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DEVELOPMENT OF RC COLUMN WITH EMBEDDED MESNAGER HINGE FOR BEYOND DESIGN BASIS EVENTS

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Abstract

After the 2011 Tohoku Earthquake, the concept of "Anti-Catastrophe" has been proposed and the behavior of RC columns in beyond design basis event (BDBE) became important at seismic design. Especially, it is necessary to predict fracture behavior of RC column in BDBE in advance. However, failure behavior of a plastic hinge in a conventional RC column is known to become uncontrollable and unexpected in BDBE. Therefore, "Embedded Mesnager hinge RC column" and "Embedded Mesnager hinge UBRC column" whose behavior in BDBE can be predicted are proposed. Embedded Mesnager hinge RC column has a Mesnager hinge embedded at the base of the column which can reduce the uncertainty of the fracture behavior of it in BDBE. Embedded Mesnager hinge UBRC column consists unbonded high-strength bars and embedded Mesnager hinge RC column with reference to UBRC structure are proposed by Iemura et al. The high-strength bars installed into the embedded Mesnager hinge UBRC column can increase the stability of the column in BDBE. In order to evaluate the seismic performance of these structures, cyclic loading tests were carried out. Results show that the embedded Mesnager hinge prevented uncontrollable destruction of the column in BDBE by suppressing the axial and shear deformation at the base of the column. Besides, the restoring force of the Embedded Mesnager hinge RC column decreased in BDBE more slowly than that of conventional RC column. Additionally, the elastic force added by the installed PC bars canceled *P-Δ* effect and kept the positive restoring force of the column under large deformation. Therefore, it was found that the fracture behaviors can be predicted and the stability of the column was secured in BDBE by installing a Mesnager hinge and PC bars to RC columns.

Keywords: RC column, Mesnager hinge, UBRC structure, Cyclic loading test, Beyond design basis event

1. Introduction

After the 2011 off the Pacific coast of Tohoku Earthquake, the risks of unexpected earthquakes were recognized, and anticipation of extreme events has become a major concern in Japan. As a result, anti-catastrophe is proposed as a new concept, which is mentioned in the design code of Japanese railway structures [1]. In this paper, events expected at seismic design are called design basis events (DBE), and events which are not expected at seismic design are called beyond design basis events (BDBE) referring to Takeda and Nishimura [2].

In conventional behavior of RC column, a plastic hinge is formed at the base of the column in design basis events, and uncontrollable destruction occurs at plastic hinge in beyond design basis events. It is very likely for another strong earthquake like the Tohoku Earthquake or the Kumamoto Earthquake to strike again in the next few decades. Therefore, it is necessary to predict behavior of RC columns in beyond design basis events.

Therefore, "Embedded Mesnager hinge RC column" and "Embedded Mesnager hinge UBRC column" are newly developed and proposed as RC columns whose behavior in beyond design basis events can be predicted. Embedded Mesnager hinge RC column has a Mesnager hinge embedded at the base of the column. Embedded Mesnager hinge UBRC column consists unbonded high-strength bars and embedded Mesnager hinge RC column with reference to UBRC structure proposed by Iemura et al. [3]. In order to evaluate the seismic performance of these structures, cyclic loading tests were carried out.

2. Proposal structures

2.1 Functions of plastic hinge in RC columns

The plastic hinges need to satisfy two functions. First is hinge function to transmit axial and shear forces and to maintain continuity of deflection. Second is absorption of seismic energy and improvement of deformation performance by plasticization. In design basis events, since the hinge function can be satisfied without taking any measures, previous studies focused on the absorption of seismic energy and improvement of deformation performance.

However, in beyond design basis event, there is no guarantee that the hinge function can be satisfied in plastic hinge in RC columns. If plastic hinge loses its hinge function for beyond design basis event, unexpected deformation at plastic hinge may occur such as axial settlement and shear deformation. Therefore, it is important to guarantee the continuity of deflection in the plastic hinge in that the behavior of RC columns for beyond design basis events can be predicted.

2.2 Embedded Mesnager hinge RC column

As indicated in 2.1, the plastic hinges need to satisfy two functions. However, it is difficult to keep both function of the plastic hinge in beyond design basis events. Therefore, "Embedded Mesnager hinge RC column" is newly developed and proposed as RC columns to maintain hinge function for beyond design basis events which is important for predicting the behavior of RC columns. Mesnager hinge is a concrete hinge composed of crossing rebars and cover concrete. It transmits shear force and axial force without bending moment [4]. A Mesnager hinge is embedded at the base of the column in embedded Mesnager hinge RC column. On one hand, for design basis event, embedded Mesnager hinge RC column is expected to absorb seismic energy and to improve deformation performance by forming plastic hinge in the same way as conventional RC columns. On the other hand, for beyond design basis events, the performance of plastic deformation such as energy absorption and improvement of deformation performance is sacrificed, and the required performance of the column is limited only to the maintenance of the hinge function of the base of the column by an embedded Mesnager hinge. In other words, the purpose of embedded Mesnager hinge RC column is to minimize the uncertainty in the fracture behavior of RC columns by actively generating hinge behavior for beyond design basis events.

2.3 Embedded Mesnager hinge UBRC column

As indicated in 2.2, embedded Mesnager hinge RC column is expected to minimize the uncertainty in the fracture behavior of RC columns by actively generating hinge behavior by Mesnager hinge for beyond design basis events. However, when hinge behavior by Mesnager hinge is generated, embedded Mesnager hinge RC column may self-collapse due to P-Δ effect. Therefore, embedded Mesnager hinge UBRC column which consists unbonded high-strength bars and embedded Mesnager hinge RC column with reference to unbonded bar reinforced concrete reinforcement structure (UBRC structure) proposed by Iemura et al. [3] is newly developed and proposed. The high-strength bars installed into the embedded Mesnager hinge UBRC column can increase the stability of the column in beyond design basis events because positive restoring force is given to RC column by high-strength bars. Besides, in order to obtain the stable positive restoring force by high-strength bars in the large deformation, it is necessary to guarantee that the bars behave in the elastic manner. The unbonding treatment is performed in order to make the strain of high-strength bars smaller.

2.4 Control of damage in Embedded Mesnager hinge RC column and Embedded Mesnager hinge UBRC column

In conventional Mesnager hinge, upper portion and lower portion is connected only by crossing rebars, and notch exists in the concrete around the intersection of crossing rebars (Fig. 1). Therefore, since the deformation is localized at the intersection of crossing rebars, the hinge behavior is surely generated at the intersection of the crossing rebars. On the other hand, in embedded Mesnager hinge RC column, longitudinal bars exist with crossing rebar and there is no notch of concrete around the Mesnager hinge. Therefore, in order to generate hinge behavior at the intersection of crossing rebars, it is necessary to actively control the complex and uncertain fracture behavior of RC columns. Thus, loop reinforcement with 90-degree hook is arranged and large space of hoop reinforcement is adopted at the base of column in order to induce buckling of longitudinal bars in expected portion (Fig. 2).

Additionally, spiral reinforcement is arranged above the base of the column in order to prevent damage of the base of the column from propagating to upper of the column (Fig. 2). These methods were referred from previous study [5].

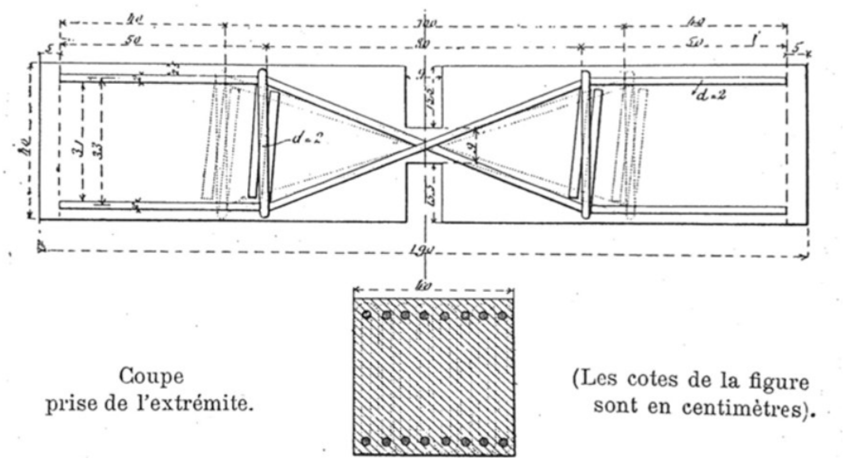


Fig. 1 – Mesnager hinge

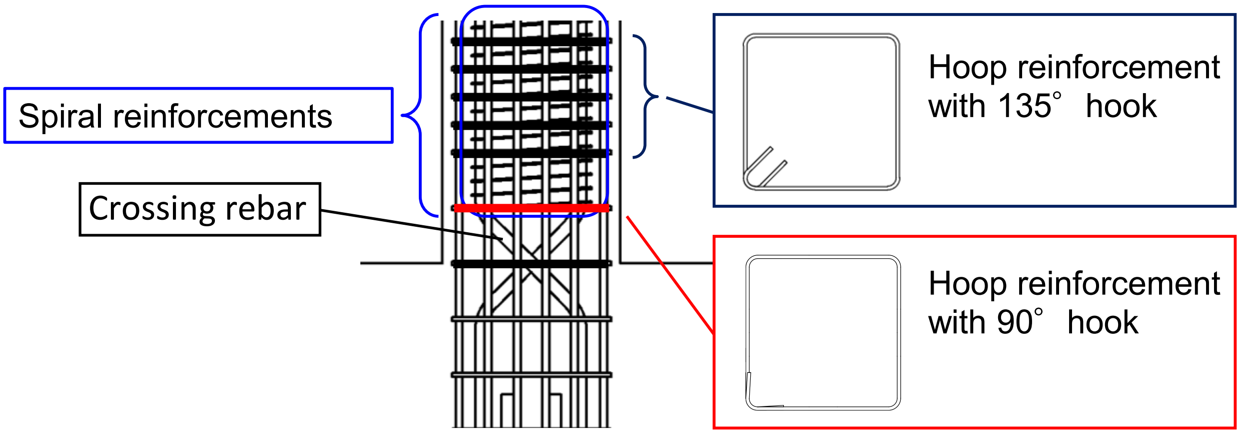


Fig. 2 – Method of Control of damage in embedded Mesnager hinge RC column and Embedded Mesnager hinge UBRC column

3. Detail of cyclic loading test

3.1 Test specimens

Cyclic loading tests were conducted for three specimens. Fig. 3 shows the dimensions of the column and the details of rebar arrangement. C50-RC is a conventional RC column that meets existing design basis. C100-EM-RC is an embedded Mesnager hinge RC structure. Longitudinal bars in C100-EM-RC are arranged the same as C50-RC. Mechanical properties of crossing rebars of Mesnager hinge were decide based on the Japanese seismic code described in Design Manual of Bridge Bearing [6]. C100-EM-UBRC is an embedded Mesnager hinge UBRC structure. Aim at design of C100-EM-UBRC is that restoring force of RC column maintains positive and unbonded high-strength bars maintain elastic up to 20δy deformation (deformation amplitude is 100mm). Thus, the mechanical property and the position of unbonded high-strength bars was determined by the numerical analysis in order to satisfy the aim at design of C100-EM-UBRC.

In C100-EM-RC, the spiral reinforcements were arranged from 100 mm to 650mm in height, while in C100-EM-UBRC, the spiral reinforcements were arranged only from 100 mm to 250mm in height. The influence of the difference in the arrangement of the spiral reinforcements would be discussed in 4.2.2.

Besides, it should be noted that the buckling of longitudinal bars is defined as the ultimate state of RC columns. Thus, beyond design basis events mean events after buckling of longitudinal bars in these experiments.

3.2 Loading system and Loading pattern

The loading system is shown in Fig. 4. In the system, the computer controls horizontal and vertical actuator. The cyclic horizontal loadings were applied by displacement control at quasi-static rate. The amplitude of the horizontal displacement was increased by 1δ_y (5mm), and the number of repetitions of cyclic loading was 3 times. The constant axial stress was set to 1.0MPa.

3.3 Measured data

Restoring force and axial force were measured by the load cells on both horizontal and vertical actuators. Horizontal displacement was continuously measured by a wire displacement gauge at the height of the loading point. Strain of crossing rebars was continuously measured by strain gauges attached to the intersection of crossing rebars.

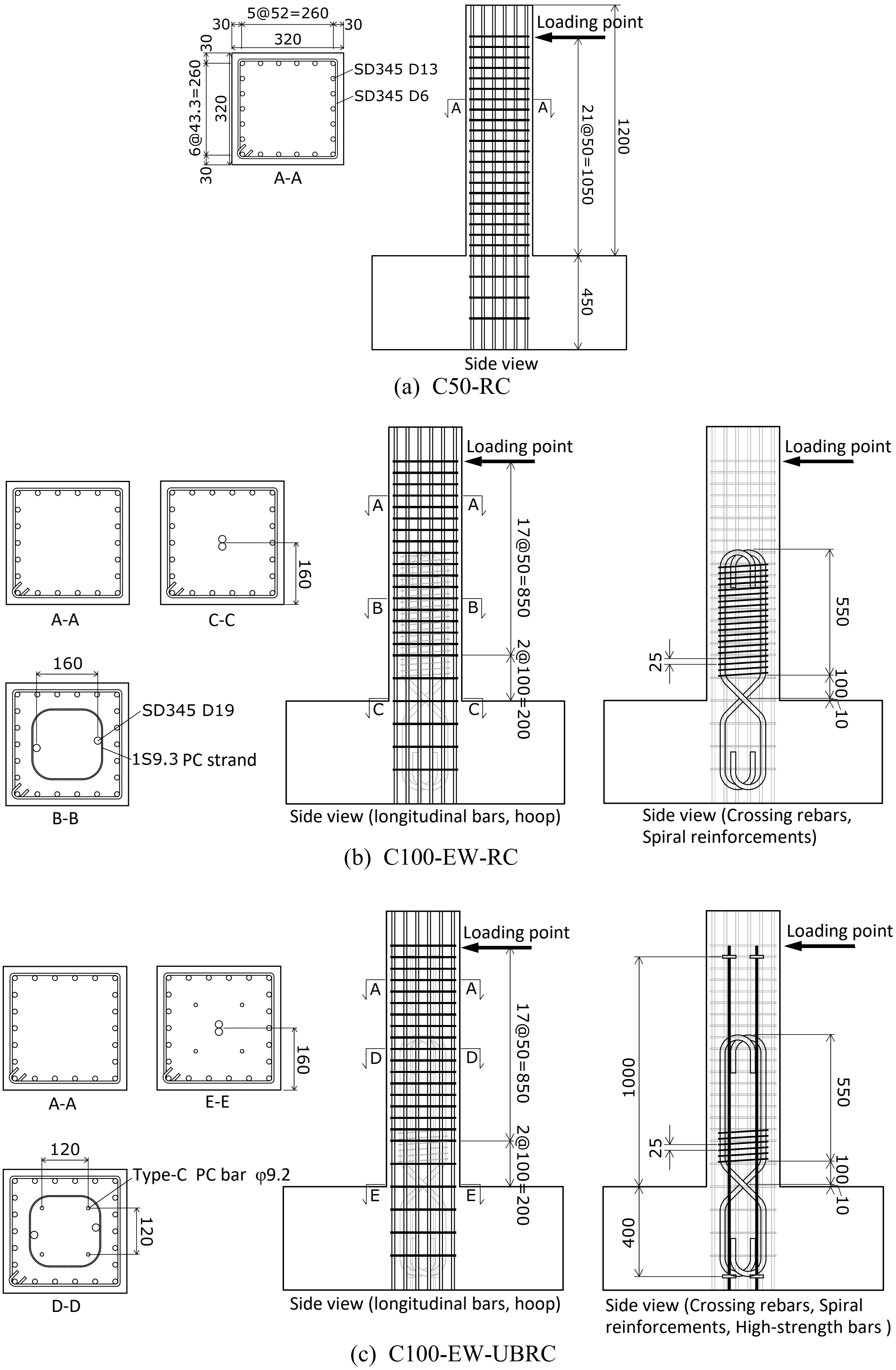


Fig. 3 – The dimensions of the column and the details of rebar arrangement

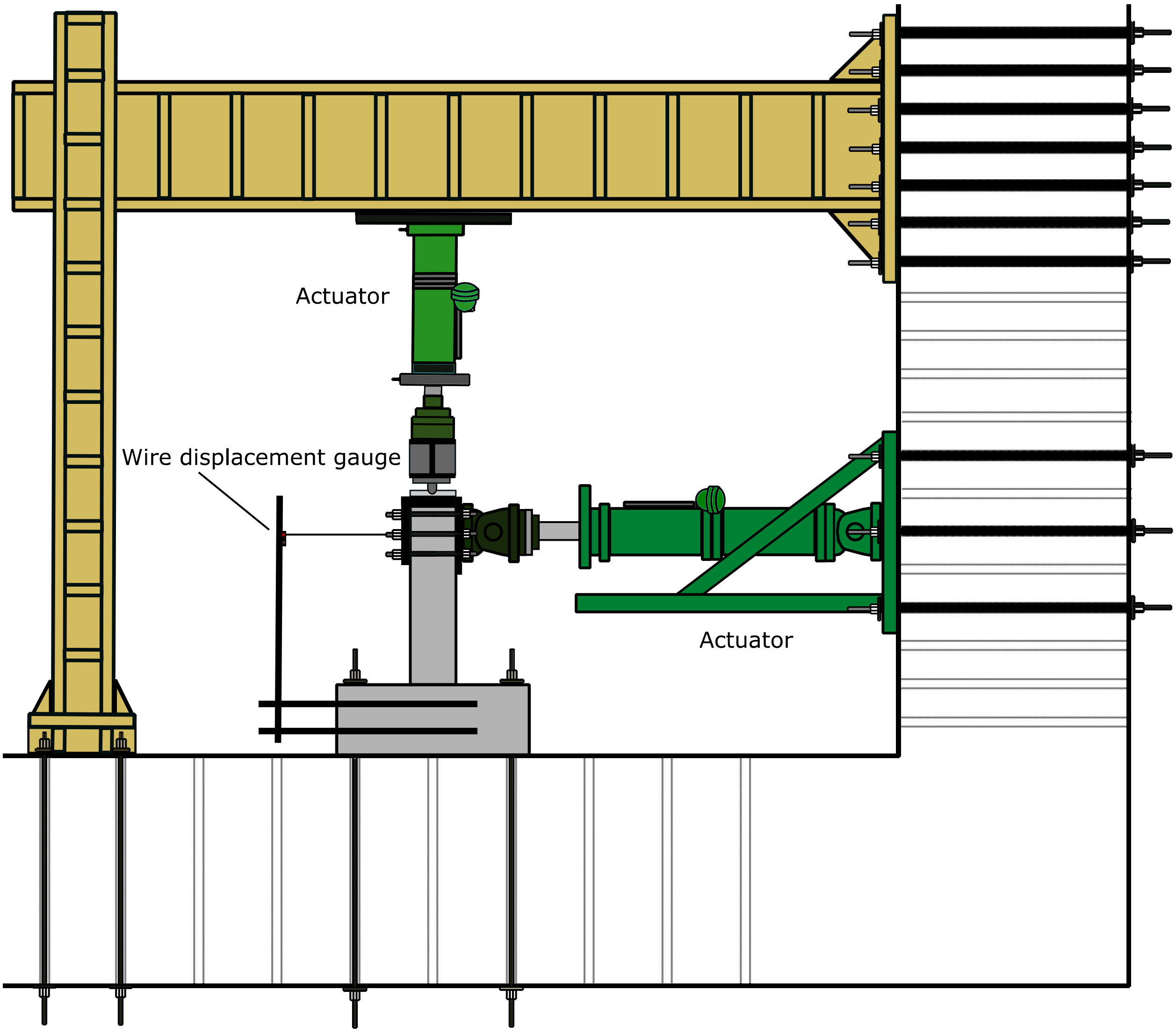
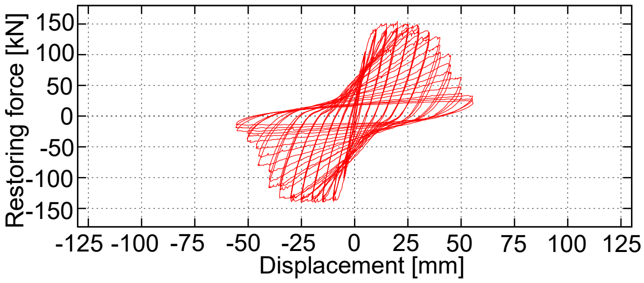


Fig. 4 –The loading system

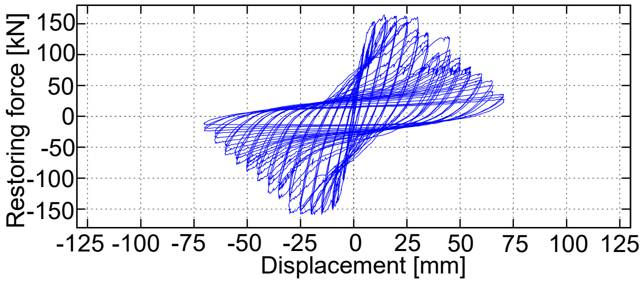
4. Experimental result

4.1 Restoring force - Displacement hysteresis loop

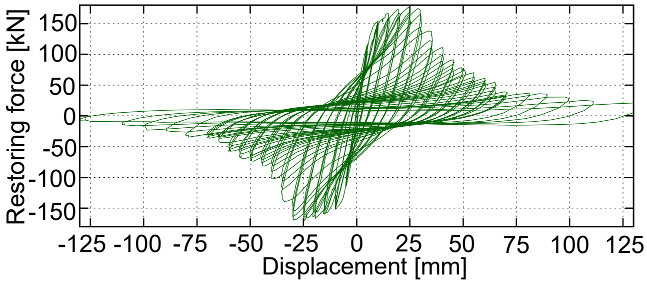
Fig. 5 shows the Restoring force - Displacement hysteresis loop. It should be noted that beyond design basis events are defined as events after buckling of longitudinal bars in these experiments as indicated 3.1. It was found that all specimens showed almost the same behavior for design basis events. On the other hand, for beyond design basis events, gradual decrease of restoring force can be achieved in case of C100-EM-RC and C100-EM-UBRC while large decrease of restoring force was observed in case of C50-RC. Therefore, post-peak behaviors in beyond design basis events were improved in case of C100-EM-RC and C100-EM-UBRC. This mechanism would be examined in 4.3.2.



(a) C50-RC



(b) C100-EM-RC



(c) C100-EW-UBRC

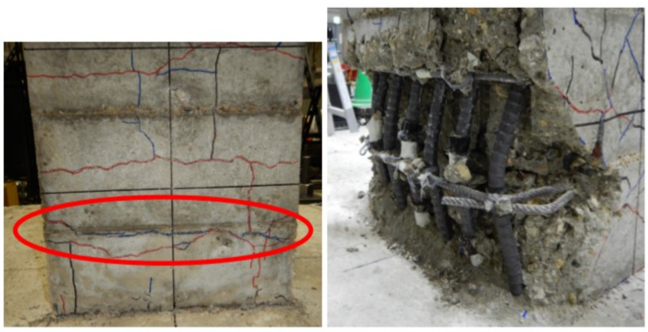
Fig. 5 – Restoring force - Displacement hysteresis loop

4.2 Damage control

4.2.1 Control on buckling portion of longitudinal bars by hoop reinforcement with 90-degree hook

Fig. 6 shows the failure pattern of C100-EM-RC and C100-EM-UBRC. In case of C100-EM-RC and C100-EM-UBRC, after a horizontal crack was generated at the height of 100 mm, the crack opened due to the buckling of the longitudinal bars. It was also confirmed that the peak of buckling deformation was located at the position of the hoop reinforcement with 90-degree hook. Therefore, it was considered that the buckling portion of longitudinal bars can be controlled by using hoop reinforcement with 90-degree hook.

(a) C100-EM-RC



(b) C100-EW-UBRC

Fig. 6 – Control on buckling portion of longitudinal bars by hoop reinforcement with 90-degree hook

4.2.2 Prevention of damage propagation to upper of the column by spiral reinforcements

In case of C50-RC, the core concrete damaged at the base of the column, and the damage progressed up to the height of 200mm. On the other hand, in case of C100-EM-RC and C100-EM-UBRC, the core concrete protected by the spiral reinforcements remained without damage although the cover concrete spalled off up to the height of 300mm. The damage of core concrete was limited to the height of less than 100mm. Therefore, it was considered that the spiral reinforcements prevented the damage of the base of the column from propagating to upper of the column. Moreover, the amount of the spiral reinforcement in C100-EM-UBRC is smaller than that of C100-EM as indicated in 3.1. However, the amount of the spiral reinforcement in C100-EM-UBRC was found to be enough, because the effect of the spiral reinforcement on the prevention of damage propagation can be confirmed.

(a) C50-RC (b) C100-EM-RC (c) C100-EW-UBRC

Fig. 7 – Prevention of damage propagation to upper of the column by spiral reinforcements

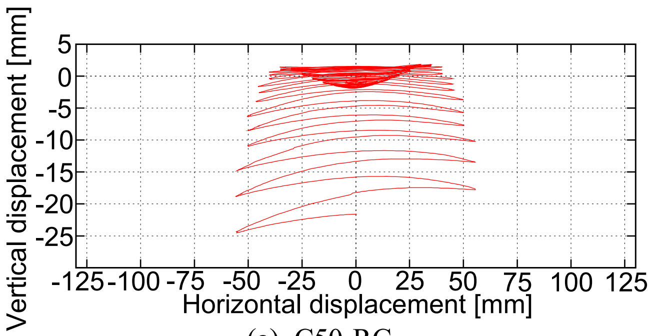
4.3 Hinge function of embedded Mesnager hinge in C100-EM-RC and C100-EM-UBRC

4.3.1 Prevention of the settlement at the base of column

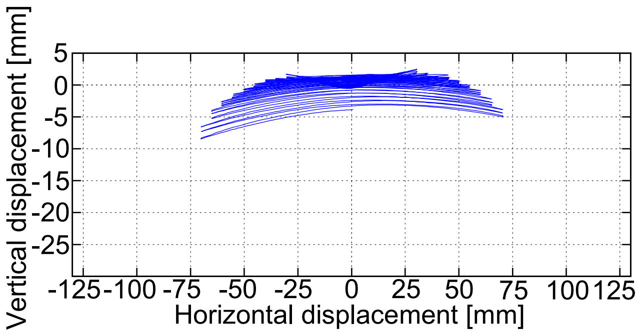
Fig. 8 shows the relationship between vertical displacement and horizontal displacement of each specimen in design basis events (before buckling of longitudinal bars occurred) and in beyond design basis event (after buckling of longitudinal bars occurred). In design basis events, settlement of the column was not observed in all specimens. On the other hand, in beyond design basis events, large settlement of the column was observed in case of C50-RC, while settlement of the column was prevented in case of C100-EM-RC and C100-EM-UBRC.

Fig. 9 shows the relationship between axial force by a crossing rebar and horizontal displacement of RC column in design basis events (before buckling of longitudinal bars occurred) and in beyond design basis events (after buckling of longitudinal bars occurred). It is noted that positive value of the axial force by a crossing rebar means tensile force, and negative value means compression force. Fig. 9 illustrates that only tensile force acted on the crossing rebar and worked as tensile members in design basis events. On the other hand, in beyond design basis events, compressive force equivalent to 25% of the external axial force acted on the crossing rebar. When compressive force acting on the crossing rebar is converted to two rebars, it was found that the embedded Mesnager hinge supported the axial force equivalent to 50% of the external axial force.

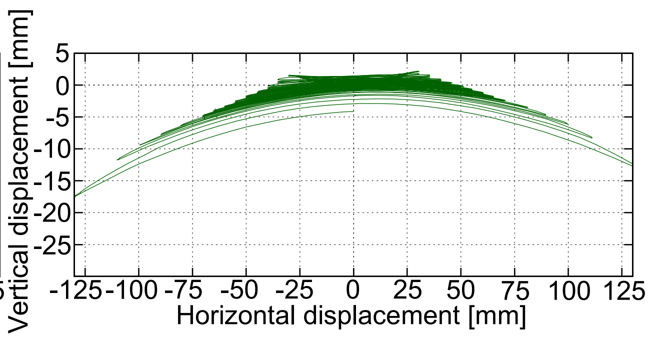
Therefore, it was found that the embedded Mesnager hinge played a role of supporting the external axial force and preventing the settlement at the base of column.



(a) C50-RC

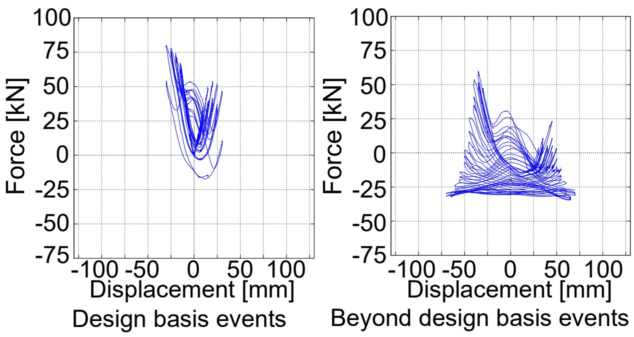


(b) C100-EM-RC

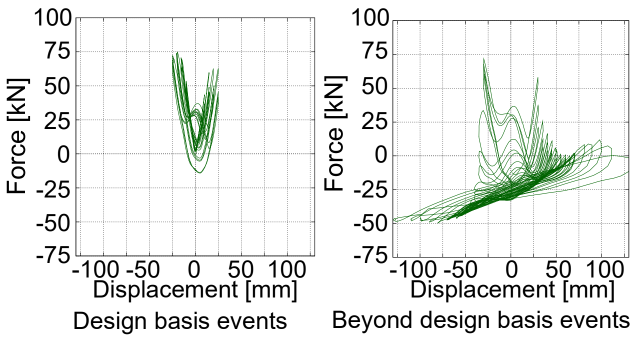


(c) C100-EM-UBRC

Fig. 8 – The relationship between vertical displacement and horizontal displacemen



(a) C100-EM-RC



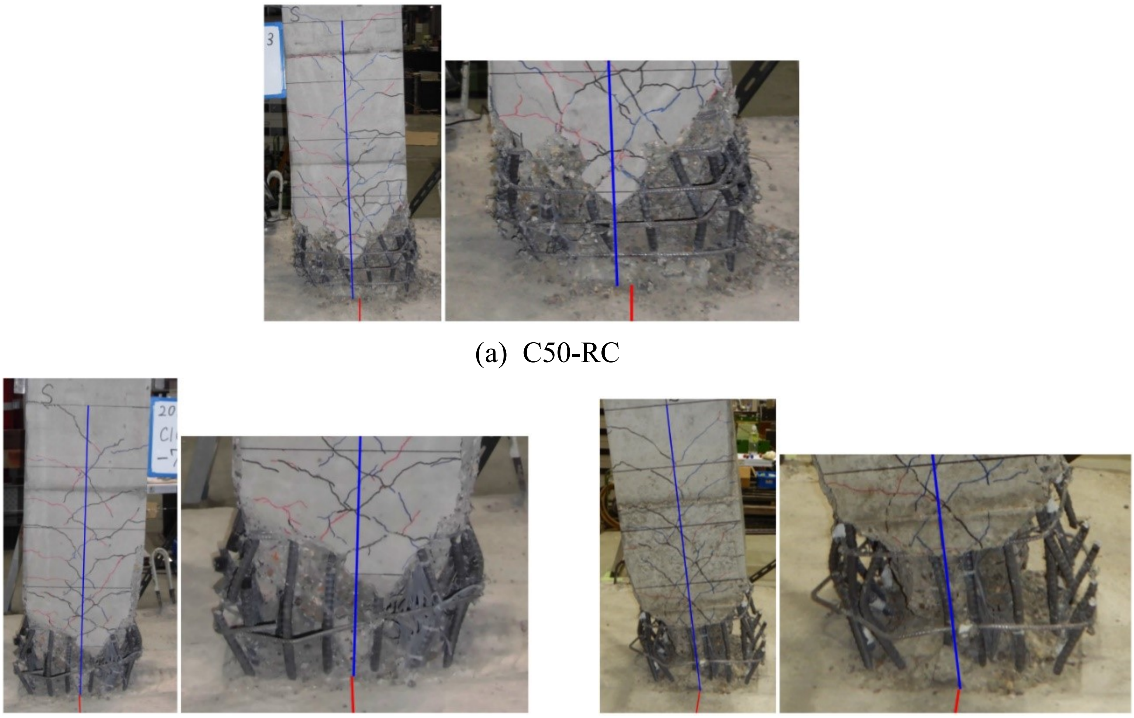
(b) C100-EM-UBRC

Fig. 9 – The relationship between axial force by a crossing rebar and horizontal displacement (Tensile force : Positive value, Compresive force : Negative value)

4.3.2 Prevention of the shear deformation at the base of column

Fig. 10 shows the all specimens at maximum displacement in beyond design basis event (after buckling of longitudinal bars occurred). It was found that shear deformation of about 40 mm occurs at the base of the column in C50-RC. This shear deformation at the base of the column was uncontrollable and unexpected destruction. On the other hand, shear deformation was prevented by embedded Mesnager hinge in C100-EM-RC and C100-EM-UBRC. Therefore, in case of C100-EM-RC and C100-EM-UBRC, the uncertainty in the fracture behavior of RC columns can be minimized by actively generating hinge behavior for beyond design basis events.

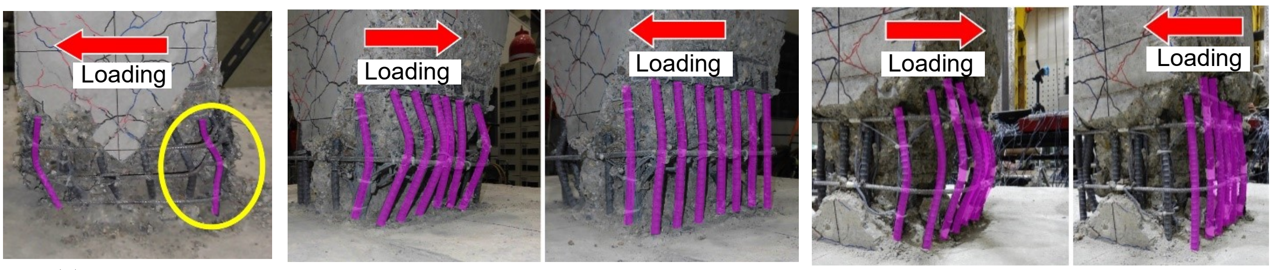
Moreover, in case of C50-RC, the buckled longitudinal bars didn't get tensed at tensile deformation due to shear deformation in the base of the column (Fig. 11(a)). Therefore, large decrease of restoring force occurred in design basis event (after buckling of longitudinal bars) indicated in 4.1. On the other hand, in case of C100-EM-RC and C100-EM-UBRC, the buckled longitudinal bars got tensed at tensile deformation due to prevention of shear deformation in the base of column (Fig. 11(b),(c)). Thus, gradual decrease of restoring force can be achieved in design basis event (after buckling of longitudinal bars) indicated in 4.1



(a) C50-RC

(b) C100-EM-RC (c) C100-EM-UBRC

Fig. 10 – The prevention of the shear deformation at the base of column



(a) C50-RC (b) C100-EM-RC (c) C100-EM-UBRC

Fig. 11 – The behaviors of buckled longitudinal bars

4.4 The behavior of unbonded high-strength bars in C100-EM-UBRC

As mentioned in 3.1, the aim at design of C100-EM-UBRC is that unbonded high-strength bars maintain elastic and restoring force of RC column maintains positive up to $20\delta y$ deformation (deformation amplitude is

100mm). In this chapter, the stain of unbonded high-strength bars and the influence of unbonded high-strength bars on restoring force of C100-EM-UBRC would be discussed.

4.4.1 The strain of unbonded high-strength bars

Fig. 12 shows the strain distribution of unbonded high-strength bars. If the high-strength bars bond to the concrete perfectly, the strain distribution becomes triangle. However, the strain distribution of the unbonded high-strength bars became constant even in design basis event (after buckling of longitudinal bars). Moreover, the unbonded high-strength bars remained in elastic up to 20δy deformation (deformation amplitude is 100mm). From the results, it was found that the unbonded bars treated by the tube can work well even in the large deformation. It was found that the unbonded high-strength bars behaved as expected at the design.

4.4.2 The influence of unbonded high-strength bars on restoring force of C100-EM-UBRC

Fig. 13 shows the restoring force of unbonded high-strength bars acting on C100-EM-UBRC. Fig. 13 illustrates that the restoring force of unbonded high-strength bars was the same level as P-Δ effect of the column. Therefore, unbonded high-strength bars installed into C100-EM-UBRC generated the stable positive restoring force in beyond design basis events and canceled *P-Δ* effect of the column.

Moreover, when the restoring force of unbonded high-strength bars was removed from that of C100-EM-UBRC**,** the negative stiffness and the negative restoring force of the column were confirmed as indicated in Fig. 14. Therefore, it was found that the behavior of the column in beyond design basis events can maintain stable by the positive restoring force of unbonded high-strength bars.

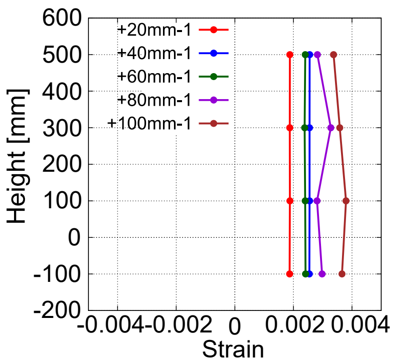


Fig. 12 – The strain distribution of unbonded high-strength bars

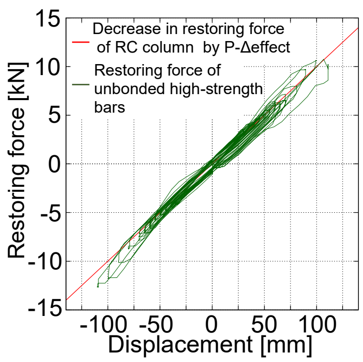


Fig. 13 – The restoring force of unbonded high-strength bars acting on C100-EM-UBRC

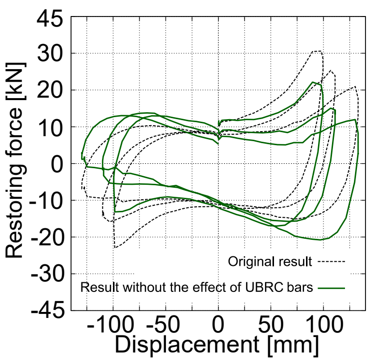


Fig. 14 – The restoring force of C100-EM-UBRC without the effect of unbonded high-strength bars

5. Conclusion

In this study, "Embedded Mesnager hinge RC column" and "Embedded Mesnager hinge UBRC column" are newly proposed as RC columns whose behavior in beyond design basis events can be predicted, the cyclic loading tests were carried out in order to obtain the fundamental performance. From this study, the following results are obtained:

- In case of conventional RC column, large decrease of restoring force was observed in beyond design basis events. On the other hand, in case of embedded Mesnager hinge RC column and embedded Mesnager hinge UBRC column, gradual decrease of restoring force can be achieved in beyond design basis events.

- In beyond design basis events, large settlement of the column was observed in case of conventional RC column, while settlement of the column was prevented in case of embedded Mesnager hinge RC column and embedded Mesnager hinge UBRC column. Moreover, it was found that the embedded Mesnager hinge supported the axial force equivalent to 50% of the external axial force.
- In case of embedded Mesnager hinge RC column and embedded Mesnager hinge UBRC column, the buckling portion of longitudinal bars can be controlled by using hoop reinforcement with 90-degree hook. Moreover, the spiral reinforcements prevented the damage of the base of the column from propagating to upper of the column in case of embedded Mesnager hinge RC column and embedded Mesnager hinge UBRC column.
- Shear deformation at the base of the column was prevented by embedded Mesnager hinge in embedded Mesnager hinge RC column and embedded Mesnager hinge UBRC column, while the large shear deformation occurs at the base of the column in conventional RC column. Therefore, in embedded Mesnager hinge RC column and embedded Mesnager hinge UBRC column, the uncertainty in the fracture behavior of RC columns can be minimized by actively generating hinge behavior for beyond design basis events.
- Unbonded high-strength bars installed into embedded Mesnager hinge UBRC column generated the stable positive restoring force in beyond design basis events and canceled $P\text{-}\Delta$ effect of the column. Therefore, the behavior of the column in beyond design basis events can maintain stable.

6. Acknowledgements

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