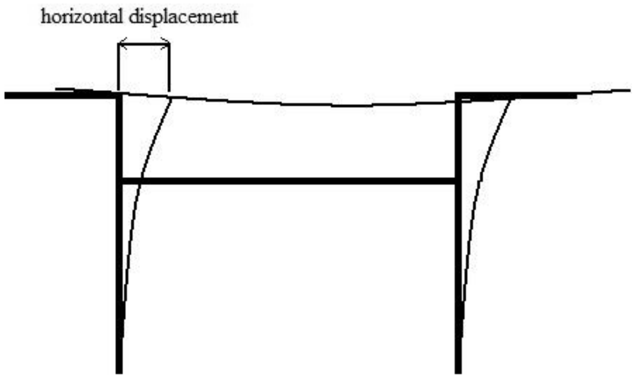


Fig. 5a: Horizontal global displacement

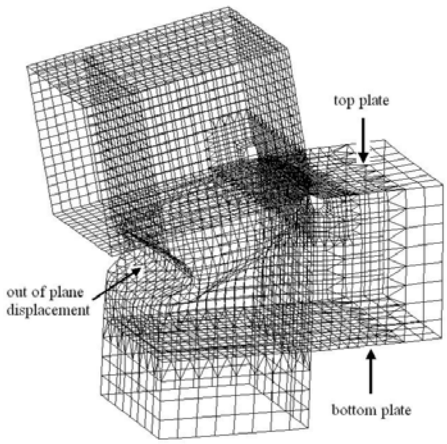


Fig. 5b: Out of plane displacement

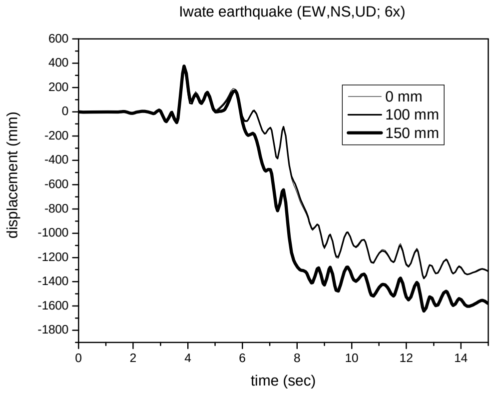


Fig 6: Top displacement, Iwate EQ

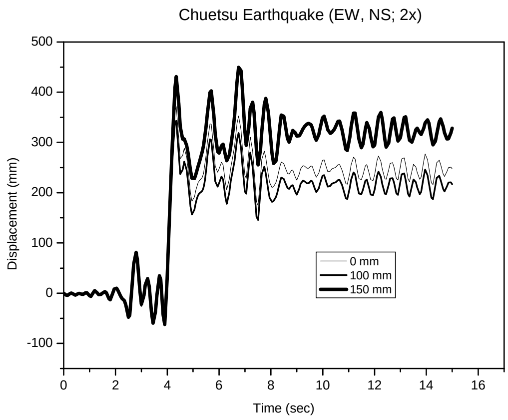


Fig 7: Top displacement, Chuetsu EQ

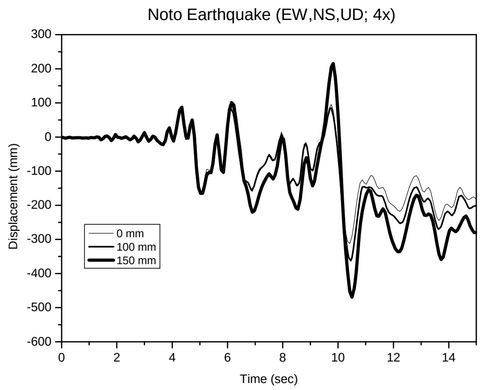


Fig 8: Top displacement, Noto EQ

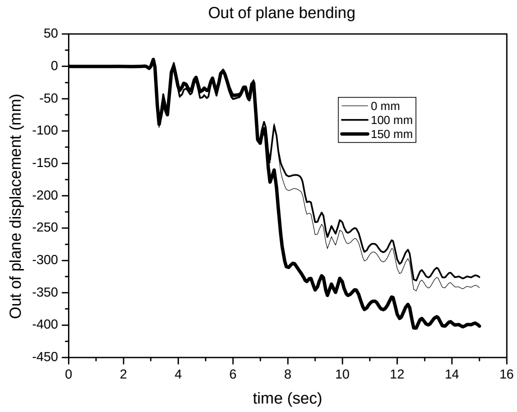


Fig 9: Out of plane displacement, Iwate EQ

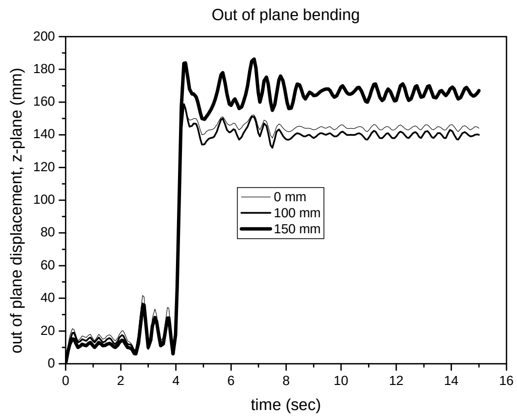


Fig 10: Out of plane displacement, Chuetsu EQ

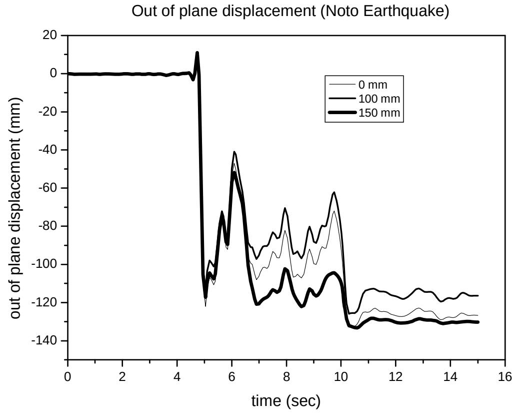


Fig 11: Out of plane displacement, Noto EQ

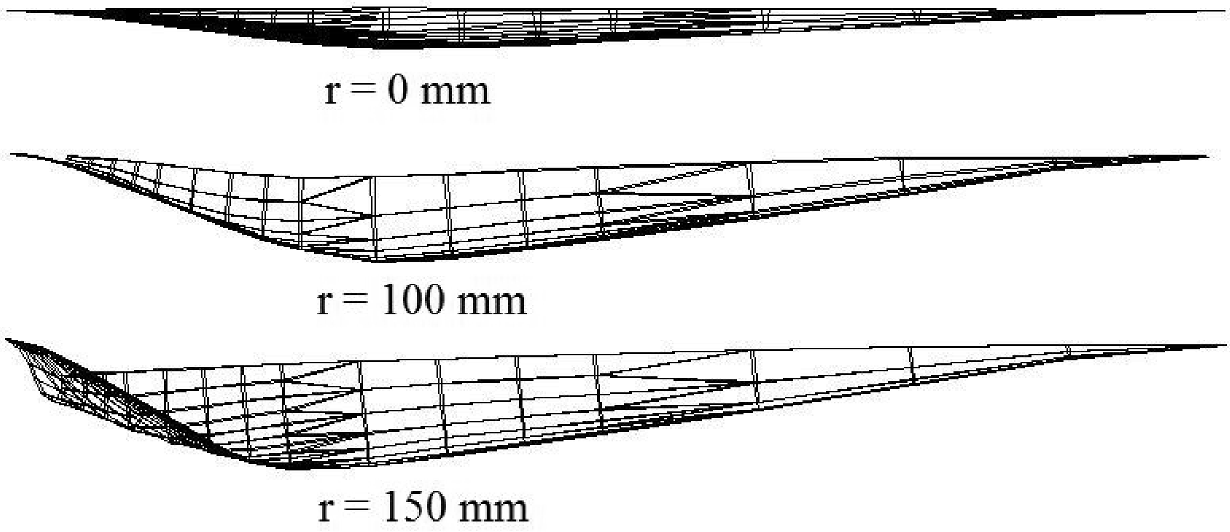


Fig. 12: Local displacement of top plate (Chuetsu earthquake)

	Iwate earthquake			Chuetsu earthquake			Noto earthquake		
	EW	NS	UD	EW	NS		EW	NS	UD
Frequency (Hz)	4.0	3.6	14	0.8	5.0		0.6	0.7	0.73
Peak acc (gal) (Multiplied by factor)	4140	2340	2640	3350	1860		1520	1240	640

Table 1: Characteristic properties of the earthquake used in this study

	r = 0 (%)	*r = 100 (%)*	*r = 150 (%)*
(a) Iwate earthquake			
Global Residual displacement (mm)	1300(0)	1300 (0)	1580 (22)
Global Maximum displacement (mm)	1370 (0)	1370 (0)	1640 (20)
Out of plane displacement (mm)	342 (0)	326 (-5)	402 (18)
(b) Chuetsu earthquake			
Global Residual displacement (mm)	250 (0)	215 (-14)	320 (30)
Global Maximum displacement (mm)	370 (0)	345 (-7)	450 (22)
Out of plane displacement (mm)	144 (0)	140 (-3)	167 (16)
(c) Noto earthquake			
Global Residual displacement (mm)	175 (0)	208 (19)	267 (53)
Global Maximum displacement (mm)	310 (0)	355 (15)	470 (52)
Out of plane displacement (mm)	72 (0)	62 (-25)	104 (45)

Table 2: The effect of hole radius