13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3490

THE EXPERIMENTAL STUDY ON THE SHEAR STRENGTH OF THE H-SHAPED STEEL BEAM-TO-COLUMN CONNECTION PANEL SUBJECT TO WEAK AXIS BENDING

Akira MATSUO [1], Hideaki YAMADA[2], Takao TAKAMATSU[3]

SUMMARY

Subassemblages of several panel aspect ratios consisting of weak-axis H-column and strong-axis H-beam are first analyzed and it is examined in what range weak panel structures are achieved. Then, cross-type steel subassemblages consisting of weak axis H-column and strong axis H-beam are tested under cyclic horizontal loads and the constant axial force of the column. Theoretical plastic shear strength Q_{pp} of a weak axis panel is presented and simplified plastic strength is also presented for designer's convenience. Yield strength of the panel is obtained by Q_{pp} /1.5. Validity of these analytical strengths are proved by these experimental results

INTRODUCTION

Yield and plastic shear strength of various types of steel beam-to-column connection panel are listed in Recommendation for Design of Connections in Steel Structures published by Architectural Institute of Japan (AIJ)[1]. However, the strength of the H-shaped weak axis column -to-strong axis beam connection panel is not listed in it. On the other hand Recommendation for Limit State Design(LSD) of Steel Structures by AIJ[2] recommended total volume of two column flanges as an effective volume of the panel for evaluating the yield strength of the shear panel of weak axis column. Nakao[4] suggested that this effective volume gives overestimate of the experimental strengths. This comes from neglecting the effect of the bending moment in the panel. In this paper subassemblages of several panel aspect ratios consisting of weak axis H-column and strong axis H-beam are tested by cyclic horizontal loads under the constant axial force of the column. Theoretical shear strength of a weak axis panel considering the bending moment is derived and the simplified formula is also presented.

EXPERIMENTAL PLAN

[1] Professor, Hiroshima University, Higashi-Hiroshima, Japan, Email:matu12@hiroshima-u.ac.jp
[2] Graduate student, Hiroshima University, Higashi-Hiroshima, Japan
[3] Professor, Hiroshima Institute of Technology, Hiroshima, Japan

Panel strength ratio

Panel plastic strength ratios R_{pp} for combinations of a beam and a column of various panel aspect ratios R_{asp} are calculated under several column axial forces and the results are plotted in Fig.1. The definition of R_{pp} and R_{asp} in this paper are the ratio between the horizontal loads at plastic shear strength of the panel and plastic bending strength of the column and the ratio between column height and beam height, respectively. Plastic shear strength Q_{pp} of the panel is obtained from eq.(1). Figure 1 shows that panel remains elastic for the range of aspect ratios of greater than 1.5.

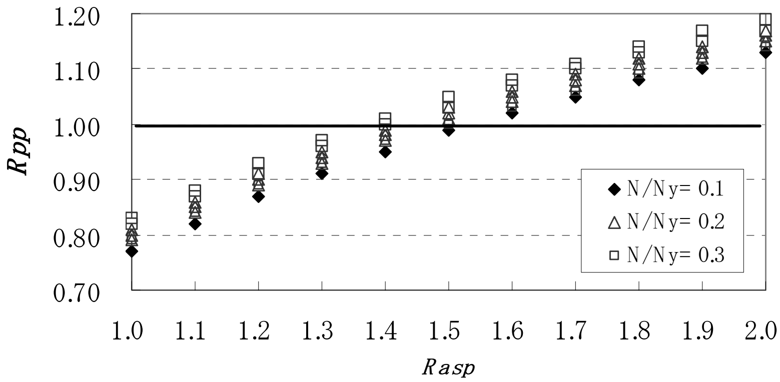

Figure 1 Relation between R_{pp} and R_{asp}

Experimental specimens and materials

Shape and size of the experimental specimens are illustrated and listed in Fig.2 and Tab.1, which are decided considering Fig.1. Shaded specimens are made of SN400B, others are of SS400. Mechanical properties are listed in Tab.2. The definition of panel yield ratio R_{py} in this paper is the ratio between yield shear strength of the panel and yield bending strength of the column. Yield shear strength Q_{py} of the panel is obtained by Q_{pp} /1.5, where 1.5 is the ratio between maximum and average shear stress for rectangular beam sections. Anti-symmetric cyclic horizontal loads are applied under the constant column axial load. Amplitudes of cyclic horizontal loads are equivalent to 4, 8 and 12 times as much as plastic shear deformation of the panel.

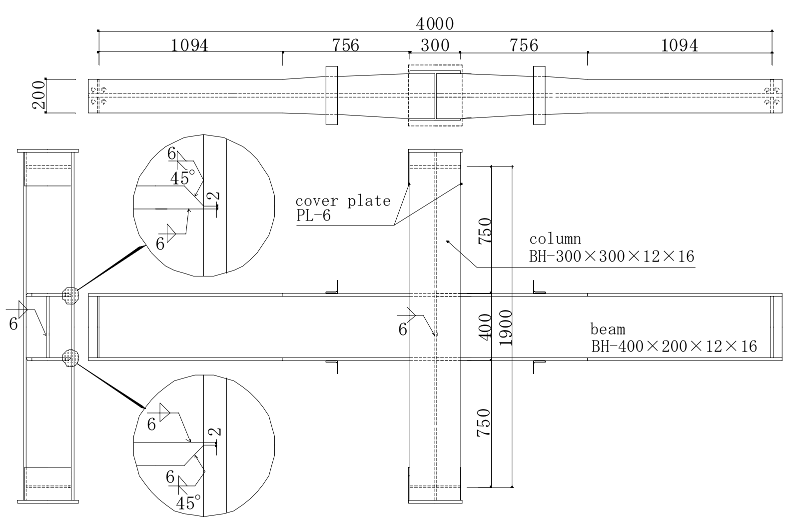

Figure 2 Shape and size of the specimen

Table 1 Size of the specimens

Specimens	column	beam	Rasp	N/Ny	Rpy	Rpp
X1010	300×300×12×16	300×200×12×16	1.0	0.1	0.9	0.8
X1020	300×300×12×16	300×200×12×16	1.0	0.2	1.01	0.8
X1030	300×300×12×16	300×200×12×16	1.0	0.3	1.12	0.77
X1320	300×300×12×16	400×200×12×16	1.3	0.2	1.21	0.96
X1330	300×300×12×16	400×200×12×16	1.3	0.3	1.34	0.93
X1510-6	300×200×12×16	300×200×12×16	1.5	0.1	1.11	0.97
X1510-9	300×300×12×16	450×300×12×16	1.5	0.1	1.15	1.02

Table 2 Mechanical properties of steel

materials	t (mm)	σ_y (N/mm2)	σ_u (N/mm^2)	YR (%)	EL (%)
SN400B	12	282	423	66.6	25.5
SS400		302	447	67.6	26.4
SN400B	16	271	437	62.0	27.4
SS400		268	420	63.8	31.0

ANALYTICAL PLASTIC STRENGTH OF THE PANEL

Figure 3 shows the areas in a H-column, which resist bending moment, axial force and shear force respectively. This figure suggests that bending moment is shared by the edges of the flange, axial force by the web and central part of the flanges and shear force by the remaining areas. As bending moment distribution is linear in the panel, which gives rise to not uniform shear deformation, $2_cM/3$ is adopted as a representative value of bending moment for the evaluation of plastic shear strength of the panel. $_cM$ is the face moment of the column. The basic idea of Ito[5] is applied to weak-axis panel. The plastic shear strength Q_{pp} of the panel is given by eq.(1). The yield shear strength Q_{py} is given by Q_{pp} /1.5. Approximate simplified equation (2) is given by assuming $\alpha_N = 0$ and $\mu = 2_bH/3\sqrt{3}\,_cB$.

$$Q_{pp} = (2\,_p\sigma_y/\sqrt{3})\,_cB\,_ct_f(\alpha_N+\mu)\left[-1+\sqrt{1-(\alpha_N^2-1)/(\alpha_N+\mu)}\right] \qquad (1)$$

$$,where\ \alpha_N = (N-\,_c\sigma_y\,_ch\,_ct_w)/2\,_cB\,_ct_f\,_c\sigma_y,\ when\ \alpha_N>0,\quad \alpha_N=0,\ \ when\ \alpha_N<0$$

$$and\ \ \mu=(2_bH/3\sqrt{3}\,_cB)(1-_bH/_cL)/(1-_cB/_bL-_bH/_cL)$$

$$Q_{pp} = \,_p\sigma_y\,_ct_f\left[_cB-\,_bH/4\right] \qquad (2)$$

In Fig.3 and above expressions following terms are used.
$_cL$: height of the story, $_bL$: span length, $_cB$: width of column flanges, $_ct_f$: thickness of column flanges, $_bH'$: distance between beam flange centers, $_ch$: column depth - 2_ct_f, $_p\sigma_y$: panel yield strength, $_c\sigma_y$: column web yield strength, $_cM$: face moment of the column, N : axial force of the column, $_cB\alpha_M$: length of the area resisting bending moment in the column flange, $_cB\alpha_N$: length of the area resisting axial compression in the column flange.

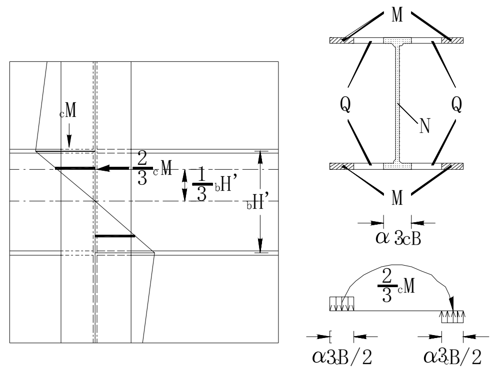

Figure 3 Areas resisting M, N and Q in the panel

EXPERIMENTAL RESULTS AND DISCUSSIONS

Load-Deformation relations

Load-deformation relations of each member are illustrated in Figs.4, where δ, ${}_p\delta$, ${}_c\delta$ *and* ${}_b\delta$ indicate the deformation of total frame, panel, column and beam. Figures 5 show the skeleton curves which are made by chaining newly appeared curve in the higher load range of the successive cycles than the maximum load in the preceding cycles. In these figures $Q_{1/3}$ indicates experimental yield strength, which is the point where tangent modulus becomes one third of elastic modulus. $Q_{0.35\%}$ indicates experimental plastic strength, whose offset strain is 0.35%. ${}_cQ_p$ and ${}_bQ_p$ indicate experimental plastic strength. For specimens X1010, X1020 and X1030, whose R_{pp}<0.9, panel yield precedes beam and column and panel deformation is predominant. For those specimens of 0.9< R_{pp} <1.0 panel and column yield simultaneously and both deformations are large.

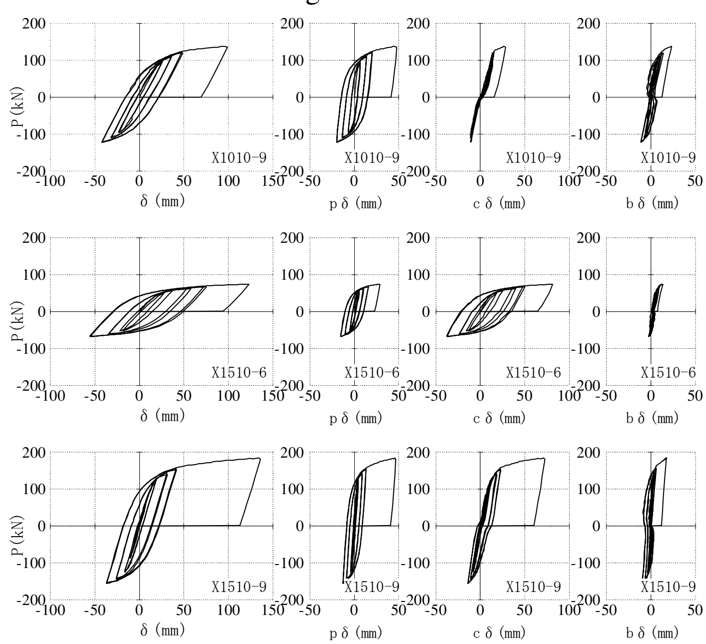

Fig.4.1 Load-deformation relations of each member

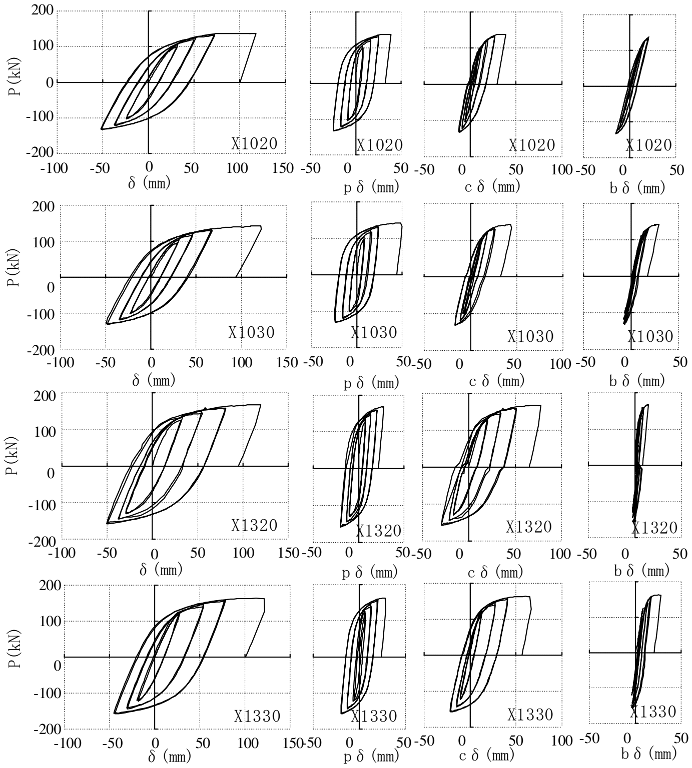

Fig.4.2 Load-deformation relations of each member

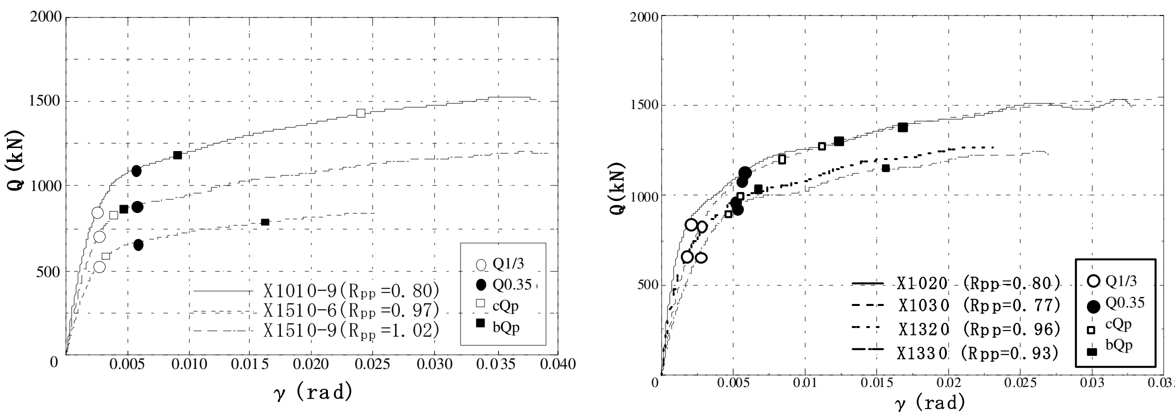

Fig.5 Skeleton curves for panel shear force-shear strain relations

Experimental and analytical strength of each member

In all specimens local buckling of the column flange is recognized after the formation of the plastic hinge. The horizontal load corresponding to experimental and analytical strengths of each member are listed in Tab.3. In this table subscripts b, c and p indicate beam, column and panel, y and p indicate yield and plastic. Three analytical plastic strengths of the panel are compared with experimental one in Fig.6. Q_{pp} is the plastic strength obtained by eq.(1). It estimates the experimental strength well. In Japan they have two other analytical evaluation methods which are recommended in LSD[2] and Recommendation of Plastic Design of Steel Structures[3]. In Fig.6 these are called Q_{pL} and Q_{ps}, respectively. Q_{pL} neglects the interaction with bending moment, which overestimates the experimental plastic strength $Q_{0.35\%}$ very much. Q_{ps} considers the interaction with face moment of the column ${}_{c}M$, which underestimates $Q_{0.35\%}$. Simplified equation (2) is compared with eq.(1) in Tab.4, which suggests simplified equation (2) is effective for the column axial force under 0.3Ny. Table 5 shows analytical and experimental yield strength of the panel.

Table 3 Experimental and analytical strength of each member

Specimen	Experimental						Analytical						Exp./Analytical					
	${}_{p}P^{e}{}_{y}$ (kN)	${}_{p}P^{e}{}_{p}$ (kN)	${}_{c}P^{e}{}_{y}$ (kN)	${}_{c}P^{e}{}_{p}$ (kN)	${}_{b}P^{e}{}_{y}$ (kN)	${}_{b}P^{e}{}_{p}$ (kN)	${}_{p}P^{c}{}_{y}$ (kN)	${}_{p}P^{c}{}_{p}$ (kN)	${}_{c}P^{c}{}_{y}$ (kN)	${}_{c}P^{c}{}_{p}$ (kN)	${}_{b}P^{c}{}_{y}$ (kN)	${}_{b}P^{c}{}_{p}$ (kN)	${}_{p}P_{y}$	${}_{p}P_{p}$	${}_{c}P_{y}$	${}_{c}P_{p}$	${}_{b}P_{y}$	${}_{b}P_{p}$
X1010	77	99	119	128	102	106	62	93	77	115	125	167	1.24	1.06	1.55	1.10	0.71	0.64
X1020	78	103	94	116	117	126	61	92	60	115	125	167	1.28	1.12	1.56	1.01	0.94	0.76
X1030	76	100	93	110	115	126	59	89	53	115	125	167	1.28	1.13	1.76	0.95	0.92	0.75
X1320	89	129	111	131	95	132	78	117	64	123	171	244	1.13	1.10	1.72	1.07	0.55	0.54
X1330	88	126	97	120	120	151	76	114	56	123	171	244	1.15	1.11	1.72	0.97	0.70	0.62
X1510	47	58	47	51	64	69	34	51	34	53	141	162	1.38	1.14	1.38	0.96	0.45	0.43
X1510	110	137	112	127	127	133	87	131	84	128	243	283	1.26	1.05	1.33	0.99	0.52	0.47

Note ${}_{p}P^{e}{}_{y}$: experimental yield load corresponding to $Q_{1/3}$. ${}_{c}P^{e}{}_{y}$, ${}_{b}P^{e}{}_{y}$: experimental yield load of the column and beam. ${}_{p}P_{pe}$: experimental plastic load corresponding to $Q_{0.35\%}$, ${}_{c}P_{pe}$, ${}_{b}P_{pe}$: experimental plastic load of the column and beam. ${}_{p}P_{pc}$: analytical plastic load corresponding to eq.(1), ${}_{p}P_{yc} = {}_{p}P_{pc}/1.5$ and ${}_{c}P_{pc}$, ${}_{b}P_{pc}$: analytical plastic load of columns and beams according to AIJ[3].

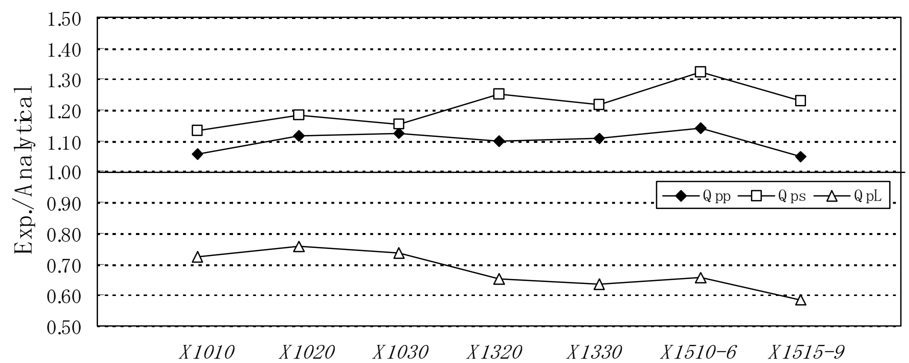

Fig.6 Analytical strength of the panel

Tab.4 Q_{pp} obtained by eqs.(1) and (2)

Specimen	N/Ny	Analytical		Q_{pp} (1)/Q_{pp} (2)
		Q_{pp} (1) (kN)	Q_{pp} (2) (kN)	
X1010	0.1	1006	982	1.02
X1020	0.2	1006	982	1.02
X1030	0.3	973	982	0.99
X1320	0.2	883	875	1.01
X1330	0.3	855	875	0.98
X1510-6	0.1	570	553	1.03
X1510-9	0.1	829	821	1.01

Tab.5 Yield strengths of the panel

Specimen	Exp.	Analytical	Exp./Analytical
	$Q_{1/3}$ (kN)	Q_{py} (kN)	$Q_{1/3}/Q_{py}$
X1010	839	679	1.24
X1020	850	671	1.27
X1030	832	648	1.28
X1320	666	589	1.13
X1330	659	570	1.16
X1510-6	530	385	1.38
X1510-9	704	559	1.26

Panel Yield Percentage(PYP)

Rosett strain gauges are pasted in the panel to know the yielding of each point. PYP is defined by eq.(3), which is derived from von Mises yield criterion.

$$PYP(\%) = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 + 3\tau_{12}^2} / \sigma_y \qquad (3)$$

, where suffixes 1, 2 and y indicate two axes of the rosset gauges and yield stress. Figure 7 shows the positions of rosett gauges. When PYP reaches 100%, it suggests the point of the rosett gauge yields. Figures 8 show the change of PYP against panel shear force Q. Initial yield starts from gauge No.4 and 5, where bending stress is larger than other measuring points. Figure 8 suggests that yield of gauge No.5 mostly agrees with Q_{py}. Equation (1) adopted $2_cM/3$ as a representative bending moment in the panel and derived Q_{pp}, where $2_cM/3$ is the value at the centroid of the bending moment distribution in the panel. Rosett gauges No.6 to 10 are pasted at this section. Figure 8 also shows that almost all gauges at this section are yielded at $Q_{0.35\%}$. This suggests that it is reasonable to derive Q_{pp} from $2_cM/3$.

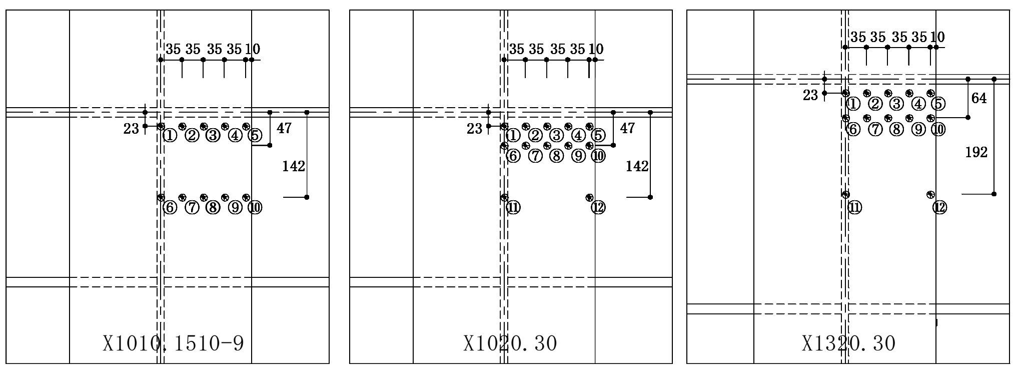

Fig.7 Position of rosett strain gauges

CONCLUSIONS

According to experimental and analytical study following conclusions are derived.

(1) Analytical plastic strength of the panel, eq.(1), gives good approximation of the experimental results.
(2) Simplified equation (2) derived from eq.(1) is effective for the column axial force under 0.3Ny.
(3) Yield strength of the panel is given by Q_{pp} /1.5, which mostly agrees with yield of gauge No.5.

REFERENCES

1. AIJ: Recommendation for Design of Connections in Steel Structures, 2001.11
2. AIJ: Recommendation for Limit State Design of Steel Structures, 2002.9
3. AIJ: Recommendation of Plastic Design of Steel Structures, 1975.11
4. M. Nakao and H. Osano: A study on the behaviour of weak axis H-column to strong axis H-beam connection panel, A paper for Annual meeting of AIJ, 1981.9, pp2005-2006
5. S. Ito, H. Okamoto, and H. Kamura: Yield Strength of Beam-to-Column Joint Panel of Hollow Sections, AIJ Journal of Technology and Design, No. 1, 1995.12, pp173-178

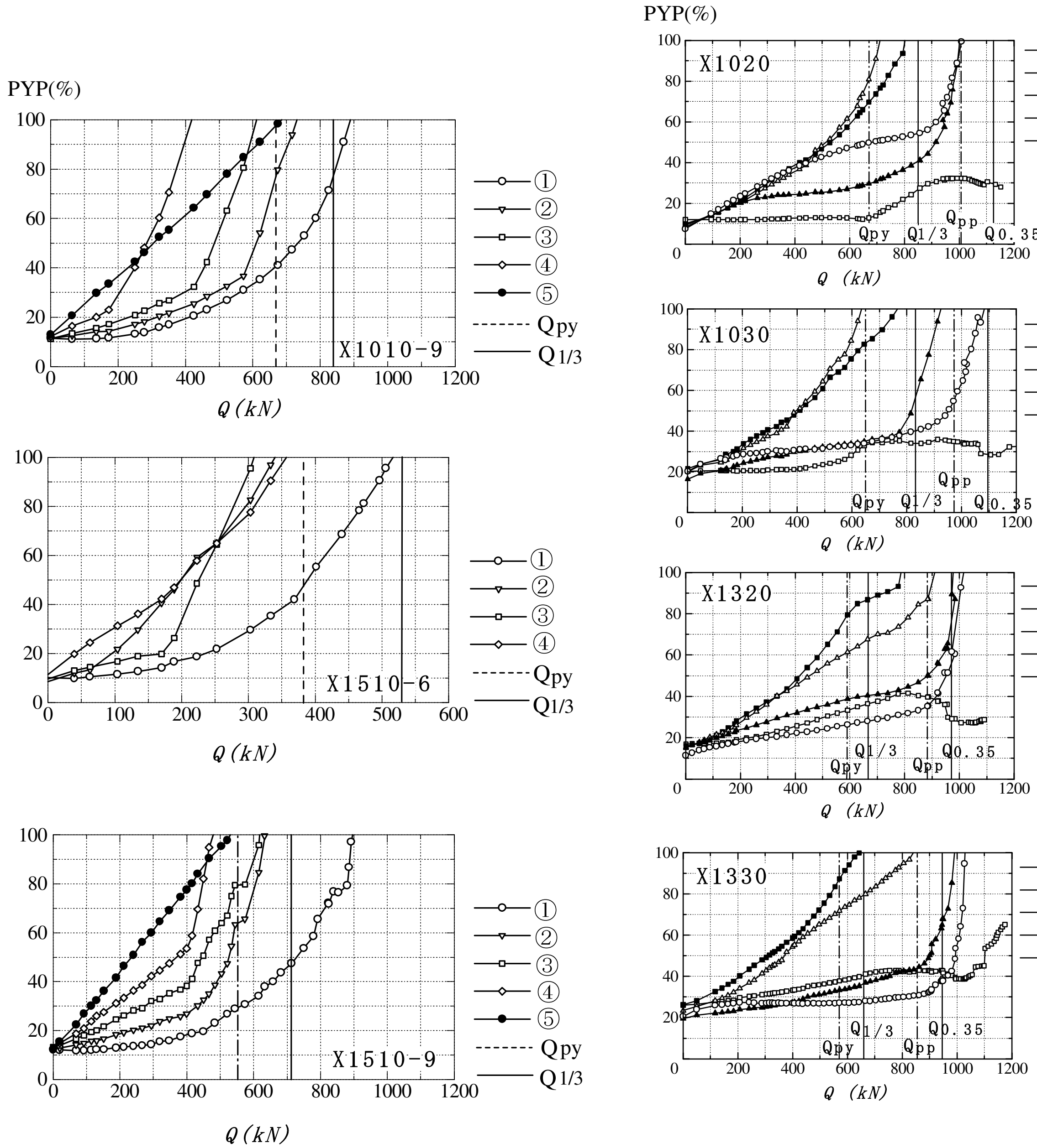

Fig.8 Panel yield percentage