Deployable Reinforcement Cage System for Cast-in-place Concrete Piles

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ABSTRACT

In recent years, as a consequence of urbanization, there has been an increasing number of construction projects related to renewal or extension of railway structures in Japan. Nevertheless, in those projects, since the construction space is limited due to the existing structures, it is difficult to construct the piles in narrow space or with small overhead clearance. To address this problem, the authors have developed a deployable reinforcement pile cage system which is used for bored cast-in-place concrete piles in the severe conditions as mentioned above. PC strands are applied as longitudinal reinforcement of the cage. To form the cylindrical cage, special rotation devices are arranged at the intersections of the longitudinal reinforcement and the hoop reinforcement that are able to make the PC strands rotate 90 degrees. By twisting the cylindrical cage with those devices installed, the longitudinal strands are deformed into helical shape and the cage can be folded; or easily deployed by twisting in the opposite direction. This paper describes the structure details and the formation method of the reinforcement cage including the fundamental design of bending and torsion resistance of the cage focusing on the strength of the rotation devices.

Key words: *cast-in-place, deployable reinforcement cage, PC strand*

1. Introduction

In recent years, as a part of urban revitalization, the number of construction projects of railway structures related to quadruple-track, track elevation and renewal has been increasing. It is extremely difficult to construct the cast-in-place concrete piles in these projects since the overhead space is restricted, the construction space around the pile is not secured; furthermore, many projects can be implemented in the night time only. With the consideration of the increasing situation of the urban revitalization in Japan, the improvement of workability of the cast-in-place concrete piles in small overhead clearance and narrow space conditions has become urgent.

Up to now, for drilling method for the cast-in-place piles, Bottom Circulation Hole (BCH) method (Tajima *et al*., 2007) whose boring machine with the height reduced to 2.7m can be applied. Additionally, a method using the reduced height boring machine to construct piles in ultra-low overhead clearance had been developed (Takeda *et al*., 2017), which was able to construct pile with a diameter of up to 3.0m. It can be applied to the construction site with overhead restriction such as under platforms or under bridges.

Meanwhile, there has been no improvement in reinforcement work of steel cage for cast-in-place piles at the construction sites where the space is narrow. In the conventional construction method, several short reinforcement cages are joined by connecting the longitudinal reinforcement to form a cage that leads to various problems such as increase of cost related to joint of reinforcing bars, extension of working time and reduction of pile quality due to adhesion of slime to reinforcement. To improve the construction of reinforcement cage in a small overhead space, a method using a special machine to assemble the reinforcement cage right above the borehole, which applies PC strands as longitudinal reinforcement to eliminate the joints of longitudinal reinforcement, has been developed (Tsukishima *et al*., 2002). Although this method can be used for construction with small overhead condition, since the cage is assembled while it is immersed into the hole, the matter of construction space and time still remains.

In this regard, to improve the workability at the sites, a new method (Yamanobe *et al*., 2008) in which the reinforcement cage can be deployed into borehole has been developed. Up to present, construction applicability of this method has been experimentally conducted on piles with diameter of 1.2, 1.8 and 2.0 m. In addition, cyclic loading tests of members using PC strands as the longitudinal reinforcement were carried out to examine the stiffness and flexural capacity of the pile using this construction method.

This paper describes the details and construction method of the reinforcement cage. As for the design of the deployable cage, the characteristic of the cage was taken into account with the load acting on rotation devices.

2. Structural details of cage and assemble method

Photo 1 shows the folded state and folding condition of the reinforcement cage of the pile with a diameter of about 1.2 m. Taking advantage of flexibility of the PC strands, when the entire cage is twisted, the strands can be deformed spirally, thus, the cage is folded. When twisting in the opposite direction, the reinforcement cage can be easily deployed.

2.1. Structural details of cages

The ordinary reinforcement cage for the cast-in-place concrete piles is formed by circularly distributed longitudinal reinforcing bars, which are tied by distributed circular shape hoops. In the newly deployable method, PC strands are used as the longitudinal reinforcement, while at the intersection of the hoops and the longitudinal reinforcement, special devices are installed that make the strands able to rotate 90 degrees to form the cage.

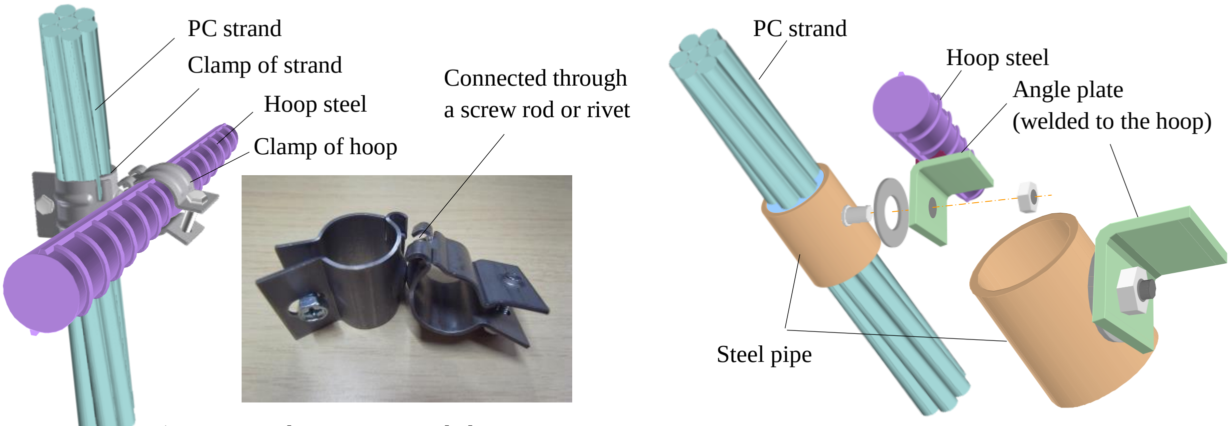
Various types of PC strands can be adopted in this construction method; however, for prototype and construction experiment, multi-stranded cable (SEEE strand, F50) made of double layers of strands with excellent flexibility, are adopted. The material properties of F50 strands are given in **Table 1**.

Table 1. Properties of strands (F50)

	7 x ϕ8.1
Diameter	24.3 mm
Cross-section area	277.1 mm^2
Tensile load	500 kN
Yielding load*	426 kN
Elongation	3.5%

*: 0.2% proof force

Photo 1. Folded state of cage (left) and folding of cage (right)



a) Rotation device using steel clamps b) Rotation device using steel pipe and angle

Fig. 1 Details of rotation device

Deformed steel bars specified in Japanese Industrial Standard, JIS G 3112, are used as the hoops. As the hoop needs to be a perfect circular shape without any connection with anything such as a lap joint, the hoops with closed butt joint are used. At the intersections of the longitudinal strands and the hoops, the devices that can change the intersection angle between two members are installed. Examples of the rotation devices are shown in **Fig. 1**. In **Fig. 1a)**, a clamp of strand and a clamp of hoop are connected through a screw rod or a rivet so that they can rotate. The clamps, which are made of two halves of cylindrical metal shapes and screws, are rotatably connected by rivets. In **Fig. 1b)**, the other type of device that consists of a steel pipe, in which the strand passes through, and an angle plate is welded to the hoop steel. The two parts are connected by a screw rod. As the gap between the strand and the pipe is filled by epoxy resin, this device can also be adopted to pre-grouted PC strands with polyethylene Sheath. Although it is necessary to consider the quality control of welding of the steel, the angle plate can be used regardless of reinforcing bar diameters. After attaching to the strand and the hoops separately, the pipe and angle plate are connected by inserting a washer and screwing a nut as shown in the figure.

By adopting those structures, the reinforcement cage can be assembled with high accuracy as shown in **Photo 2** as far as the positons of the attaching devices are accurate.

2.2. Method of installation of reinforcement cage

Fig. 2 shows a process of installing reinforcement cage. First, the cage in folded and tied state is transferred and temporarily set up right above a borehole. Then, two wires suspend the cage by hooking the head and the bottom stiffener ring, which were attached rotatably to the strands in a similar way as the hoop. In the next step, the cage is untied, the wire hooking the bottom is winded downward, and then the reinforcement cage is deployed into the borehole. At this time, since the stiffener ring of the pile head is fixed, the spiral strands turn into straight lines from the upper part, the cage is deployed into the hole while it is twisted. After the cage is totally deployed, the weight of the cage is carried by only the wires at the pile head. Finally, the deployed reinforcement cage is lowered to predetermined depth and the process of installation is completed.

Photo 3 shows the deployed reinforcement cage of a pile into a borehole with slurry with a diameter of 1.8 m and length of about 10 m. The time for deploying process of the cage from temporary receipt to completing was extremely short, just about 1 minute to deploy the cage of 10 m length. In this construction experiment, a crane is adopted to deploy the cage. However, since the actual construction is carried out in a low overhead clearance condition, three dimensional frame equipped with two winches (**Fig. 2**) will be used.

After installation of the cage, it is necessary to collect the hanging wires. Hanging equipment of the wires as shown in **Photo 4**, is attached at the bottom of the cage. By using remote control from ground surface, the wires can be removed from slurry, and collected.

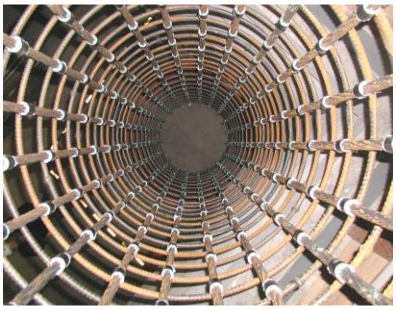


Photo 2. Accuracy of assembled cage

Photo 3. Cage deployed into borehole

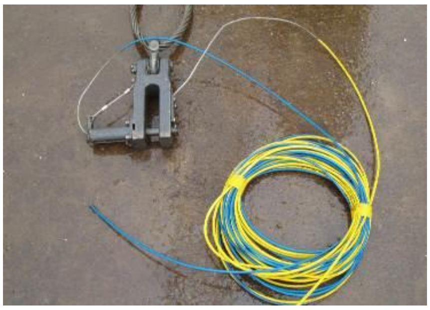


Photo 4. Hanging equipment

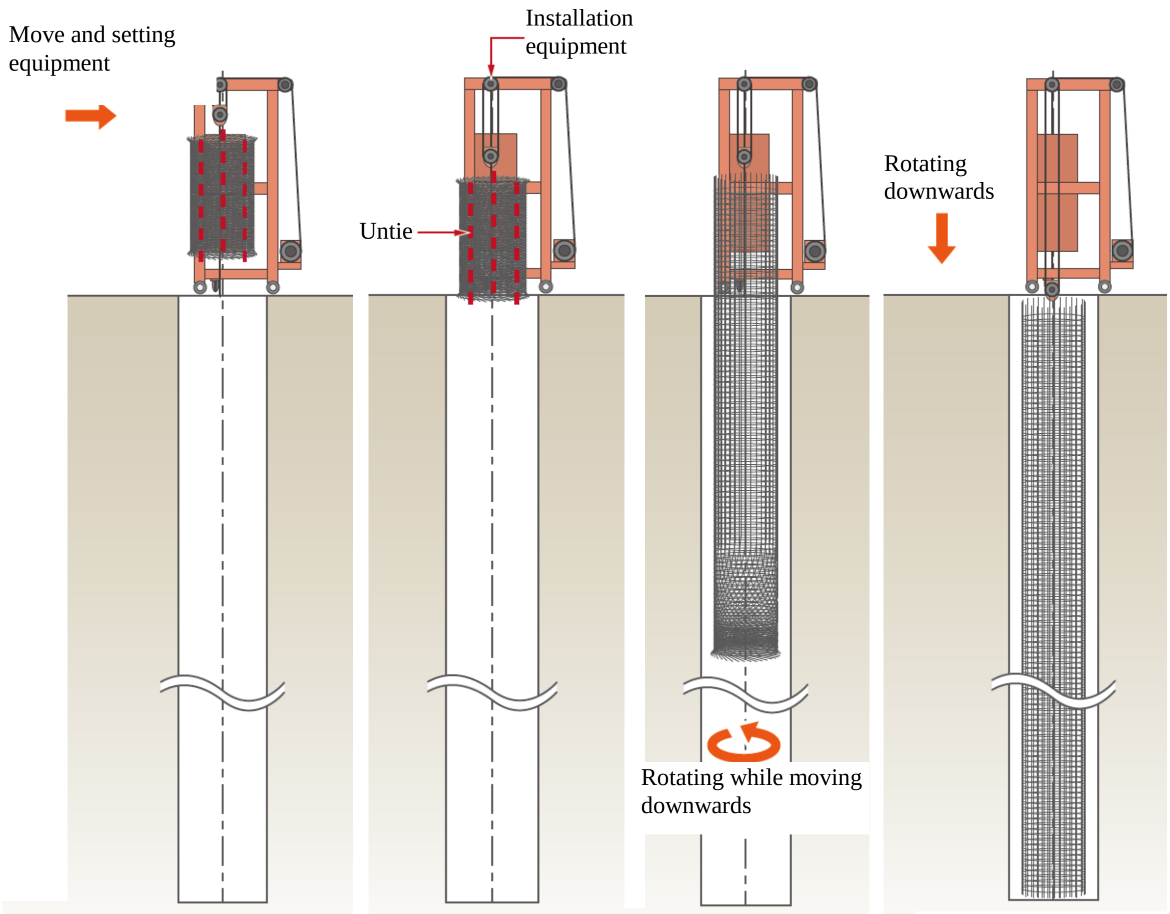


Fig. 2 Process of installation of reinforcement cage

3. Principle of folding and deployment of the cage

3.1. Equations of strands in cage folding state

When the cage is folded, each strand has a spiral shape and is under bending and torsion as shown in **Fig. 3**. Considering equations of this state, bending and torsion deformation, sectional forces acting on the strands and the load acting on the rotation device as well can be derived. The force required for folding the cage can also be calculated.

As mentioned above, when the cage is twisted, the strands deform into a spiral shape. Assuming that the gravity does not act on the cage, the deformation is uniformly on the whole length of the strand, the equations of this state can be as following:

The coordinate **r** of any point on axis of a strand is:

$$\mathbf{r} = (x, y, z) \tag{1}$$

$$x = R \cdot cos\ st$$

$$y = R \cdot sin\ st$$

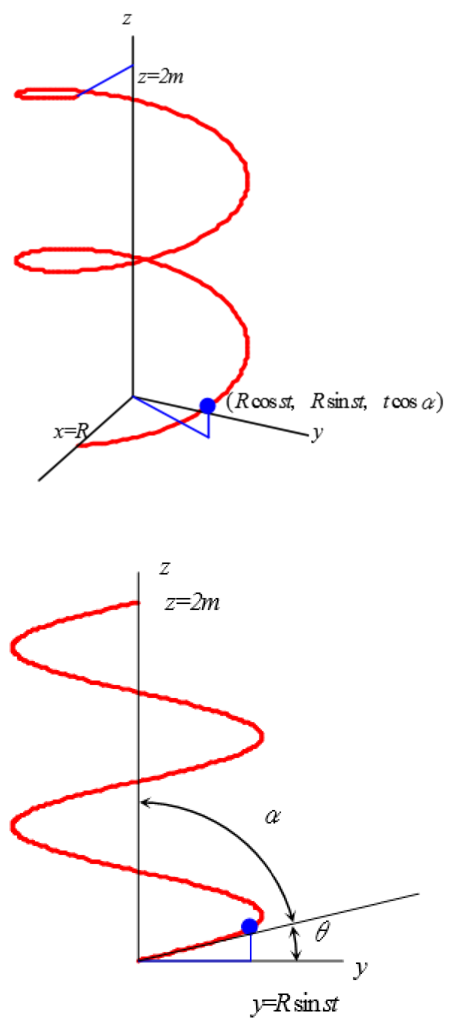


Fig. 3 Deformation of strand

$z = t \cdot \cos\alpha$

where,

R: diameter of strand position

α: angle of strand and z axis, so-called helical pitch angle

s: constant, $R \cdot s = \sin\alpha$

t: arc length

With *m* is folding pitch (a change in *z* coordinate after one round is folded) and θ = π/2 –α is angle of device (the angle between strand and the hoop), we have m = 2π*R*·tan*θ*.

Curvature of strand *κ* and the torsion rate *ρ* (torsional deformation per unit length) can be obtained from different geometry of three dimensional curve as follows:

$$\kappa = \sqrt{\left(\frac{d^2x}{dt^2}\right)^2 + \left(\frac{d^2y}{dt^2}\right)^2 + \left(\frac{d^2z}{dt^2}\right)^2} \quad (2)$$

$$= R \cdot s^2 = \frac{\sin^2\alpha}{R}$$

$$\rho = \frac{1}{\kappa^2}\begin{vmatrix} dx/dt & dy/dt & dz/dt \\ d^2x/dt^2 & d^2y/dt^2 & d^2z/dt^2 \\ d^3x/dt^3 & d^3y/dt^3 & d^3z/dt^3 \end{vmatrix}$$

$$= \frac{1}{\kappa^2}\begin{vmatrix} -R\cdot s\cdot\sin st & R\cdot s\cdot\cos st & \cos\alpha \\ -R\cdot s^2\cdot\cos st & -R\cdot s^2\cdot\sin st & 0 \\ R\cdot s^3\cdot\sin st & -R\cdot s^3\cdot\cos st & 0 \end{vmatrix}$$

$$= \frac{R^2\cdot s^5\cdot\cos\alpha\,(\sin^2 st + \cos^2 st)}{(R\cdot s^2)^2}$$

$$= s\cdot\cos\alpha = \sin\alpha\cdot\cos\alpha\,/R \quad (3)$$

Considering the curvature κ and the torsion rate as a function of the pitch angle α, it can be found that the curvature κ becomes minimum at α = 90º and the radius of curvature 1/κ fits the radius of strand placement R. The torsion rate ρ is maximum (0.5/R) when α = 45º. At the pitch angles α = 0º (the cage is fully deployed) or 90º (the cage is completely folded), there is no torsion in the strands.

On the other hand, the direction of center of curved strand, which is normal vector, can be derived from differentiating tangent vector along arc length as follows:

$$\mathrm{v} = \frac{d\mathrm{r}}{dt} = \left(\frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt}\right)$$

$$= (R\cdot s\cdot\sin st,\quad R\cdot s\cdot\cos st,\quad \cos\alpha) \quad (4)$$

$$= (-\sin\alpha\cdot\sin st, \sin\alpha\cdot\cos st,\quad \cos\alpha)$$

$$\frac{d\mathrm{v}}{dt} = \left(\frac{d^2x}{dt^2}, \frac{d^2y}{dt^2}, \frac{d^2z}{dt^2}\right) \quad (5)$$

$$= (-Rs^2\cos st,\quad -Rs^2\sin st,\quad 0)$$

with

$$\kappa = \sqrt{\left(\frac{d^2x}{dt^2}\right)^2 + \left(\frac{d^2y}{dt^2}\right)^2 + \left(\frac{d^2z}{dt^2}\right)^2} = Rs^2 \quad (6)$$

The normal vector can be written as:

$$\frac{d\mathrm{v}}{dt} = \kappa\cdot\mathrm{c} \quad (7)$$

Thus, the unit normal vector c becomes:

$$c = (-\cos st, \quad -\sin st, \quad 0) \tag{8}$$

Since the center of curved strand at any position points towards the center of the cage at the same z coordinate, when the devices on the strands were installed towards the center of the cage, no bending and torsion act on the rotation devices except those at the top and bottom ends.

3.2. Section force of strand and load acting on rotation device

Since the bending deformation and torsion deformation of the strands, represented by the curvature and torsion rate, can be obtained from the **Eqs. 2 and 3**, the bending moment and torsion moment of the strands can be calculated. Thus, the characteristics of the cage can be discussed.

For instance, at the top and the bottom of the cage, since the bending and torsion at both ends of the strands are fixed by the rotation device, the bending and torsion moment acting at the top and the bottom ends of the strands becomes the load acting on the rotation devices at the top and the bottom part. Therefore, to bear the load acting on the devices at that location, material and member of the devices need to be selected and designed.

When the cage is folded or deployed uniformly, the curvature and the torsion rate are constant regardless of location on the strands. Consequently, as the curvature is constant, shear force is not generated on the strand.

As shown in **Fig. 4**, at the end point *i* and *j* of the strand of infinitesimal length, there are bending moment *M*i, *M*j and torsion moment *T*i, *T*j. As an example, the following calculation was performed with conditions given in **Table 2**. The moment of inertia of area and polar moment of inertia of area of the strands are greatly different between the case where wires are fixed without slip and the case that the wires slip freely without fixing. In this construction method, as prestress is not introduced in the strands, the wires are not fixed, planar and polar moment of inertia are calculated by multiplying the value of one strand by the number of strands. The relationship between radius of curvature and torsion rate corresponding to rotation angle of device at the intersection are shown in **Fig. 5a) and b)**. In addition, the bending moment $M=EI\kappa$ and torsion moment $T = GJ\rho$ obtained from the cross-sectional dimensions of the strand is shown in **Fig. 5c)**. The moment acting on the device is a vector ($\sqrt{M^2+T^2}$) composed by bending moment *M* and torsion moment *T*. As can be seen from **Fig. 5c)**, the maximum bending moment of the device occurs when the cage is completely folded as θ = 0° so that the design of

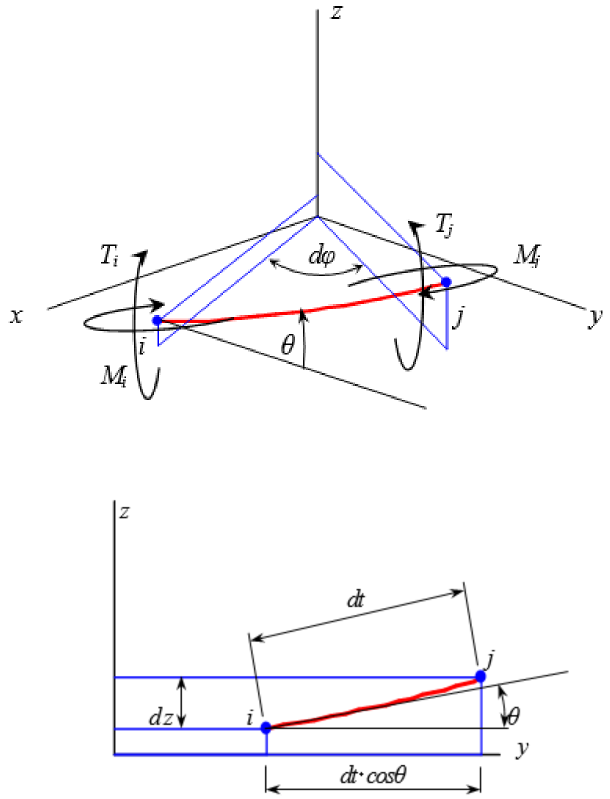
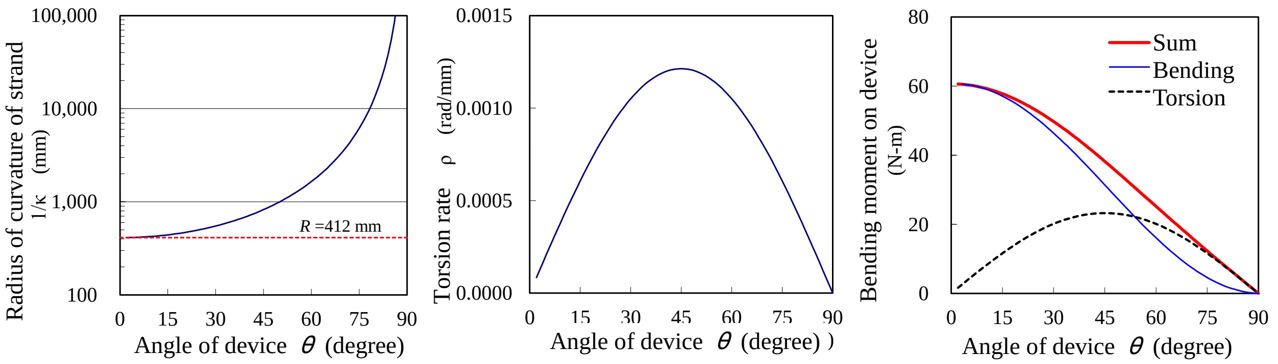


Fig. 4 Strand element of infinitesimal length in deformed state

Table 2. Specified cross section properties of cage and strand

Diameter of pile		φ1,200 mm
Diameter of hoop		φ900 mm
Radius of position of longitudinal steel (strand)		R = 412 mm
Length of cage		5,400 mm
Longitudinal steel material		20 - F50
Sectional dimensions of strand (F50)	Wire component	7×φ8.1 mm
	Cross sectional area	A= 277.1 mm^2
	Planar second moment of area	I = 125 mm^4
	Polar second moment of area	J = 249 mm^4
	Elastic modulus	E = 200 kN/mm^2
	Shear modulus	G=76.9 kN/mm^2



a) Radius of curvature of strand **b)** Torsion rate of strand **c)** Moment acting on devices at end parts

Fig. 5 Radius of curvature, torsion rate and section force of devices in folding process

the device shall be done at this condition. At that time, the radius of curvature 1/κ is the same as the radius of the longitudinal strand position. Furthermore, the maximum of torsion moment is at θ = 45°. Stress magnitude of the device due to those moments are summarized as below:

As shown in **Fig. 5c)** at the completely folded condition, the bending moment on a screw rod with diameter of 16 mm is M = 60.7 kN-mm, thus, the bending stress magnitude is 151 N/mm^2 which is smaller than allowable stress of normal steel SS400 grade. For the device shown in **Fig. 1b)**, it is necessary to verify the stress magnitude of the welding part between the pipe and the steel rod; however, it is supposed that a plate of 6 mm thick and welding length of 25 mm are sufficient.

In this way, the bending moment of rotation devices at the end of strand can be calculated by assuming the completely folded state. At the top and the bottom of the cage, the reinforcement rings are added to both outer and inner sides of the cage. As the strands are fixed to the reinforcement rings by screw rods from inside and outside, the diameter of the stud can be reduced. For the type of device shown in **Fig. 1b)**, the diameter of screw rods of rotation devices at the top and the bottom parts are chosen as the same as the general part to unify the screw rods applied.

The maximum torsion moment is T = 23.2 N-m at the intersection angle of 45° (**Fig. 5c)**). Thus, the grip force of the device in **Fig 1a)**, and the strength of the resin in the device in **Fig. 1b)** should be examined.

3.3. Load acting on device when folding and deploying at gravitational field

The equation above stands on the assumption that the whole cage is deployed or folded uniformly over its full length so that the curvature and torsion rate are constant regardless of the location of strand. It corresponds to the state of the cage laid on a floor, twisted horizontally. As shown in **Photo 1** (right), when the cage is lifted by a crane, the deformation of strand is not uniform due to effect of gravity. However, if the shape of a strand under gravity can be formulated, the bending and torsion of the strands can be obtained by the same process as mentioned above. The load acting on devices at each position can be obtained assuming that the devices are supporting a load corresponding to the difference in bending and torsion between next devices.

The change of pitch angle α along the arc length t can be determined from the folding or deploying state. **Photo 5** shows states of the cages with different sizes folded or deployed by crane. From the state of completely folded α to state of completely deployed α = 0 °, it takes about 1/4 round = 0.5πR. At the state of completely folded α= 90 °, assuming that there are two devices in the length of 0.5πR, the load that a device need to resist is about 1/3 of the aforementioned load. With the same method, the load acting on the device can be determined taking the distance of the hoops or position of the devices, whether the devices are arranged at every intersection or staggered into account.

4. Summary

The state equations of strands in the deployable reinforcement cage and the design for rotation device have been summarized in this paper. It is possible to carry out a construction plan with consideration of the head clearance restriction and so on. The finding are drawn as following:

a) ϕ1.2 m

b) ϕ1.8 m

c) ϕ2.0 m

Photo 5. Deployment of cages with various diameters in gravity field

(1) As bending and torsion occurred in the spiral strand in folding process, the relation between the intersection angle and the reduction ratio of the device are summarized.

(2) The bending moment of rotation devices to restrain bending and torsion of the strands is acting only at the top and the bottom of the cage. The bending moment during folding process has the maximum when the cage is completely folded. Thus, the design moment of rotation devices can be calculated using the radius of position of the longitudinal strands at completely folded state.

Up to now, construction experiments have been carried out with the pile diameters varied from 1.2 m to 2.0 m, and the strand F50 were applied. The yield strength of SEEE cable F50 (tensile load 500 kN, 0.2% proof load 426 kN) is similar to that of deformed bar D41, SD345 or D38, SD390. When the pile diameter becomes larger than that of actually experimented one, it is supposed that a greater amount of strand such as F70 (0.2% proof load 608 kN) or F100 (proof load 823 kN) should be applied. Even in those cases, the cage can be designed in accordance with the fundamental design method presented in this paper.

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