Innovative Column-Base Details Capable of Tuning Rigidity and Strength for Low to Medium-Rise Steel Structures

T. Yamanishi & K. Kasai
Tokyo Institute of Technology, Japan.

T. Takamatsu
Hiroshima Institute of Technology, Japan.

H. Tamai
Nagasaki University, Japan.

SUMMARY:
An anchor-bolt-yield-type exposed column-base is typically used in low to medium-rise steel buildings. These column-base details are generally designed to consider the semi-rigid rotation spring, that caused by elastic/plastic elongation of anchor bolts. Such semi-rigid rotation spring stiffness (rotational rigidity) of column-base have a large effect on the seismic behavior of the building. This paper proposes innovative column-base details that can be much better tuned for desired hysteretic properties, compared with conventional details.

Keywords: steel column-base, rotational rigidity, bending yield strength

1. INTRODUCTION

Generally, an exposed column-base consists of anchor-bolts and thick base plate, connecting steel column and concrete foundation (Akiyama 1985, Yamanishi et al. 2006, 2007 and 2008). These column-bases showed semi-rigid behavior, caused by anchor-bolt elongation and base plate bending deformation out of plane, which can be evaluated using elasto/plastic rotation spring in numerical analysis (Sawada et al 2008). Such semi-rigid rotation spring stiffness (rotational rigidity) of column-base had large effect on the structure natural period (Tamai et al 2006, 2008, Takamatsu et al 2008).

The conventional column-base detail is very difficult to tune for desired rigidity and strength. Moreover, it will be destroyed and become unreparable under a major seismic attack. Therefore, it will be advantage us, if the column-base is repairable.

In this paper, the authors propose a new type of column-base, that has rotational rigidity control function and repair performance. The proposed column-base is validated through experiments and detailed analyses using cyclically applied rotations. Theoretical equations to predict the elastic rotational stiffness are also proposed, and they appear to correlate well with both experimental and analytical results. The so-called “performance curve” useful for design of the new column-base is given by plotting such equations.

2. CONCEPT OF NEW TYPE OF COLUMN-BASE

The consist of new type column-base is shown in Figure 1. The bolt had three parts, that set up from yield bolt (anchor bolt), coupler and elastic bolt (anchorage). The coupler is joint parts for anchor bolt and anchorage. Anchor bolt setting plate (Anchor stand) was welding joint between column and column foot.

Rotational rigidity control concept is shown in Figure 2.

Anchor bolt stiffness had large effect on column-base rotational rigidity. Anchor bolt stiffness are observed to be variable due to anchor stand level adjusting, caused by the anchor bolt length changed. Which, column-base rotational rigidity was more small, that by anchor stand level higher.

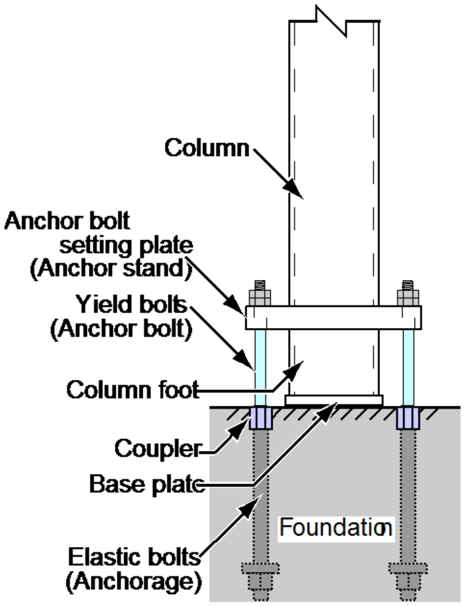


Figure 1. New type column-base

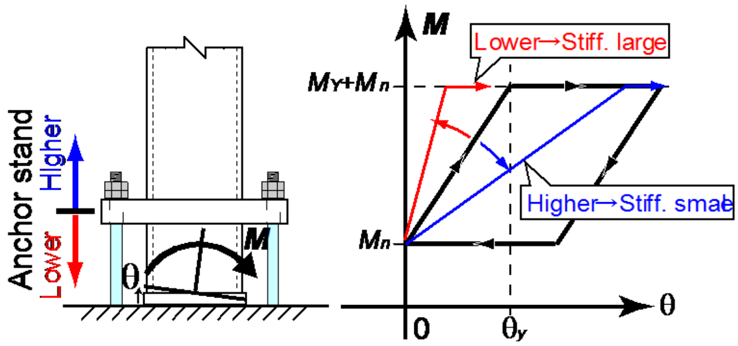


Figure 2. Rotational rigidity control concept

3. EXPERIMENT

Experiment were carried out on cantilever column with new type column-base subjected to an constant compression axial force and cyclic horizontal force. Experiment parameter was anchor stand level $_{F}h$.

3.1 Specimen

Specimen's material properties are shown in Table 3.1. Column-base detail and anchor bolts are shown Figure 3 and 4. Specimen setup is shown in Picture 1.

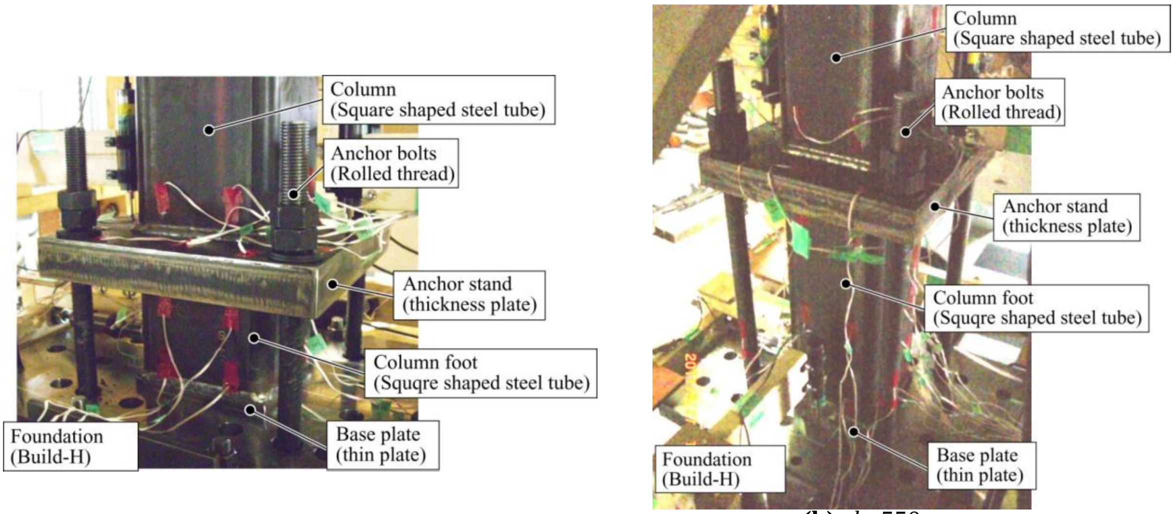
Since the experiments focused on the elastic-plastic deformation behavior of the anchor bolts, the column, anchor stand, column foot, base plate and foundation were maintained in the elastic region. A steel foundation (BH-390x500x32x50) was employed instead of a concrete one and failures of base mortar and foundation concrete were ignored.

A column (□-200x200x12), an anchor stand (PL-55x375x375), a column foot (□-200x200x12), a base plate (PL-16x200x200) and four anchor bolts (${}_{F}h$=200 : M30, ${}_{F}h$ =550 : M36) were used. The column, anchor stand, column foot and base plate were fillet welded to each member. Rolled thread anchor bolts to Japan Society of Steel Construction standard were employed. Each was subjected to thirty percent yield tension as the pre-tension.

Table 3.1. Material properties

		Material	E	σ_y	Main dimension
			N / mm^2	N / mm^2	mm
Anchor bolt	M30	SNR400B	205,000	286	ϕ_g=27.2
	M36	SNR400B	205,000	271	ϕ_g=33.0
Anchor stand		SS400	205,000	327	PL-55x375x375
Column, column foot		BCR295	205,000	387	□-200x200x12
Base plate		SS400	205,000	366	PL-16x200x200

E : Young's moduls σ_y : Yield stress ϕ_g : Shank diameter



(a) ${}_{F}h$=200 **(b)** ${}_{F}h$=550

Picture 1. Specimen setup

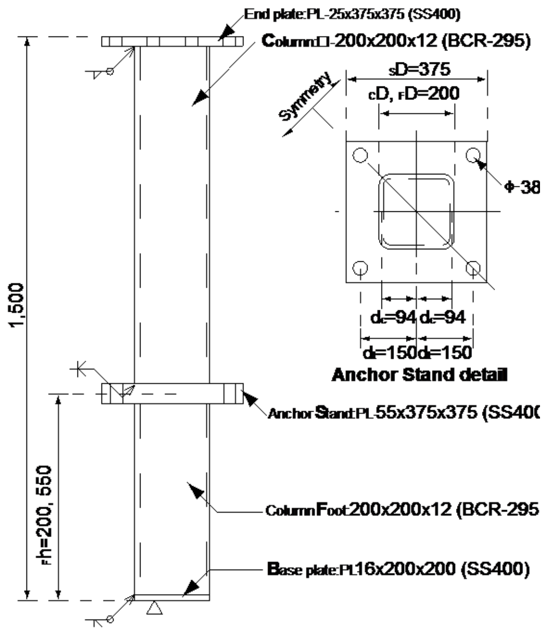
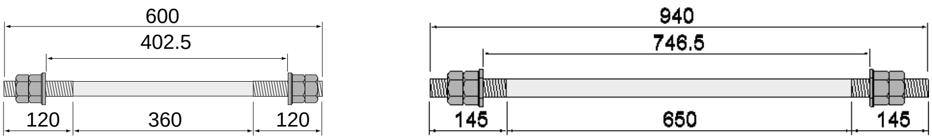


Figure 3. Column-base detail



(a) $_{F}h$=200 **(b)** $_{F}h$=550

Figure 4. Anchor bolt

3.2 Loading Method

Loading apparatus is shown in Figures 5, and loading method shown in Figure 6. The horizontal loadings were introduced from the horizontal jack of slide table and two vertical jacks of loading frame. The cyclic horizontal loadings were controlled by the rotation of the base plate. The constant variable loading were within ten percent of yield compression of the column member (=266 (kN)).

Column moment plot was like cantilever column in horizontal loading time, that by two vertical jack force balanced.

3.3 Measurement

Base-plate displacements were measured to obtain their rotations. Both vertical and horizontal loads were measured by load cells.

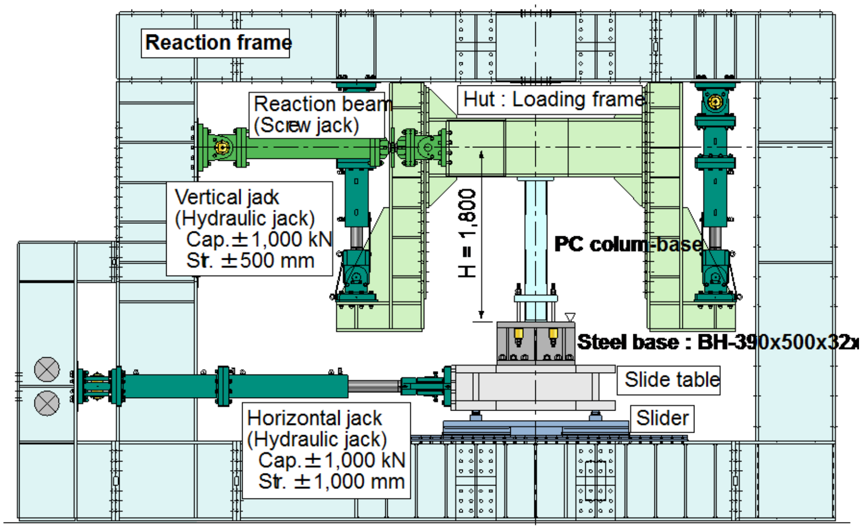


Figure 5. Loading apparatus

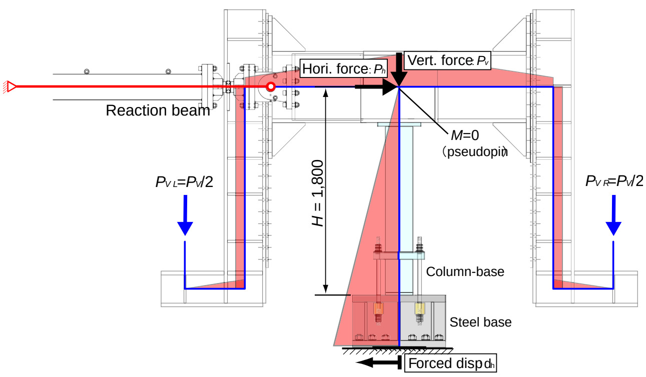


Figure 6. Loading method

4. THEORY & MODEL

Resisting mechanism and each element deformation are shown in Figure 7.

Additional bending resist, yield bending strength and elastic rotational stiffness are obtained from resisting mechanisms.

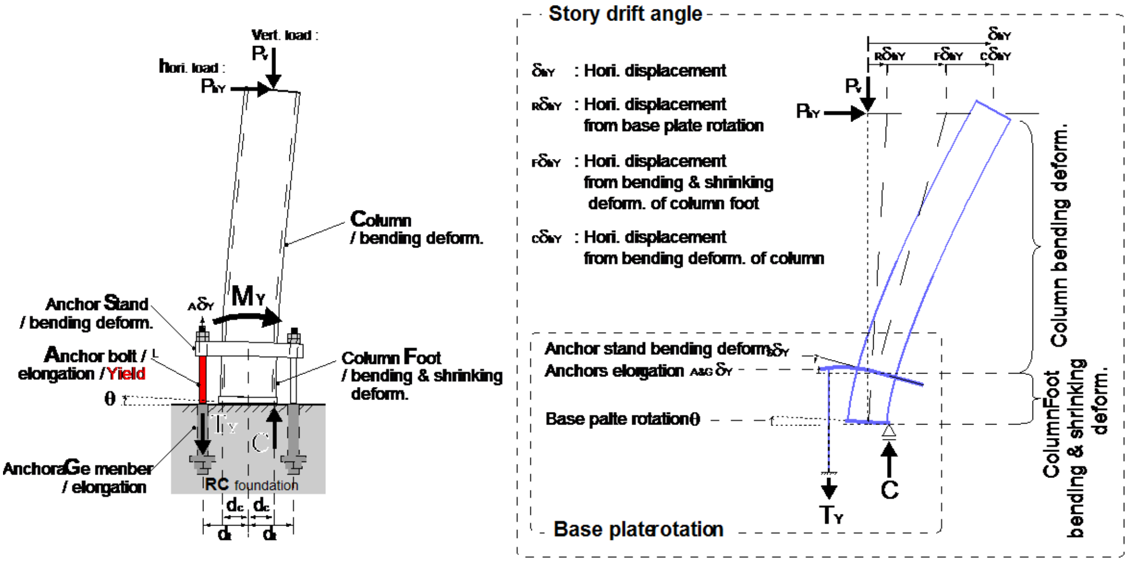


Figure 7. Resisting mechanism & deformation of each elements

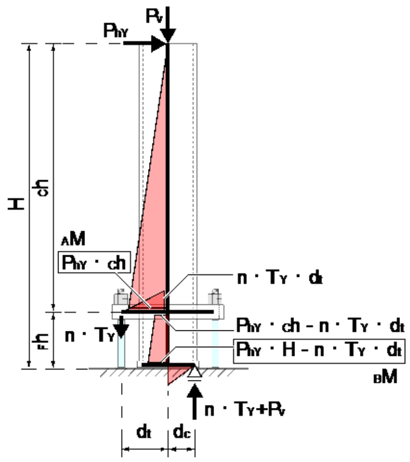


Figure 8. Bending stress of new type column-base

4.1 Assumption

Models of restoring force characteristics are based on the following assumptions.

1) The anchor bolts are the only yielding elements in the column base.
2) For the base plate in contact with the foundation, the position of compressive reaction of the foundation is at the edge of the base plate and the anchor bolts on the tension side resist bending moment.
3) When the base plate is in contact with the foundation, friction between base plate and foundation resists shearing force, but when it is separated, the anchor bolts resist the shearing force.
4) The perfectly elastic-plastic model is used to define the material properties of the anchor bolts.

4.2 Strength

The additional bending resist M_n from column axial force is obtained from Equation (4.1).

$$M_n - N \cdot d_c \tag{4.1}$$

The yielding bending moment M_Y of the column base with the anchor-bolts yielding is obtain from Equation (4.2).

$$M_Y = n \cdot {}_A A \cdot {}_A \sigma_Y \cdot \left(d_c + d_t\right) - N \cdot d_c \tag{4.2}$$

where, n is the number of anchor bolts on the tension side, A_A is the gross area of the anchor bolts, ${}_A\sigma_Y$ is the yield stress of the anchor bolt, d_t is the distance from the center of the column cross-section to the line of the tensile anchor bolts (shown in Figure 3 and 7), d_c is the distance from the edge of the base plate to the center of the column cross-section (shown in Figure 3 and 7), N is the axial force.

These equation was same the conventional exposed column-base evaluated method.

4.3 Rotational Rigidity

Anchor stand and column foot moment plot is shown in Figure 8. The elastic rotational rigidity of the column base ${}_AK_B$ is obtain from the elastic elongation of anchor bolts by Equation (4.3).

$$ {}_B K_A = \frac{\left[n \cdot E \cdot \left(d_c + d_t\right)\right] \cdot \left(\sqrt{\left({}_F h + \frac{{}_S t}{2} \right)^2 + \left(d_c + d_t\right)^2} \right) \cdot \cos\left(\tan^{-1} \frac{{}_F h}{d_c + d_t} \right)}{\frac{{}_A L}{{}_A A} + \frac{{}_G L}{{}_G A} + \frac{4 \cdot d_t^3}{{}_S B \cdot {}_S t^3} + \frac{n \cdot {}_F h}{{}_F A} + \frac{n \cdot \left(d_c + d_t\right) \cdot {}_F h^2 \cdot d_t}{2\, {}_F I} + \frac{n \cdot d_c \cdot {}_F h \cdot d_t}{2\, {}_F I}} \tag{4.3}$$

where, E is Young's modulus, ${}_AL$, ${}_GL$ is the effective length of the anchor bolt and anchorage, ${}_st$ is anchor stand thickness, ${}_GA$ is the gross area of the anchorage, ${}_Fh$ is anchor stand level, ${}_sB$ is anchor stand width and ${}_FI$ is moment inertia of column foot.

4.4 Models of Restoring Force Characteristics

Models of restoring force characteristics are shown in Figure 9. The hysteresis shows slip-phenomenon and additional bending resist from column axial force. It hysteresis was same the conventional exposed column-base.

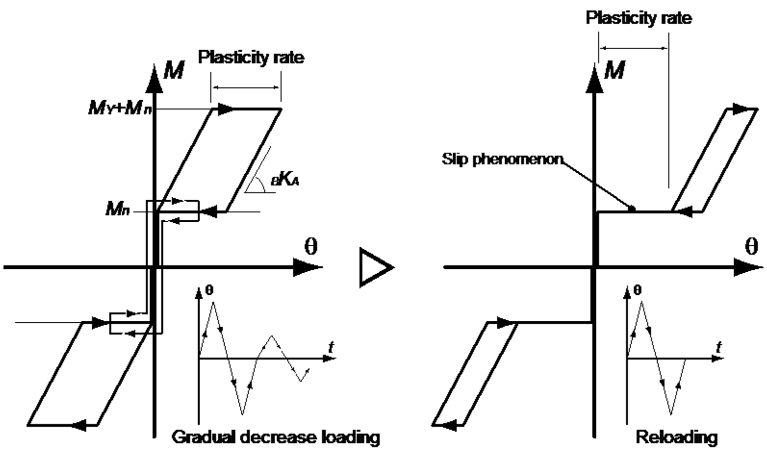


Figure 9. Models of restoring force characteristics

5. FEM ANALYSIS

FEM analysis model for new type column-base is shown in Figure 10. A general-purpose finite element program ADINA ver. 7.1. was used to analytical study. FEM analysis two kinds of analyzed.

Series I was had same shape of experiment specimens, that for discussion of examines experiment and FEM analysis.

Series II models detail is shown in Figure 11. Rotational rigidity control function of new type column-base discussion, that use these models result. The analysis parameter was anchor stand level $_Fh$ = 100, 200, 400, 550, 800, 1000. All element had steel young's module (=205,000 N/mm^2), poisson's ratio (=0.3) and yield stress of material test (shown in Table 1). However, foundation was rigid body, because steel foundation used in loading test.

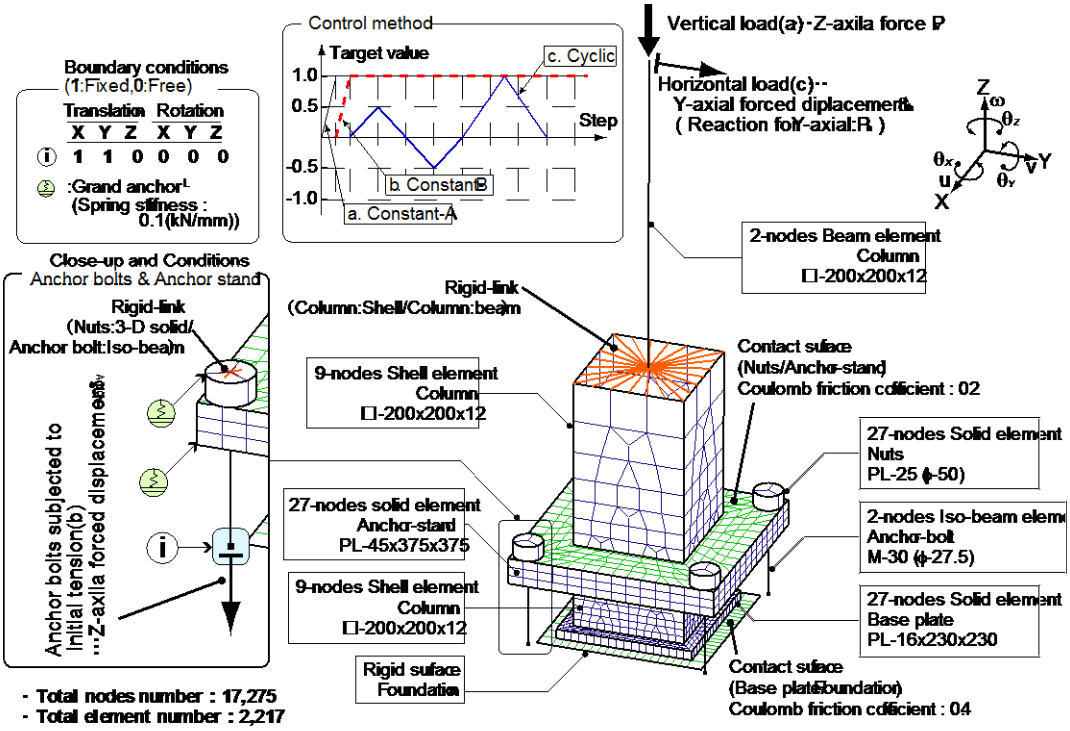


Figure 10. Resisting mechanism & deformation of each elements

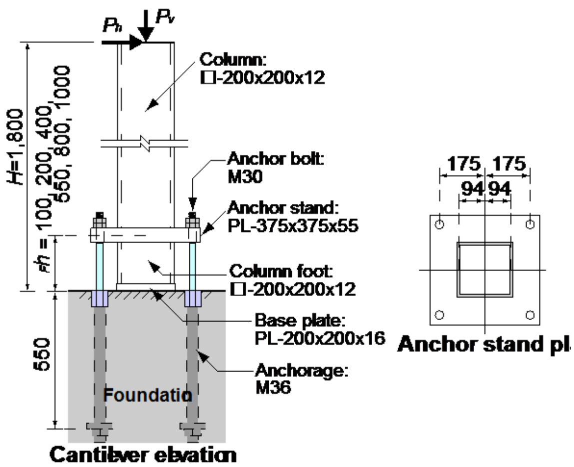


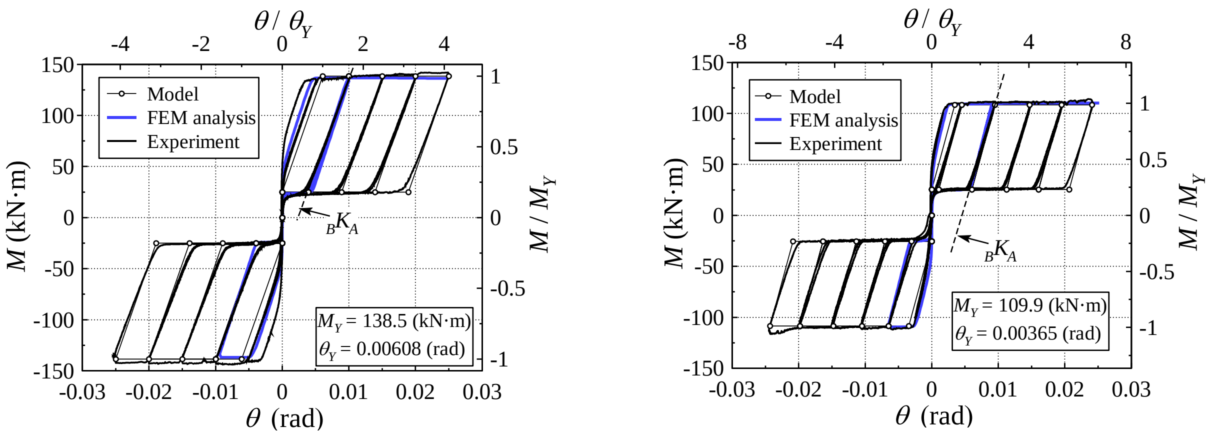
Figure 11. Dimension for FEM analysis model

6. RESULTS & DISCUSSION

Bending moment of base plate level *M* v.s. base plate rotation θ relationship for experiment specimen or FEM analysis series II are shown in Figure 12 and 13. A solid line is experiment results, bold line is FEM analysis results and circle and slid line is model obtain from section 4. Yield strength and Elastic rotational rigidity for experiment specimen or FEM analysis series II. Rotational rigidity performance curve (${}_{A}K_{B}$ v.s. ${}_{F}h$ relationship) and Yield strength performance curve (M_Y v.s. ${}_{F}h$ relationship) are shown in Figure 14 and 15. A solid line is calculated value obtain from Equation (4.2) and (4.3), and a square symbol is FEM analysis series II results. Each specimen & model yield strength & Elastic rotational rigidity are shown Table 6.1 and 6.2. An anchor bolts thread dimensions for after and before experiment are shown in Table 6.3. New type column-base repair method is shown in Figure 16.

6.1 Experiment Specimen

The experimental results showed slip-phenomenon, it with the additional bending resist from column axial force. The models of restoring force characteristics showed good agreement with the experiment results. The rotational rigidity was lower ${}_{F}h$=550 from ${}_{F}h$ =200, because anchor bolts became long.



(a) ${}_{F}h$=200 (b) ${}_{F}h$=550

Figure 12. Bending moment of base plate level *M* v.s. Base plate rotation *θ* relationship (Experiment)

Table 6.1. Yield strength & Elastic rotational rigidity

	M_Y (kN·m)					${}_{B}K_{A}$ (kN·m/rad)				
	Exp.	Calcu.	FEM	Calcu./ Exp.	FEM/ Exp.	Exp.	Calcu.	FEM	Calcu./ Exp.	FEM/ Exp.
${}_{F}h$ = 200	109.1	109.9	108.8	1.01	1.00	23,100	24,900	25,700	1.06	1.10
${}_{F}h$ = 550	137.6	138.5	136.5	1.01	0.99	18,900	19,900	20,900	1.04	1.09

6.2 FEM Analysis Series II

The models of restoring force characteristics showed good agreement with FEM analysis results. The performance curve showed column-base rotational rigidity variable, that became small from ${}_{F}h$ grows big. Such, even if ${}_{F}h$ changed, the yield strength was constant. Because, column-base strength obtain from equilibrium of base plate under-surface, which independent value of ${}_{F}h$.

6.3 Repaired

New type column-base showed anchor bolt only yield, and other element showed elastic behaviour. New type column-base can anchor bolts exchange after the elasto-plastic loading experiment, that used rolled thread anchor bolts. Therefore, new type column-base having repair performance, if anchor bolts plastic elongation by the earthquake.

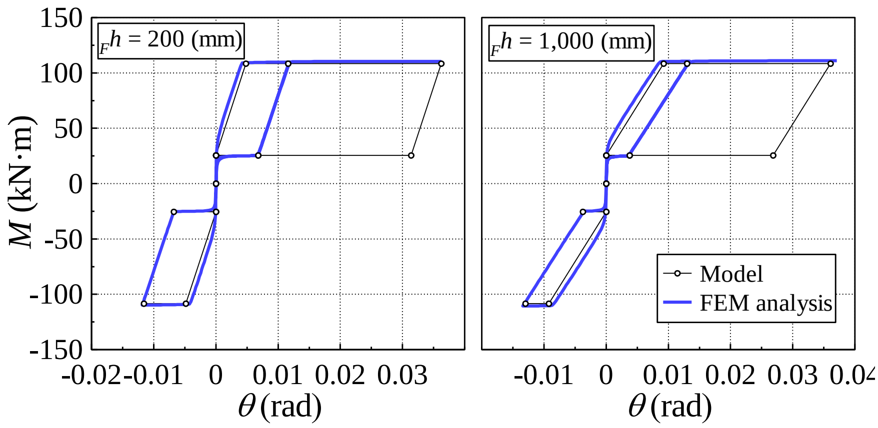


Figure 13. Bending moment of base plate level M v.s. Base plate rotation θ relationship (FEM analysis series II)

Table 3. Yield strength & Elastic rotational rigidity (FEM analysis series II)

	M_Y (kN·m)			$_BK_A$ (kN·m/rad)		
	Calcu.	FEM	Calcu. / FEM	Calcu.	FEM	Calcu. / FEM
$_Fh$ = 100	108.5	108.4	1.00	19,500	19,900	0.98
$_Fh$ = 200	108.5	108.7	1.00	16,900	17,200	0.98
$_Fh$ = 400	108.5	108.1	1.00	13,800	13,600	1.01
$_Fh$ = 550	108.5	108.8	1.00	11,900	11,900	1.00
$_Fh$ = 800	108.5	108.5	1.00	9,600	10,000	0.96
$_Fh$ = 1,000	108.5	108.4	1.00	8,800	9,000	0.98

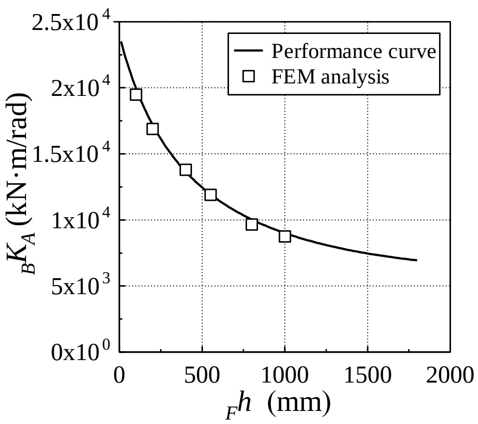


Figure 14. Rotational rigidity $_AK_B$ - Anchor stand level $_Fh$ relationship

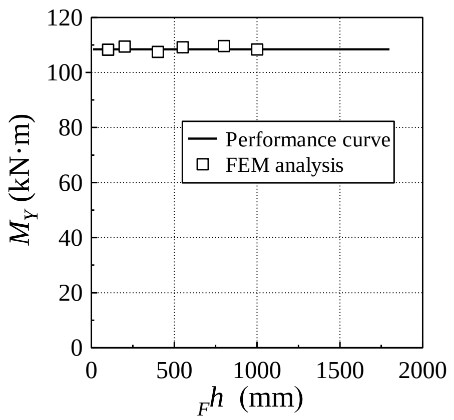


Figure 15. Yield strength M_Y - Anchor stand level $_Fh$ relationship

Table 4. Anchor bolt deform value

	$_AL$ (mm)		Screw pitch※	
	Before Exp.	After Exp.	Before Exp.	After Exp.
M30 : $_Fh$=200	402.5	409.5 (17,400μ)	3.51 = 28.02/8	3.56 =28.5/8 (14,200μ)
M36 : $_Fh$=550	746.5	752.0 (7,400μ)	4.00 =40.04/10	4.03 =40.33/10 (8,250μ)

※Nominal value M30 : 3.5, M36 : 4.0 - JIS B 1220 - ( ) : Global stra

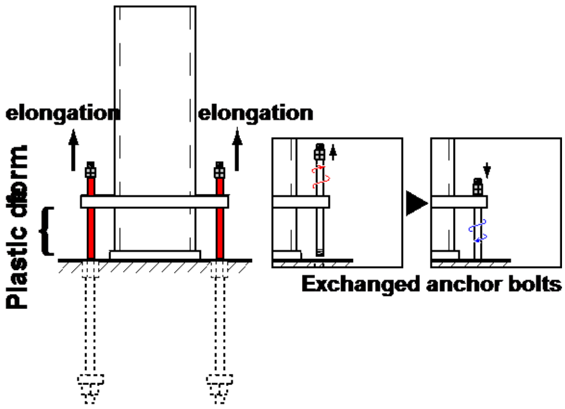


Figure 16. Repair method of column-base

7. CONCLUSION REMARKS

An experimental and analytical study were carried out on new type column-base subjected to axial force and cyclic horizontal loadings. The following conclusions were obtained.

1) Rotational rigidity of column base variable by means of the adjusting of anchor bolt length & column-base detail.
2) Cyclic behaviour showed slip-type restoring force characteristics subjected to cyclic horizontal loading, that same to conventional anchor-bolt-yield-type exposed column-base.
3) The FEM analysis results and proposed models of the restoring force characteristics showed good agreement with the experimental results for all specimens.
4) New type of column base having repaired performance, because anchor bolts of these column-base can exchanged after the earthquake.

REFERENCES

Akiyama, H., (1985). *Seismic resist design of steel column-base*, **Giho-do press** (in Japanese).

Sawada, K., Takamatsu, T., Tamai, H., Matsuo, A., Yamanishi, T., (2008), Evaluation of the self-centering capability and cumulative damage response of steel frames with non-sli-type exposed column-base by seismic response analysis, ***Journal of Structural and Construction Engineering, Architectural Institute of Japan*. Vol. 73, No. 629**, 1151-1157 (in Japanese)

Takamatsu, T., Tamai, H., Yamanishi, T., Sawada, K. & Matsuo, A., (2008), Shaking table experiment of steel portal frame structure with anchor-bolt-yield-type exposed column-base, ***Journal of Constructional Steel, Japanese Society of Steel Construction* : Vol. 16**, 545-552 (in Japanese)

Tamai, H., Yamanishi, T., Takamatsu, T., Shiraki, T. & Tada, M., (2006). Collaborate pseudo dynamic test on full scale non-slip-type exposed column-base, ***Journal of Constructional Steel, Japanese Society of Steel Construction* : Vol. 14**, 269-276 (in Japanese)

Tamai, H., Takamatsu, T., Yamanishi, T., Tada, M. & Matsukage, T., (2008). Collaborative seismic performance evaluation by use of distributed loading system -pseudo dynamic tests on 5-storyes steel building with exposed column-base-, ***Journal of Structural and Construction Engineering, Architectural Institute of Japan*. Vol. 73, No. 631**, 1665-1671 (in Japanese)

Yamanishi, T., Takamatsu , T., Tamai, H. & Matsuo, A. (2006). Restoring force characteristics for anchor-bolt-yield-type exposed column-base, *Proceeding of seventh international conference on **"Behaviour of Steel Structures in Seismic Areas*** **(STESSA 2012)", Yokohama, Japan,** 363-369.

Yamanishi, T., Takamatsu , T., Tamai, H. & Matsuo, A. (2007). Restoring force characteristics of non-slip-type exposed column-base with multi-rows of anchor-bolts -Self-centering performance in case of no-axial force-, ***Journal of structural and construction engineering, Architectural Institute of Japan*: No. 621**, 155-162, 2007.11. (in Japanese)

Yamanishi, T., Takamatsu , T., Tamai, H. & Matsuo, A. (2008). Restoring force characteristics of anchor-bolt-yield-type exposed column-base subjected to axial force and bending moment, **The 14th world conference of earthquake engineering**, CD-ROM No.101885.