SIMULATION OF FAILURE MECHANISM OF VULNERABLE RC COLUMN BEFORE AND AFTER SEISMIC STRENGTHENING

by

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ABSTRACT

RC members that have terminated main reinforcing bars with inadequate anchorage length become the week points of the RC structures because significant shear failure is likely to develop at the middle part of them. So, the development of the seismic inspection method and the seismic strengthening method of the RC members with termination of main reinforcing bars is very important. In this paper, Non-linear numerical simulation of the failure mechanism of the RC bridge piers whose main reinforcing bars are terminated is carried out and in addition to that on the effect of the seismic strengthening of the piers with steel jacket is also studied. The applicability of Applied Element Method as the evaluation tool for the seismic performance and the effect of seismic strengthening of bridge piers is tested.

INTRODUCTION

RC bridge piers that have terminated main reinforcements with inadequate anchorage length become the week points of the RC bridges because significant shear failure is likely to develop at the middle part of them. When the bridge pier having sufficient shear strength is damaged at the base of the pier due to earthquake, the pier shows the ductile failure process. However, when the shear failure occurs at the mid-height of the pier, the damage to the pier progresses brittlely, and the possibility of collapse of the bridge becomes high. The latest new structures are designed in consideration of the problem resulting from termination of main reinforcements, but many structures based on the past design standard that is not taking the problem into consideration also exist. To these pre code-revision structures, sufficient earthquake strengthening should be given.

We have analyzed complicated damage behavior of RC structures using *Applied Element Method* (AEM)[1], which is newly developed non-liner simulation method, and have considered applying the simulation method to the measure against earthquakes of RC structures, as the evaluation of seismic resistance, the quick inspection of damage levels, or the selection support of suitable retrofit construction. Until now, fundamental research on the simulation of damage and collapse behavior of real structures[2], analysis of the change of dynamic characteristics of structures due to damage[2], and development of the numerical model of jacketed RC structures[3] etc. were performed towards utilization. In order to realize these techniques, it is indispensable to check whether the weak point of structures can be detected correctly by the AEM or not. Moreover, it is necessary to confirm that the effect of reinforcement to the weak point can be correctly evaluated using AEM.

Here, the problem on the RC members that have terminated main reinforcements is taken up as a weak point of RC structures. First, the failure modes of RC columns that have terminated main

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reinforcements are simulated by AEM, and it confirms whether the AEM can evaluate the influence of the anchorage length of terminated reinforcements. Next, numerical simulation of the failure modes of the RC columns retrofitted by steel jacket are performed, and it confirms whether the AEM can evaluate the effect of the height of the steel jacket that reinforces the weak part of the RC members.

TECHNIQUE OF NUMERICAL SIMULATION

Figure 1 illustrates the modeling of RC structure for the AEM. It is assumed that the structure is modeled as an assembly of small rectangular elements made by dividing the structure virtually. Each element is connected by pairs of normal and shear springs located at contact points, which are distributed around the element edges. In the case of 2-dimensional analysis, each element has three degree of freedoms. The material model of concrete is applied to each distribution spring. At the location of reinforcing bar, two pairs of springs are used one for concrete and another for reinforcing bar. Nonlinear material models of steel and concrete shown in **Figure 2** are given to the springs, respectively. If the stress of a spring exceeds its resistance, the spring can yield and cut. In this way, AEM can follow the structural behavior from elastic range to total collapse.

Two-dimensional model of the jacketed column is composed of three different types of elements. The first one is the element for the concrete inside jacket (RC Element, E_C), the second one is the element for the steel jacket installed in sides of the RC column (Side jacket Element, E_{JS}) and the third one is the element for the steel jacket between two-side jackets (Front and rear jacket Element, E_{Jb}). First one has a material property of RC and the other two types of elements have the material property of steel. There is no connection between the elements of E_{Jb} and Ec in the **Figure 3**. Because the edge elements of both E_C and E_{Jb} are connected with E_{JS}, the steel jacket can restrain the inside concrete. Inside concrete is permitted to crack and reinforcements are permitted to yield and cut.

FAILURE MECHNISM OF VULNERABLE RC COLUMNS

Outline of Experiment

Kawashima *et al.*[4] conducted the loading test of specimens of RC columns that have terminated main reinforcements with inadequate anchorage length. The details of the specimens are shown in **Table 1**. The difference among four specimens is the termination height. The termination height means the height of the upper end of terminated main reinforcements from the base. From the viewpoint of design, the standard termination height - just meet the design standard - is 116cm. The height of all main reinforcements of Specimen 3-1 is higher than 250 cm (no termination). The half numbers of the main reinforcements of Specimen 3-2, Specimen 3-3, and Specimen 3-4 are terminated at the mid-height. The height of the terminated reinforcements of Specimen 3-2 is 110cm and it is 6cm lower than the standard termination height. The termination heights of Specimen 3-3 and 3-4 are 135cm and 160cm respectively, and they are higher than the standard termination height.

The footings of the specimens are fixed to the reaction floor, and the cyclic load is applied to the head of the specimens by the dynamic actuator. In this case, no axial force is applied. The failure displacement δ_0 (=1.3cm) of the Specimen 3-1 is defined as the standard displacement, the displacements $n \cdot \delta_0$ (n=1,2,3, $\cdots$) are given to the Specimens, making the amplitude increase gradually. The number of loading cycle per 1 loading step (in the same displacement) is 10 times.

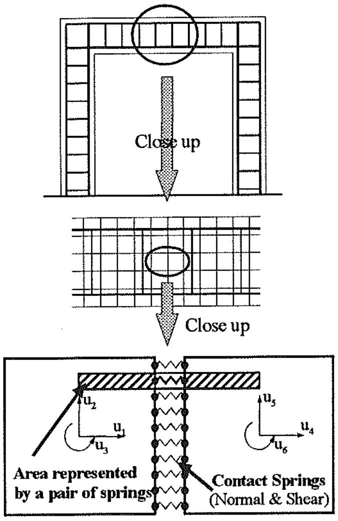

Fig. 1 Modeling of RC structure to AEM

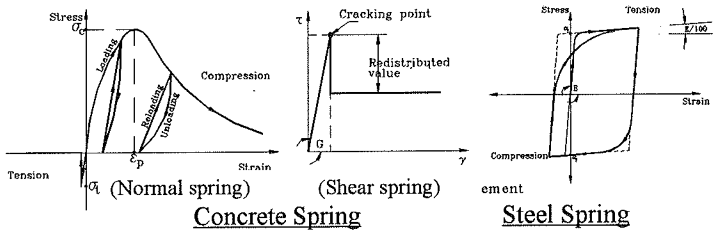

Fig. 2 Material model of concrete and reinforcement

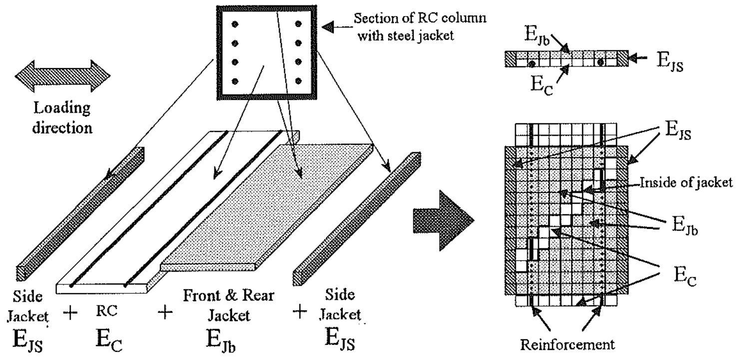

Fig. 3 Modeling of RC column with steel jacket

Table 1 Details of the specimens

Specimen No.	3-1	3-2	3-3	3-4
Dimension of cross section (cm)	50×50			
Thickness of concrete cover (cm)	3.5			
Effective height (cm)	250			
Shear span ratio	5.4			
Termination height from base (cm)	-	110	135	160
Yield stress of main reinforcement (MPa)	308			
Yield stress of hoop reinforcement (MPa)	272			
Young's modulus of reinforcement (GPa)	200			
Compressive strength of concrete (MPa)	31.3	32.0	32.5	31.9
Young's modulus of concrete (GPa)	28.0			

Outline of numerical simulation

The specimens are modeled by 620 square elements whose size is 5×5cm. The models of specimens are 2-d model and plane stress condition is assumed. The strength of concrete and steel bars of numerical models is same as the strength of real specimens. Although the same loading conditions as the experiment are adopted in the numerical analysis, the number of loading cycle per 1 loading step is one time.

Comparison of the maximum strength

Table 2 shows the results of the maximum load of the experiment and numerical simulation. The results of numerical simulation are 90-97% of the results of experiment. The maximum strength of main reinforcing bars in the numerical simulation was assumed 1.75 times of yield strength of real main reinforcements. It is considered that the maximum strength of reinforcement used in the simulation was smaller than actual value.

Table 2 Comparison of maximum strength

Specimen No.	3-1	3-2	3-3	3-4
Maximum strength obtained by experiment (kN)	167	148	161	166
Maximum strength obtained by simulation (kN)	154	143	145	160

Comparison of the failure mode

The results of numerical simulation are compared with the experiment results. **Figure 4** shows the failure mode of specimens, and **Figure 5** shows the distribution of axial strain of main reinforcement obtained by the experiment and simulation. The figures of the result of the experiment used in this paper are quoted from reference[4)].

(a) Specimen 3-1 (No termination)

In the both experiment and simulation, the damage to the RC column concentrates on the bottom part of the column. The reinforcements of the column break and the column reaches ultimate state, when the inputted displacement is $8\delta_0$ in the experiment, and $9\delta_0$ in the simulation.

(b) Specimen 3-2 (Termination height: 110cm)

In both the cases, the damage concentrates on the center of the column where the main reinforcements are terminated. The axial strain of the main reinforcement that have no termination, concentrates on the termination point. The column reaches ultimate state, when the inputted displacement is $6.5\ \delta_0$ in the experiment, and $6\delta_0$ in the simulation.

(c) Specimen 3-3 (Termination height: 135cm)

In both the cases, the damage to the RC column concentrates on the bottom part of the column, but termination part of the column is also damaged. In the experiment specimen, the damage begins to concentrate on the bottom part after the $6\delta_0$ is inputted to the column, and when the $8.5\delta_0$ is inputted, the specimen reaches ultimate state at the bottom part. In the numerical model, the hoop reinforcement brakes when the input displacement is $6\delta_0$, after that, the damage is concentrated on the bottom part.

(d) Specimen 3-4(Termination height: 160cm)

In both the cases, the damage to the RC column concentrates on the bottom part of the column. When the input displacement is $8\delta_0$, the column reached ultimate state by the cutting of the main reinforcement.

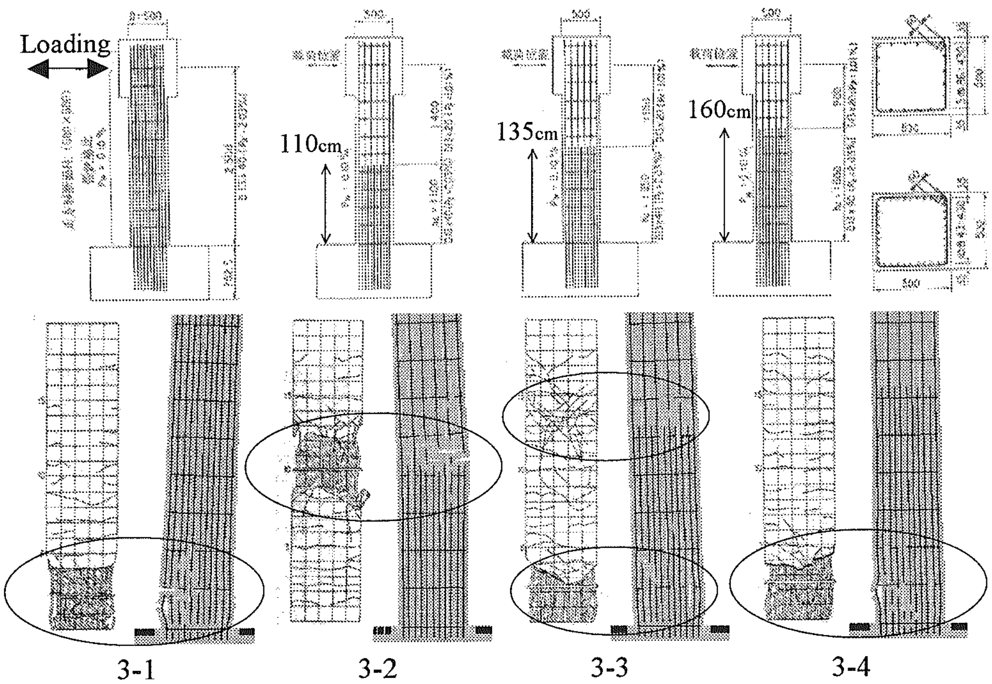

Fig. 4 Shape (upper) and failure mode (Lower: Experiment, Simulation) of specimens

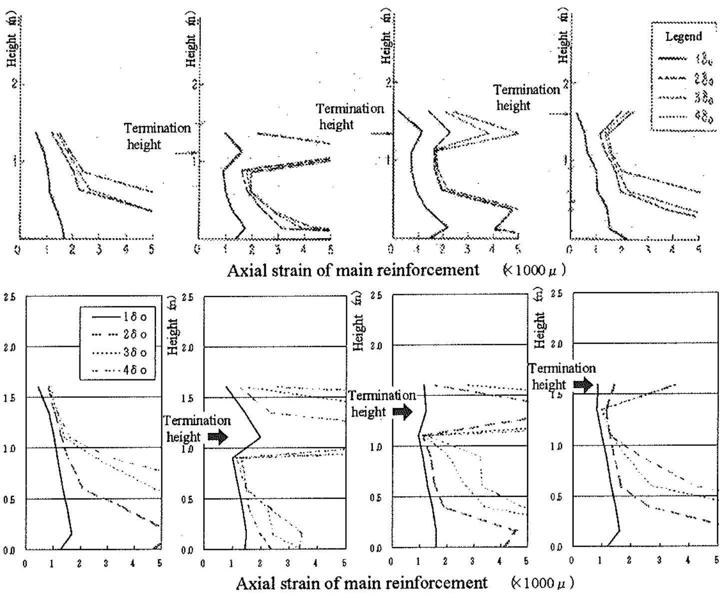

Fig. 5 Axial strain of main reinforcement (Upper: Experiment, Lower: Simulation)

Considerations

In the experiment, the Specimen 3-2 that has the lowest and inappropriate termination height, is damaged at the center of the column where the main reinforcements are terminated. As the termination position becomes high, the damage concentration part shifts to the bottom of the column, and the damage state approaches Specimen 3-1 that has no termination.

The results of numerical simulation by the AEM can follow well the phenomenon that occurred in the experiments. The simulated results of the maximum strength and the ultimate displacement, and the experiment results about them are well in agreement. The simulated axial strain of main reinforcements is sufficiently in agreement with the experiment results, and the simulated results can follow well the tendency of change of the strain distribution accompanied by the change of the termination height. It is known well that the measurement of the strain of reinforcement is very difficult in case of the damaged RC structures, and Kawashima *et al.*[4] has also indicated that a certain error might be included in the experiment result of axial strain. So the detailed argument about accuracy of the simulated strain value is avoided.

EFFECT OF EARTHQUAKE STRENGTHENING BY STEEL JACKET

Outline of Experiment

In order to check the effect of earthquake strengthening of RC pier by steel jacketing, Kawashima *et al.*[4] conducted loading test of the RC specimen with steel jacket. **Table 3** show the details of the specimen used in the experiment. The details of those specimens are almost same, but the height of the steel jacket is different. The reinforcements of all specimens are terminated. The termination height is 90cm from the base, and the termination height is 22cm lower than the standard termination height. The Specimen 4-1 is not strengthened. The steel jacket whose height is 50cm is used for the Specimen 4-2, and the center of the steel jacket is united with the termination height. The steel jacket whose height is 75cm is used for the Specimen 4-3, and the position 25cm upper from the bottom of the steel jacket is united with the termination height. The tension strength of steel jacket is 274MPa, and the space between the RC column and steel jacket is filled with the epoxy resin whose thickness is 3mm.

Table 3 Details of the specimens

Specimen No.	4-1	4-2	4-3	(4-4)
Dimension of cross section (cm)	50×50			
Thickness of concrete cover (cm)	3.5			
Effective height (cm)	260			
Shear span ratio	5.6			
Termination height from base (cm)	90			
Yield stress of main reinforcement (MPa)	409	357		
Yield stress of hoop reinforcement (MPa)	433	245		
Thickness of steel jacket (cm)	-	1.0		
Height of steel jacket (cm)	-	50	75	30
Young's modulus of reinforcement (GPa)	200			
Compressive strength of concrete (MPa)	42.0	43.8	35.6	35.6
Young's modulus of concrete (GPa)	28.0			

In this experiment, the footings of the specimens are fixed to the reaction wall, and the cyclic load is applied to the head part of the specimens by the dynamic actuator. In this case 282kN of axial force is applied to the specimens. The failure displacement δ_0 (=1.5cm) of the Specimen 4-1 is defined as the standard displacement, the displacements $n \cdot \delta_0$ $(n=1,2,3,\cdots)$ are given to the

Specimens, making the amplitude increase gradually. The number of loading cycle per 1 loading step (in the same displacement) is 10 times.

Outline of numerical simulation

The every specimen is modeled by about 640 square elements whose size is 5×5cm. The models of specimens are 2-d model and plane stress condition is assumed. The strength of concrete and steel bars of numerical models is same as the strength of real specimens. Although the same loading conditions as the experiment are adopted in numerical analysis, the number of loading cycle per 1 loading step is 1 time.

Comparison of the maximum strength

Table 4 shows the results of the maximum load of the experiment and numerical simulation. The results of numerical simulation are 100-105% of the experiment result.

Table 4 Comparison of maximum strength

Specimen No.	4-1	4-2	4-3
Maximum strength obtained by experiment (kN)	124	128	126
Maximum strength obtained by simulation (kN)	127	129	133

Comparison of the failure mode

The results of numerical simulation are compared with the experiment results. **Figure 6** shows the failure mode of specimen, and **Figure 7** shows the distribution of axial strain of main reinforcement obtained by the experiment and simulation

(a) Specimen 4-1 (Without jacketing)

In the both experiment and simulation, the damage to the RC column concentrates on the termination part. The RC column reached ultimate state, when the inputted displacement is $7\delta_0$ in the experiment, and $6\delta_0$ in the simulation.

(b) Specimen 4-2 (Height of steel jacket: 50cm)

In the both cases, the center of the column near the upper part of the steel jacket, and the bottom of the column are damaged. Finally, the damage to the bottom part becomes heavier.

(c) Specimen 4-3 (Height of steel jacket: 75cm)

In the both cases, the damage to the RC column concentrates on the bottom part of the column. The RC column reached ultimate state, when the inputted displacement is $7\delta_0$ in the experiment, and $6\delta_0$ in the simulation.

(d) Specimen 4-4 (Height of steel jacket: 30cm. (Only numerical simulation.))

Numerical model of RC column strengthened by the steel jacket with 30cm height is made in order to check the failure mode of vulnerable RC column with inappropriate steel jacketing. In this case, the damage concentrates on the RC column near the upper part of the steel jacket.

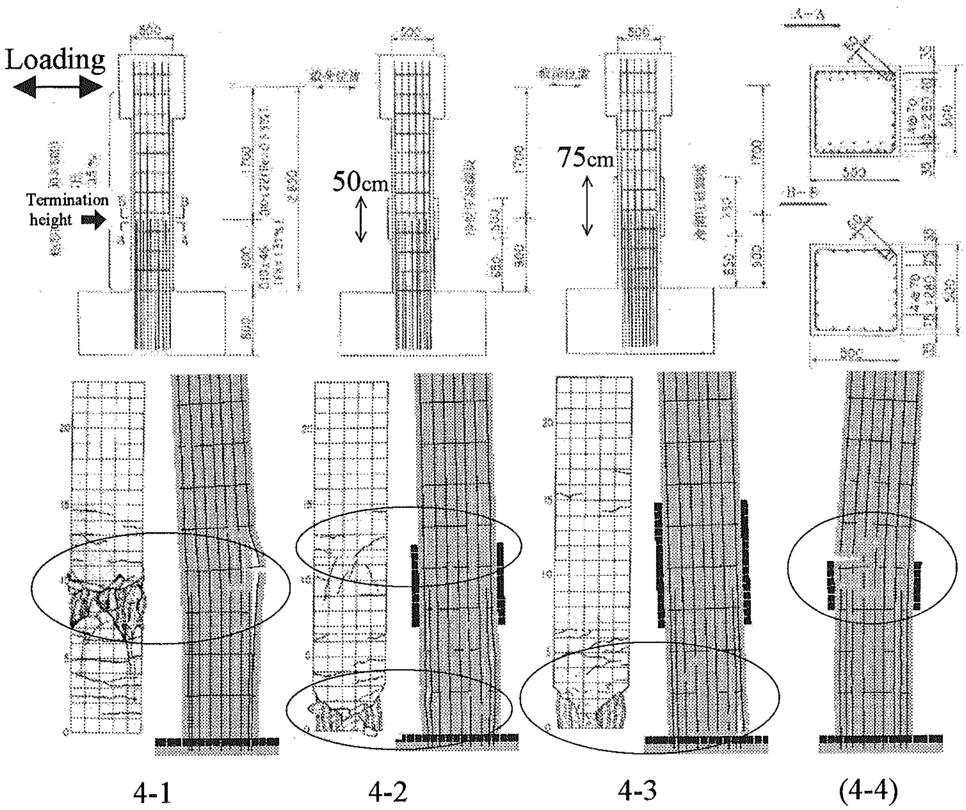

Fig. 6 Shape (upper) and failure mode (Lower: Experiment, Simulation) of specimens

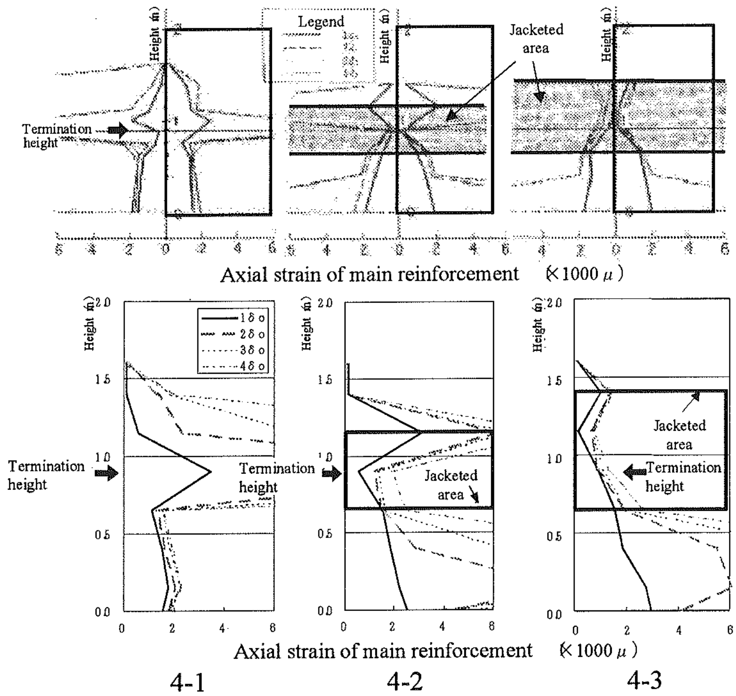

Fig. 7 Axial strain of main reinforcement (Upper: Experiment, Lower: Simulation)

CONSIDERATIONS

In the experiment, it is confirmed that the damage to the Specimen 4-1, which is not strengthened, concentrates on the center of the column where the main reinforcements are terminated, and the damage concentration part shifts to the lower part of the column as the height of the steel jacket becomes large.

The results of the numerical simulation by AEM, shows the same phenomenon that occurred in the experiments, and the simulated results of the maximum strength and the ultimate displacement have sufficient accuracy. Moreover, the result of the failure mode of the numerical model 4-4 suggests that numerical simulation by AEM may be effectively utilizable as the detection method of inadequate earthquake strengthening design.

CONCLUDING REMARKS

Through the comparison of the results of experiment and numerical simulation, it is confirmed that the AEM can simulate the damage behavior of the RC column whose main reinforcements are terminated at the mid-height and the jacketed RC column. The change of the failure mode by the change of the anchorage length of the terminated reinforcement or the height of the steel jacket is simulated with sufficient accuracy.

Our future targets are the further improvement of the numerical simulation technique, and the development of the method about the detection of a weak point of existing structures, the evaluation of the earthquake resistance of retrofitted structures, the effective retrofit of the existing pre code-revision structures, etc.

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