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INFLUENCE OF COVER CONCRETE IN MESNAGER HINGE ON ITS MECHANICAL PROPERTY

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Abstract

Mesnager hinge is a concrete hinge composed of crossing rebars and cover concrete. Japanese seismic code assumes that resist moment of Mesnager hinge is small and crossing rebars are subjected to compression force, because the influence of cover concrete in Mesnager hinge is not considered. However, the influence of cover concrete may not be negligible because Mesnager hinges commonly used in Japan have thick cover concrete compared with conventional Mesnager hinges. Moreover, cracks in Mesnager hinge are known to be generated on the hinge throat and propagate above the hinge throat (hereinafter, the crack is called "the vertical crack"). Japanese seismic code assumes that transmission force due to bond between cover concrete and crossing rebars causes the vertical cracks. However, this mechanism of the vertical crack generation may not be applicable to Mesnager hinge with thick cover concrete. Thus, this study tried to find out how cover concrete in Mesnager hinge affects its properties and crack generation according to the cyclic loading test results for Mesnager hinges with thick cover concrete carried out by previous studies. From the result, the resist moment of Mesnager hinge with cover concrete was large while that of Mesnarge hinge without cover concrete was small, and crossing rebars were subject to tensile deformation in Mesnager hinge with cover concrete. These observations contradict the assumption in Japanese seismic code. Therefore, it was found that the influence of cover concrete should not be negligible when thinking about the resist moment and the deformation characteristics of the crossing rebars in Mesnager hinges commonly used in Japan. Moreover, the vertical cracks were observed not only in Mesnager hinge with deformed rebars, but also in one with plain rebar. If the vertical cracks were caused by transmission force due to bond between concrete and crossing rebars, the vertical cracks were supposed to generate in only Mesnager hinge with deformed rebars. Thus, the assumption of the vertical crack generation in Japanese seismic code is not correct. In response to these results, the crack generation in the experiments was numerically validated by using extended finite element method. From the results of the numerical analysis, it was found that the vertical cracks generate due to not the influence of bond between cover concrete and crossing rebars, but the increase in compression force acting on cover concrete.

Keywords: Mesnager hinge, Seismic code, Cyclic loading test, Crack propagation, Extended finite element method

1. Introduction

Mesnager hinge is a concrete hinge composed of crossing rebars and cover concrete. It transmits shear force and axial force without bending moment [1]. In Mesnager hinge, cover concrete is recognized to play a role of preventing crossing rebars from buckling and corroding. Parson and Stang [2] and Moreell [3], however, confirmed that cover concrete increased resist moment of Mesnager hinge.

On the other hand, Japanese seismic code ignores the influence of cover concrete of Mesnager hinge and describes that rotational stiffness and resist moment of Mesnager hinge are small [4] although Mesnager hinges widely used in Japan have thick cover concrete. Thus, this study investigated the influence of cover concrete in Mesnager hinge on its mechanical properties referring to previous experiments for Mesnager hinges with thick cover concrete [5, 6].

2. Japanese seismic code for Mesnager hinge [4]

2.1 Rotate stiffness of Mesnager hinge

Japanese seismic code describes that rotational stiffness and resist moment of Mesnager hinge are small when the rotation angle of Mesnager hinge is smaller than 0.05 rad.

2.2 Stress of crossing rebar

Stress of crossing rebar is checked by Eq. (1) and Eq. (2) to determine the mechanical properties of crossing rebars.

$$\sigma_{sc} = \frac{N}{nA_s \cos\theta} + \frac{S}{nA_s \sin\theta} < \sigma_{yd} \tag{1}$$

$$\sigma_{yd} = \xi_1 \Phi_y \sigma_{yc} \tag{2}$$

Where σ_{sc} is the compressive stress of a crossing rebar, N is the axial force acting on Mesnager hinge, S is the shear force acting on Mesnager hinge, n is the number of crossing rebars, A_s is a sectional area of a crossing rebar, θ is the crossing rebar angle from axial direction, σ_{yd} is the limit value of compressive stress of crossing rebar, ξ_1 and Φ_y are safety factor, and σ_{yc} is the yield stress of a crossing rebar. Eq. (1) ignores resistance of cover concrete and assumes that crossing rebars are subjected to compressive stress.

2.3 Mechanism of crack generation on Mesnager hinge

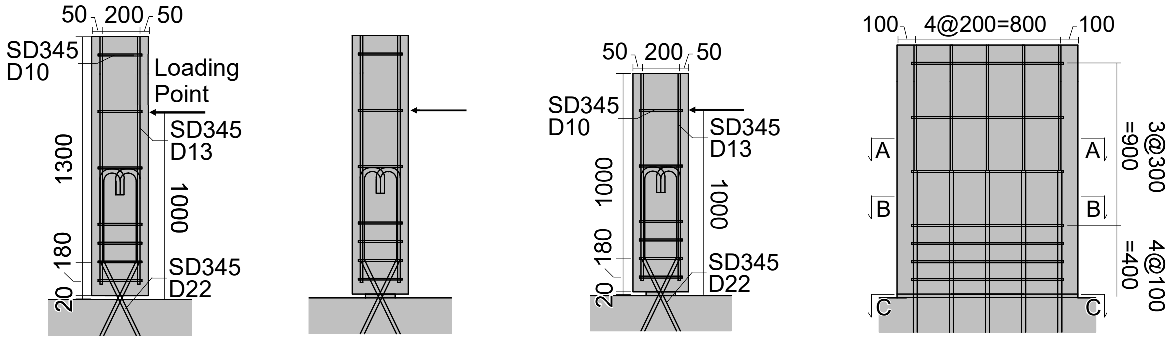
In Mesnager hinge, cracks are known to be generated on the hinge throat and propagate above the hinge throat (hereinafter, the crack is called “the vertical crack”). Japanese seismic code assumes that transmission force due to bond between cover concrete and crossing rebars causes the vertical cracks and the vertical cracks generate on cover concrete at the crossing point of rebars.

3. Cyclic loading test

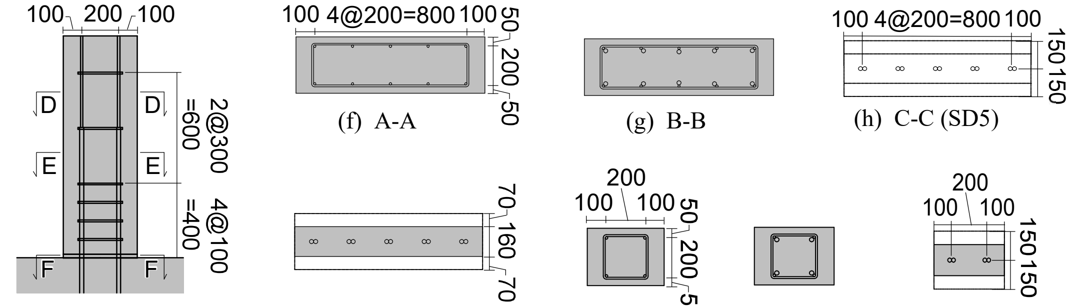
3.1 Test specimens

In this study, influence of cover concrete in Mesnager hinge on its mechanical properties was evaluated referring to previous experiments for Mesnager hinges with thick cover concrete [5,6]. Test specimens investigated in this study were designed with reffenrence to Mesnager hinges practically used in Japan. The diameter of the crossing rebars is 22.2 mm and the thickness of cover concrete is 160 mm for this test specimens. This test specimens have thick cover concrete because the diameter of the crossing rebars is 15.9 mm and the thickness of cover concrete is 50.8mm for the test specimens based on Parson’s and Stang’s [2] and Moreell’s [3] studies.

Fig.1 shows the dimensions of the column and the details of rebar arrangement in this study. SD5 compose Mesnager hinges with five pairs of crossing rebars without cover concrete. SD5-Co and SR5-Co composes Mesnager hinges with five pairs of crossing rebars and cover concrete, and SD2-Co composes one with two pairs of crossing rebars and cover concrete. In the case of SD5, SD5-Co, and SD2-Co, deformed rebars are used as crossing rebars. On the other hand, plain rebars are used as crossing rebars in the situation of SR5-Co. The concrete compressive strengths from testing standard cylinders were measured as 30.0MPa for SD5-Co and SR5-Co, and 30.1MPa for SD2-Co, respectively.



(a) SD5 (Side view) (b) SD5-Co, SR5-Co (Side view) (c) SD2-Co (Side view) (d) SD5, SD5-Co, SR5-Co (Front view)



(e) SD2-Co (Front view) (i) C-C (SD5-Co, SR5-Co) (j) D-D (k) E-E (l) F-F

Fig.1 – Geometric dimensions and arrangement of experimental specimens

3.2 Loading pattern

The cyclic loadings were applied by displacement control. All the specimens were tested under constant axial loads and reversed cyclic lateral load. Fig.2 shows the applied patterns of reversed cyclic lateral load. The constant axial stress was 1.2MPa. The horizontal displacement was applied at quasi-static rate.

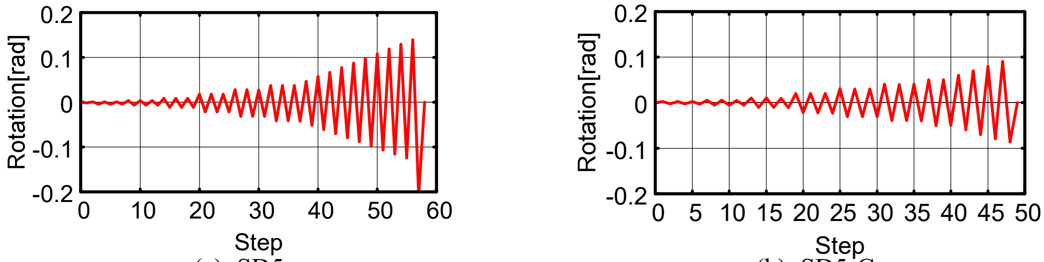
3.3 Measured data

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 crossing point of reinforcing bars.

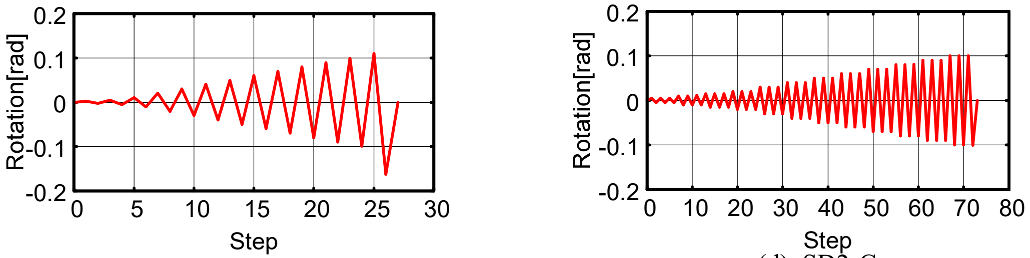
4. Test result

4.1 Relationship between rotation angle and resist moment

Fig.3 shows the resist moment – rotation angle relationship of Mesnager hinges. It should be noted that *P-Δ*



(a) SD5
(b) SD5-Co



(c) SR5-Co
(d) SD2-Co

Fig.2 – Loading pattern

effect is removed in Fig.3. The resist moment of Mesnager hinge was small in SD5, which doesn't have cover concrete in its Mesnager hinge. The maxuimum resist moment of Mesnager hinge in SD5 was 7.37 kNm. On the other hand, resist moment of Mesnager hinge was large in SD5-Co and SR5-Co both of which have cover concrete in its Mesnager hinge. Maximum resist moment within 0.05 rad rotation was 99.3kNm in SD5-Co and 92.5kNm in SR5-Co, both of which were 13 times larger than that of SD5. It is therefore considered that the description in Japanese seismic code indicated in 2.1 is incorrect for Mesnager hinges with thick cover concrete.

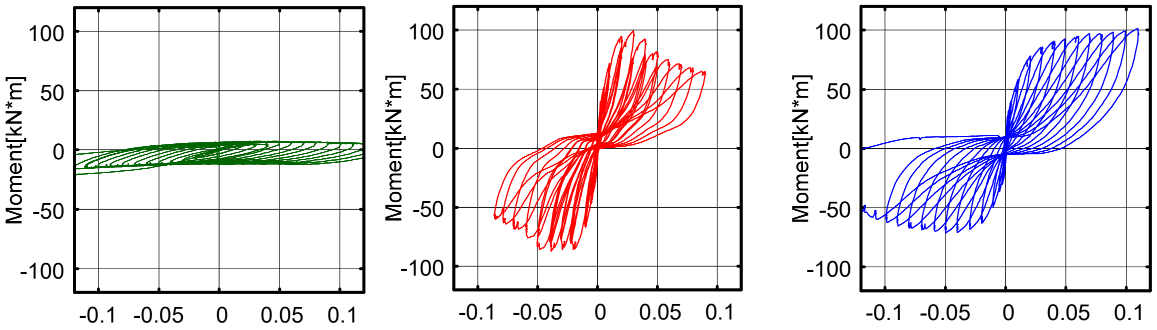
Moreover, the rotational stiffness was different between SD5-Co, in which deformed rebars are used as crossing rebars, and SR5-Co, in which plain rebars are used as crossing rebars. Thus, it is considered that the bond between crossing rebars and cover concrete affects the rotational stiffness of Mesnager hinge.

As indicate by SD5-Co and SD2-Co results shown in Fig.3 (f), maximum resist moment per each Mesnager hinge (a pair of crossing rebars with 200mm thick cover concrete) in SD5-Co and SD2-Co were almost same (SD5-Co: 19.9 kNm, SD2-Co: 18.2 kNm). However, the rotational stiffness was different between SD5-Co and SD2-Co. This mechanism would be examined in the next chapter.

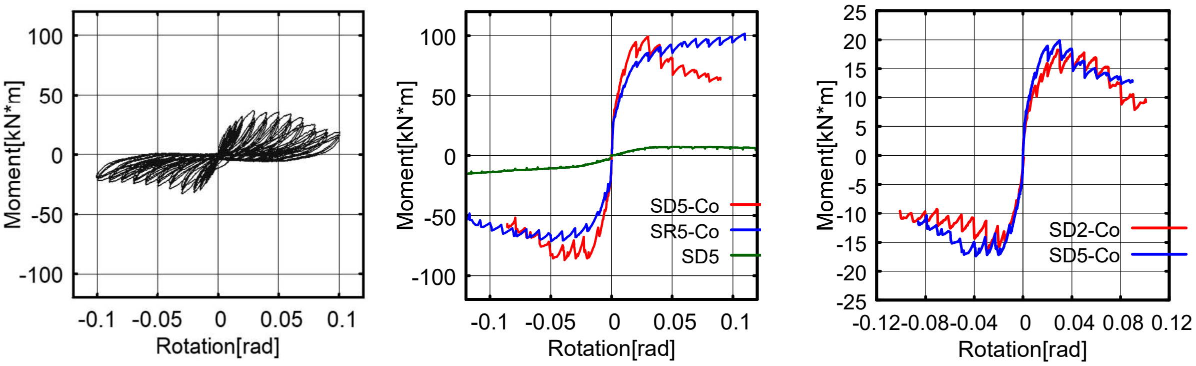
4.2 Strain of crossing rebars

Fig.4 shows the relationship between the rotation angle of the Mesnager hinge and the strain of crossing rebar at its crossing point. As shown in Fig.4, crossing rebar was bending and the axial strain of crossing rebar was negative (compressive) in SD5, which doesn't have cover concrete in its Mesnager hinge. On the other hand, crossing rebars were deformed in tensile mode in SD5-Co, SR5-Co, and SD2-Co, which have cover concrete in its Mesnager hinge, while Japanese seismic code assumes that compression force acts on crossing rebars. Considering the cross-sectional equilibrium of Mesnager hinge (Fig.5), this was because the neutral axis of cross-section was considered to move toward the compressive side due to the existence of cover concrete. Therefore, the observation contradicts the assumption in Japanese seismic code indicated in 2.2. Moreover, it was considered that combination of compressive force of cover concrete and tensile force of crossing rebars enhanced the resist moment of Mesnager hinge as indicated in 4.1.

The strain of crossing rebars in SR5-Co was smaller than that in SD5-Co and SD2-Co because deformation of crossing rebar was reduced in SR5-Co due to deterioration of the bond between cover concrete and plain rebar. This was why the rotational stiffness was different between SD5-Co and SR5-Co. Additionally, crossing rebar strain were difference between SD5-Co and SD2-Co even though diameter of crossing rebar, thickness of cover concrete, and axial stress applied on the top of the columns were same between SD5-



(a) SD5 (b) SD5-Co (c) SR5-Co



(d) SD2-Co (e) Envelope (SD5, SD5-Co, SR5-Co) (f) Per each Mesnager hinge (a pair of crossing rebars with 200mm thick cover concrete in SD5-Co and SD2-Co)

Fig.3 – Resist moment – rotation angle relationship of Mesnager hinges

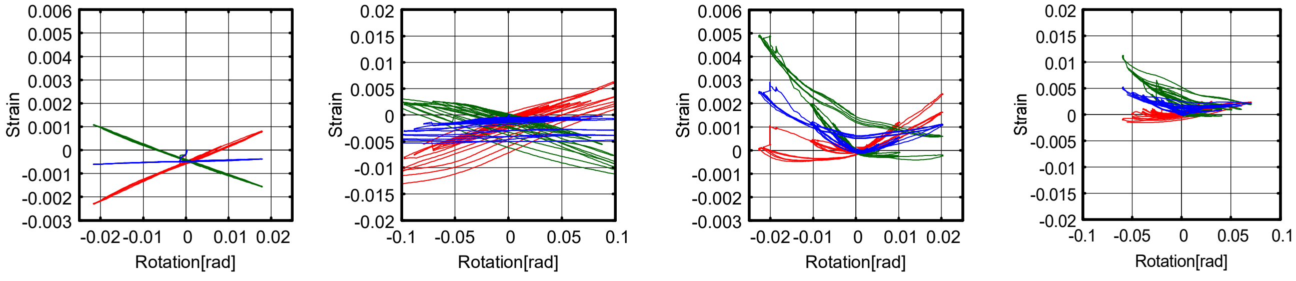
Co and SD2-Co. It was considered that the difference of the strain was attributed to bond characteristics between crossing rebars and cover concrete. The difference of strain of crossing rebars was considered to have effect on the rotational stiffness of SD5-Co and SD2-Co indicated in 4.1.

4.3 Crack on Mesnager hinge

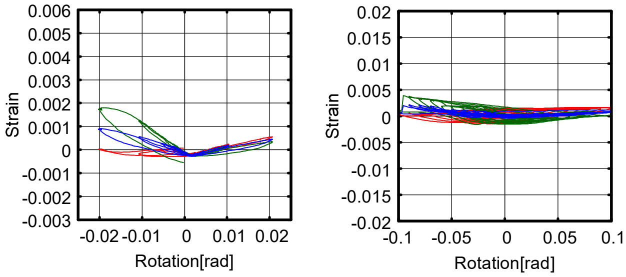
Fig.6 illustrates vertical cracks which were generated in the hinge throat and propagated above the hinge throat. The vertical cracks were observed not only in Mesnager hinge with deformed rebars, but also in one with plain rebar. Additionally, the vertical cracks did not propagate along crossing rebars. If the vertical cracks were caused by transmission force due to bond between concrete and crossing rebars, the vertical cracks were supposed to propagate along the crossing rebars. Thus, the assumption of the vertical crack generation in Japanese seismic code indicated in 2.1 is not correct.

The experimental results indicated in 4.2 revealed that crossing rebars were deformed in tensile mode. Considering the cross-sectional equilibrium of Mesnager hinge (Fig.5), compression force acting on the cover concrete of Mesnager hinge became lager when crossing rebars were subjected to tensile force. Fig.7 shows the relationship between angle of rotation and compression force acting on cover concrete of Mesnager hinge. The compression force was calculated from sum of external axial load and tensile force of crossing rebar. As shown in Fig.7, vertical cracks tended to generate at small angle of rotation when concrete in the hinge throat were subjected to large compression force per unit cross-sectional depth.

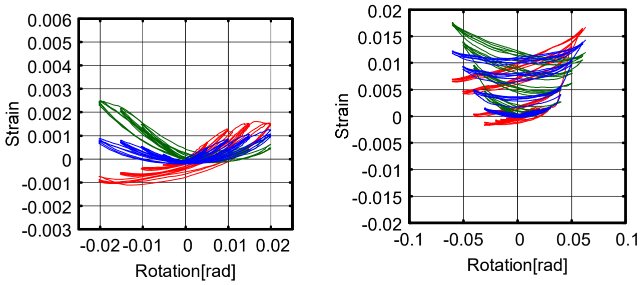
Thus, we assumed that compression force acting on cover concrete of Mesnager hinge causes the vertical cracks, and the mechanism of the cracks numerically would be validated in the next chapter.



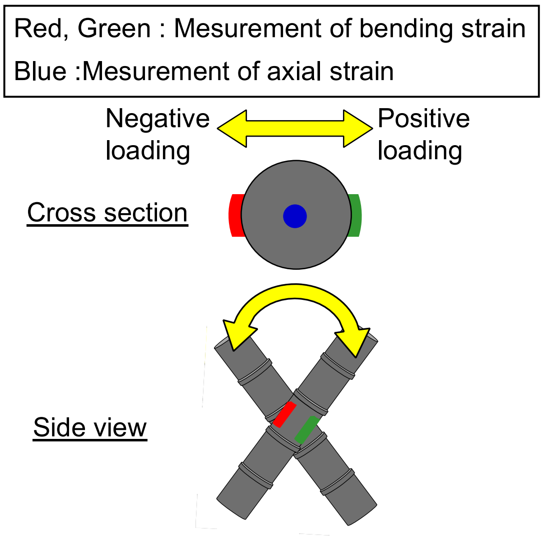
(a) SD5 (up to 0.02rad) (b) SD5 (c) SD5-Co (up to 0.02rad) (d) SD5-Co



(e) SR5-Co(up to 0.02rad) (f) SR5-Co



(g) SD2-Co (up to 0.02rad) (h) SD2-Co



(k) Mesurement of position

Fig.4 – The relationship between the rotation angle of the mesnager hinge and strain of crossing reinforcing bars at the crossing point

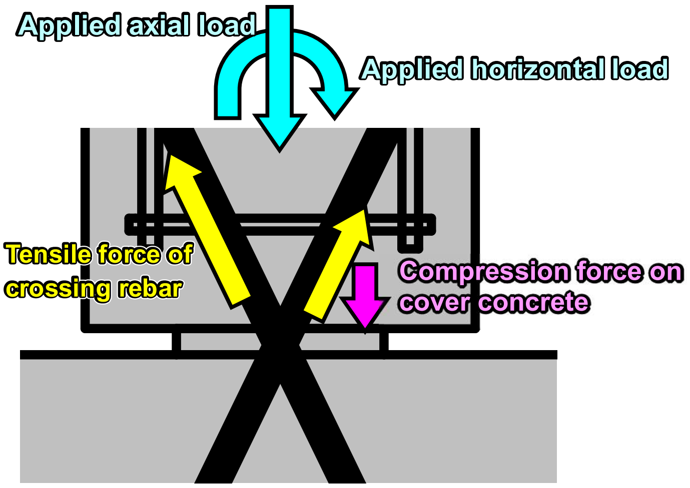
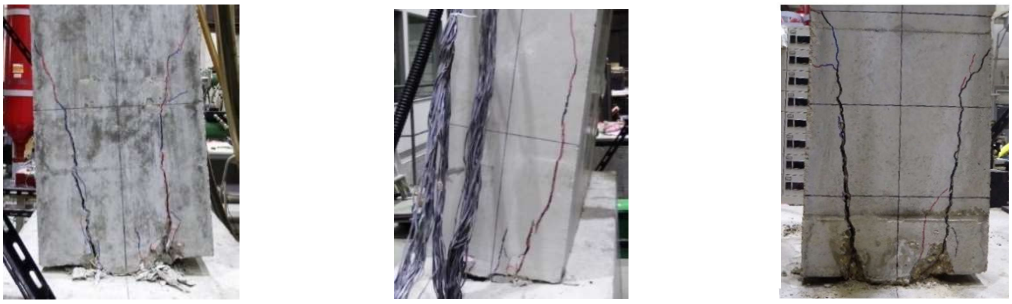


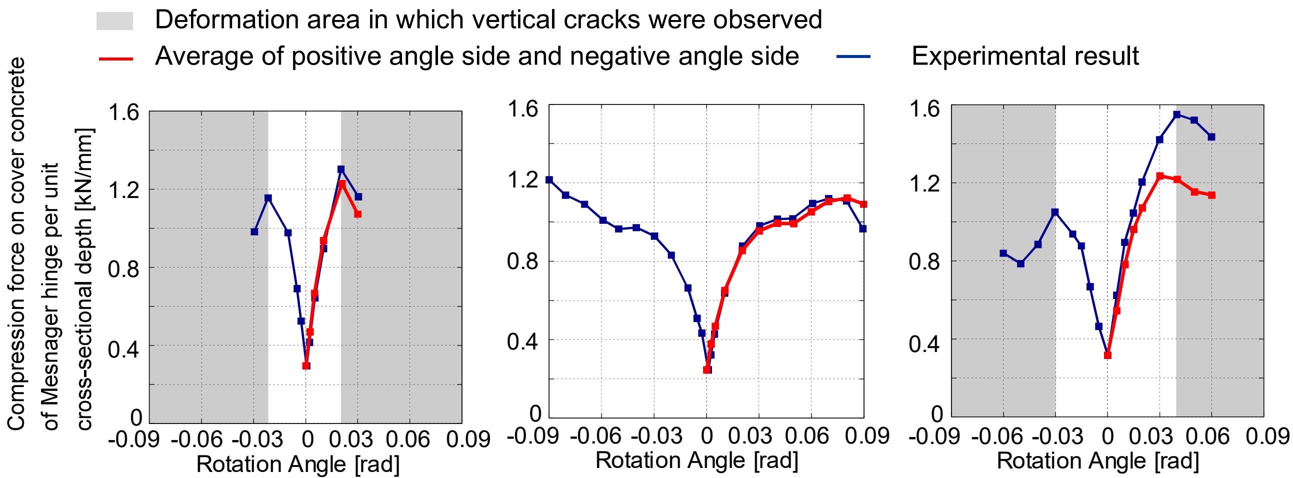
Fig.5 – Cross-sectional equilibrium of Mesnager hinge

(a) SD5-Co (Rotaion angle : 0.02rad) (b) SR5-Co (0.11rad) (c) SD2-Co (0.04rad)



(d) SD5-Co (0.09rad) (e) SR5-Co (0.18rad) (f) SD2-Co (0.10rad)

Fig.6 – Vertical cracks in experimental specimens



(a) SD5-Co (b) SR5-Co (c) SD2-Co

Fig.7 – The relationship between rotation angle of Mesnager hinge and compression force per unit cross-sectional depth acting on cover concrete of Mesnager hinge

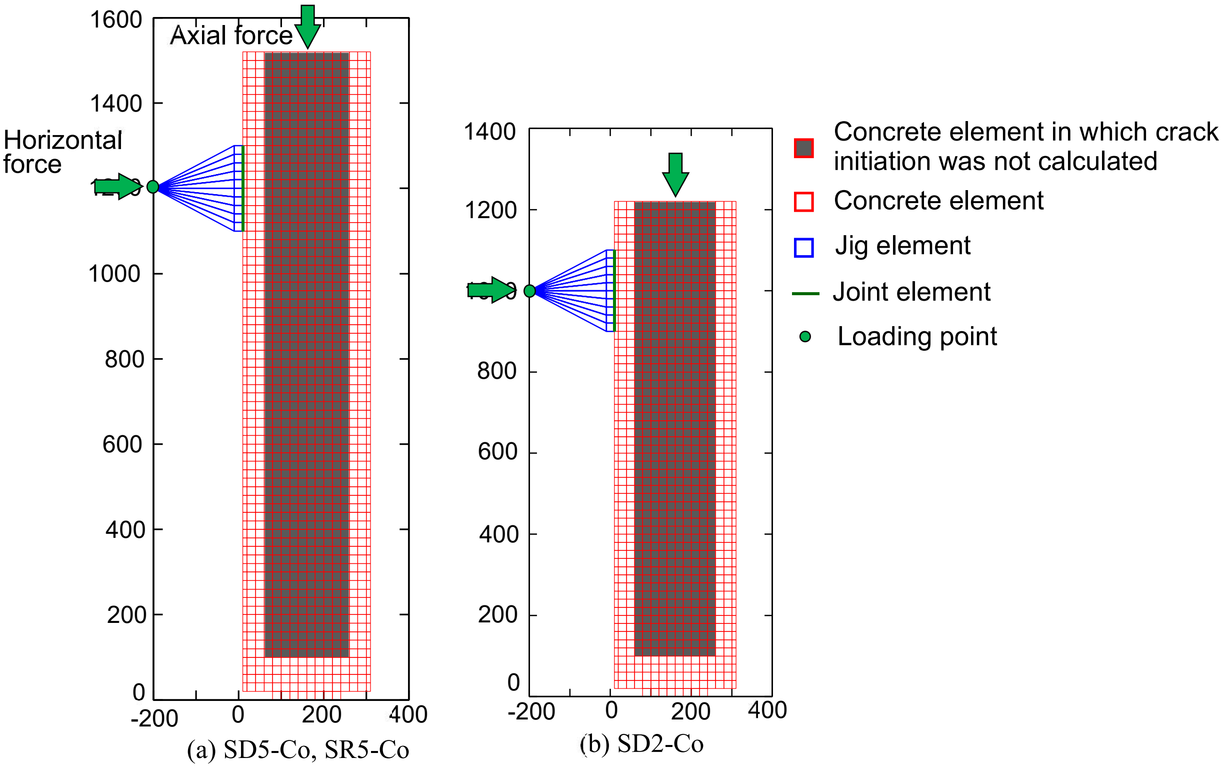
5. Numerical analysis for crack propagation on Mesnager hinge

5.1 Method

The experiments are numerically simulated by using extended finite element method (X-FEM [7, 8]). In this numerical analysis, shifted Heaviside function is used as an enrich function in X-FEM, and mass matrix is diagonalized in order to use the dynamic explicit method. The cohesive stress acting on crack surface [9] is included. Middle state elements [10] are utilized to represent the crack propagation.

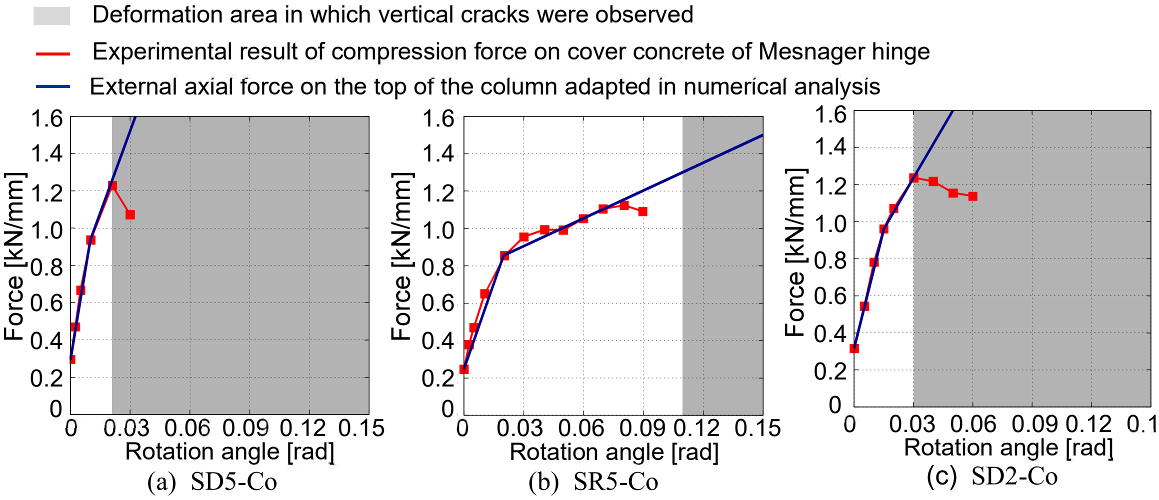
5.2 Numerical model

Fig.8 illustrates the geometry and mesh layout of the models. Linear solid elements with four nodes are used. The bottom boundary of the column is fully constrained. Young's modulus, Poison ratio, density, and crack width when cohesive stress dissipates are given as $E = 28000\text{N/mm}^2$, $v = 0.2$, and 2.5g/cm^3, $w_c = 0.03\text{mm}$. Two different uniaxial tensile strength are adopted: $f_{ct} = 2.5\ \text{N/mm}^2$ and $3.0\ \text{N/mm}^2$. The analysis in this section focuses on the relationship between compression force acting on cover concrete of Mesnager hinge and vertical cracks observed in the experiment. Therefore, crossing rebars are not included in the model. Instead, increasing of compression force is expressed by changing the external axial force applying on the top of column. The experimental result, shown in Fig.9, is applied for the time evolution.



(a) SD5-Co, SR5-Co (b) SD2-Co

Fig. 8 – The geometry and applied meshes of analysis models



(a) SD5-Co (b) SR5-Co (c) SD2-Co

Fig.9 – External axial force on the top of the column adapted in numerical analysis

Crack initiation is not allowed in coloring elements in Fig.8 because cracks are assumed not to generate on concrete surrounded by the longitudinal bar and hoop reinforcement that is evident in the experimental specimens. X-FEM is not allowed to produce cracks on the element edges though the horizontal cracks on cover concrete of Mesnager hinge were observed in the experiment (Fig.10). Therefore, cracks in the elements located on the bottom boundary are restricted in the middle of the elements, as shown in Fig.11.

Fig.10 – Horizontal cracks on cover concrete of Mesnager hinge

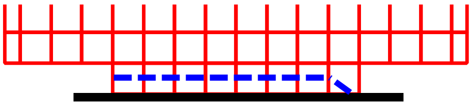
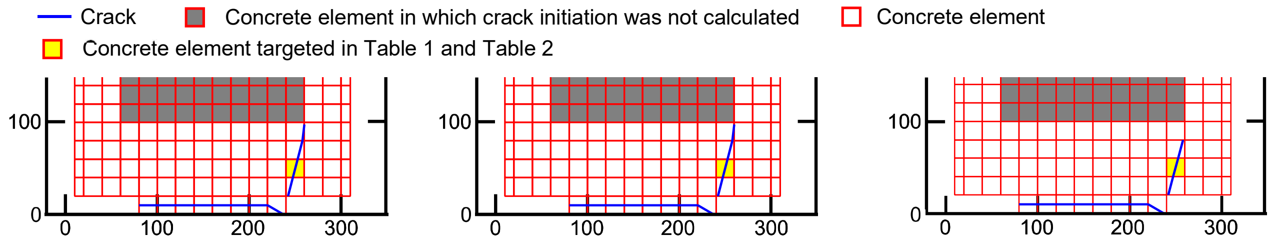


Fig.11 – Direction of crack propagation in the elements located on the bottom boundary of the column

5.3 Result

Simulated cracks are shown in Fig.12. Vertical cracks on cover concrete of Mesnager hinge are simulated by the numerical analysis. The results are thought to be reasonable because the rotation angles where the first vertical crack observed in experiments are between the numerical results with f_{ct} = 2.5 N/mm^2 and 3.0 N/mm^2 (Table 1). Moreover, Table 2 indicated that the vertical cracks observed in numerical analysis are splitting due to compression acting on cover concrete of Mesnager hinge.

From the results, the initiation of vertical cracks on cover concrete of Mesnager hinge can be reproduced by changing external axial force applying on the top of the column without modelling cross reinforcing bars. This suggests that the vertical cracks generate due to not the influence of bond between cover concrete and crossing rebars, but the increase in compression force acting on cover concrete. The assumption of vertical crack generation is not correct in Japanese seismic code. However, the direction of compression force acting on concrete in the hinge was not changed numerically regardless the rotation angle of the Mesnager hinge, and simulated crack propagations were almost the same in all models though different crack propagations were



(a) SD5-Co (b) SR5-Co (c) SD2-Co

Fig.12 – Crack pattern obtained in numerical analysis

Table 1 – Angle at which the first vertical crack was observed

	Tensile strength [N/mm^2]	The rotation angle at which the first vertical crack was observed [rad]	
		Numerical result	Experimental result
SD5-Co	2.5	0.0219	0.02
	3.0	0.0313	
SR5-Co	2.5	0.0923	0.11
	3.0	0.145	
SD2-Co	2.5	0.0322	0.04
	3.0	0.0469	

Table 2 – Principal stress and direction of stress (Tensile strength is 2.5N/mm^2)

	Minimum principal stress (Direction of stress)	Maximum principal stress (Direction of stress)
SD5-Co	-21.2 [N/mm^2] (0.258, 0.966)	2.50 [N/mm^2] (0.966, -0.258)
SR5-Co	-20.4 [N/mm^2] (0.259, 0.966)	2.50 [N/mm^2] (0.966, -0.259)
SD2-Co	-20.9 [N/mm^2] (0.258, 0.966)	2.50 [N/mm^2] (0.966, -0.258)

observed among experimental specimens. This was because of limitation of the small deformation theory. The applied directions of external axial force differ from the actual experimental conditions, which include the column tilt, under the large deformation.

6. Conclusions

This study tried to find out how cover concrete in Mesnager hinge affects its properties according to the cyclic loading test results for Mesnager hinges with thick cover concrete carried out by our previous researches. As a result, the resist moment of Mesnager hinge which has cover concrete was large, while that of Mesnarge hinge which does not have cover concrete was small. Additionally, crossing rebars were subject to tensile deformation in Mesnager hinge with cover concrete. These observations contradict the assumption in Japanese seismic code. Moreover, it was found that the bond characteristics between crossing rebars and cover concrete affects the rotational stiffness of Mesnager hinge. Besides, the vertical cracks were observed to generate on the hinge throat and propagate above the hinge throat in Mesnager hinge with cover concrete. The vertical crack was considered to be generated by compression load on cover concrete.

7. Acknowledgements

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