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Application Technology of NSHYPER BEAM™

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Abstract

This report presents application technologies taking advantage of the features of NSHYPER BEAM™: slender-web cross-sections and narrow-width cross-sections. A slender web cross section and a narrow-width cross section are cross-sections with rational economics as they can meet the performance required for a beam, maintaining their minimum weight. However, it is necessary for them to cope with local buckling and lateral torsional buckling. To solve these problems, "Design and construction method for steel beams with stiffened slender web" and "Innovative lateral torsional buckling design method for composite steel beams" are presented. "Design and construction method for steel beams with stiffened slender web" is a newly developed technology applied for slender web cross-sections that ensures deformation performance by restraining premature web local buckling by light stiffeners at beam ends. "Innovative lateral torsional buckling design method for composite steel beams" is an application technology to narrow-width cross-sections. The design method allows lateral stiffeners to be omitted provided that certain conditions are met in accordance with a newly created proof stress formula with high precision, which considers the constraining effect from horizontal displacement of the upper flange of the beam given by the constraining effect of the floor slab. A design with rational economics can be realized by taking advantage of these technologies. These technologies have been assessed by the designated performance evaluation organization, and the application results are steadily on the rise.

1. Introduction

NSHYPER BEAM™ is the hot-rolled H-shape having a uniform outer dimension. Production began in 1989 and since then, quantity of production has been accumulated. The features are as follows:

(1) Wide cross-sectional size variation range of up to a beam height of 1 000 mm and a beam width of 400 mm (NSHYPER BEAM: 609 sizes, constant inside web height H-shapes of JIS: 35 sizes (narrow-width and medium width sizes)
(2) Reduction in number of diaphragms at a column-beam connection owing to the unified beam height
(3) Excellent dimensional, shape accuracies, and so on conforming to the "Japanese Architectural Standard Specification JASS 6 Steel Work". [1)]

Further, when beam members with different thickness are joined to a column, as compared with the constant inside web height H-shapes of JIS, NSHYPER BEAM having a constant outside web height has the advantage of reducing the thickness of the reinforcing plate (diaphragm) (**Fig. 1**).

As for the steel material strength class, in addition to 400 N/mm^2 class and 490 N/mm^2 class of JIS, made available is the NSYP345 in which the yield strength is enhanced for SN490B of JIS (490 N/mm^2 class) to improve the design standard strength F value while the tensile strength and other items of the standard are made to remain same with those of SN490B as shown in **Table 1**.

Thus, owing to the rich variety of cross-sectional sizes and strength class, NSHYPER BEAM has accumulated actual produc-

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tion amount and has obtained high reliability from customers as merchandize to be used as beam members of steel frames. On the other hand, in recent years, as demand for rationalization of cost from customers is growing increasingly stronger, rationally economical construction methods with use of NSHYPER BEAM by further exploiting such features are being sought after.

This report introduces the application technology that makes the best use of the features of NSHYPER BEAM and thereby contributes to the rationalization of cost.

2. Problem in NSHYPER BEAM Application Technology

2.1 Effectiveness of slender web cross section and narrow-width cross section

A cross section excellent in weight efficiency vs. a bending moment is the section with web thickness made thin to the extent possible. In **Fig. 2**, the relationship between the slenderness ratio d/t_w, and the aspect ratio H/B of NSHYPER BEAM is shown. In the figure, values of constant inside web height H-shapes of JIS are also shown. Slenderness ratio d/t_w is defined as the ratio of inside web height of a beam to web thickness and the higher the ratio is, the relatively thinner the web thickness becomes. The aspect ratio is defined as the ratio of beam height vs. flange width and it means that the higher the ratio becomes, the narrower the cross section becomes. From the figure, a trend is found that the higher the slenderness ratio becomes, the narrower the cross section becomes and it is known that NSHYPER BEAM has cross-sectional sizes excellent in weight efficiency with the slenderer web and the narrower width as compared with the constant inside web height H-shapes of JIS (conventional H-shapes).

Table 2 shows an example of comparisons of slender web cross-sections of NSHYPER BEAM and the conventional H-shapes. NSHYPER BEAM has cross-sectional areas less by about 10%–25% than those of the conventional H-shapes for the equal section modulus Z and moment of inertia of area I. Thus, NSHYPER BEAM has shapes excellent in weight efficiency and rationally economical designing becomes possible by selecting shapes appropriately. Furthermore, when NSYP345 is employed, since the F value is higher than that of SN490B by 20 N/mm^2, the steel material weight can be saved by about 5% proportionally to the enhancement of the F value. With combined use with the steel grade, effectiveness in use of NSHYPER BEAM is further enhanced.

2.2 Problem in application technology

As shown in Section 2.1, although rationally economical shapes and steel grade are provided in NSHYPER BEAM, from the viewpoint of structure mechanics, occurrence of local buckling due to slender web and lateral buckling due to narrow-width at an early stage are concerned about (**Photo 1**). For instance, in case of NSHYPER BEAM in Table 2, because of the slenderness ratio, the beam is classified to FD rank in the classification of member material specified by building standards act notice, therefore judged as poor in strength to deformation and not usable ordinarily as beam member material. Furthermore, as the flange width is 200 mm and the buckling strength around the weak axis is lowered, arrangement of lateral braces more in number than that of conventional cases is necessitated. Below, as countermeasures to solve such problems in application technology, "Design and construction method for steel

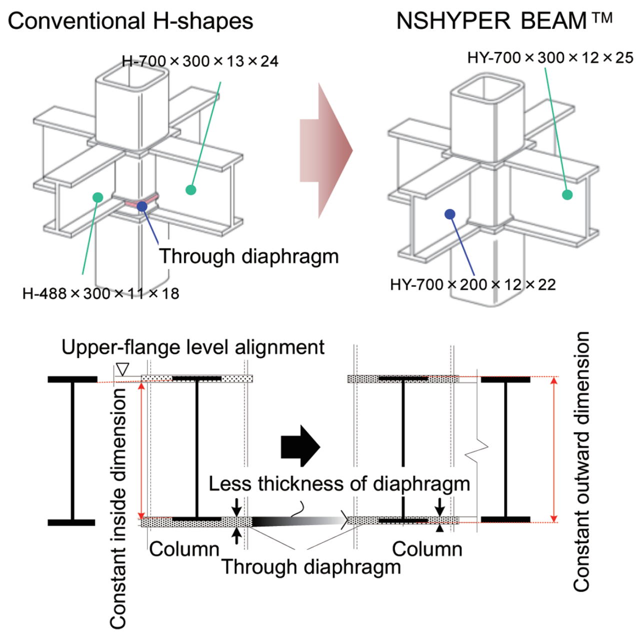


Fig. 1 Features of NSHYPER BEAM™

Table 1 Mechanical properties of NSYP345B

Steel	Yield strength (N/mm^2)	Range of yield strength (N/mm^2)	Range of tensile strength (N/mm^2)	Range of yield ratio (%)
NSYP345B	345	345–465	490–610	≤ 80
SN490B	325	325–445	490–610	≤ 80

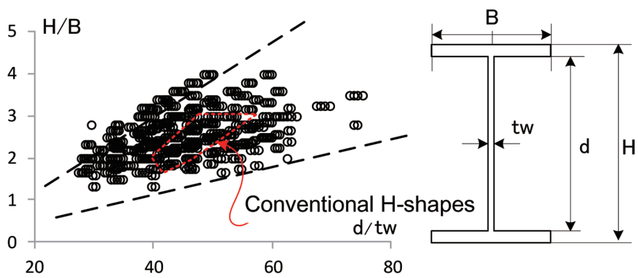


Fig. 2 Aspect ratio and web-thickness ratio of NSHYPER BEAM

Table 2 Comparison of NSHYPER BEAM with conventional H-shapes

Equivalent value	Cross-sectional size		d/t_w	H/B	Ratio of A	Ratio of I or Z
Z	HY	700 × 200 × 9 × 22	72.9	3.5	0.89	1.05
	H	582 × 300 × 12 × 17	45.7	1.9	1.00	1.00
I	HY	700 × 200 × 9 × 19	73.6	3.5	0.74	0.99
	H	588 × 300 × 12 × 20	45.1	2.0	1.00	1.00

HY: NSHYPER BEAM, H: Conventional H-shapes, Z: Section modulus, I: Moment of inertia of area, A: Cross-section

(a)Local buckling (b)Lateral buckling

Photo 1 Example of buckling mode

beams with stiffened slender web" and "Innovative lateral torsional buckling design method for composite steel beams" are introduced.

3. "Design and Construction Method for Steel Beams with Stiffened Slender Web" to Enhance Deformation Capacity of Slender Web Cross-sectional Beam

The practical design method and the construction method to apply slender web cross section NSHYPER BEAM to beams of structural constructions have been established and, in December 2012, the general rating of the Building Center of Japan (a general incorporated foundation) was obtained.

3.1 Beam-end stiffener detail

In the architectural constructions of a seismic structure, a capacity of absorbing seismic energy by plastic deformation of the beam end is sought after. This method is intended to enhance the deformability of the beam end by stiffening the slender web with stiffener plates that can realize reduction in beam weight and secure a seismic performance simultaneously. As a construction method of arranging stiffeners to suppress local buckling and shear buckling effectively, in this method, a lattice type stiffener is employed in which a vertical stiffener is arranged at the front end of the horizontal stiffener (**Photo 2**, **Fig. 3**). In this method, by preventing the early occurrence of web buckling by the stiffeners, beams can be selected and determined depending on the slenderness ratio of flange, not the ratio of web (**Table 3**).

3.2 Design of the stiffener plates

In order to prevent the deterioration of the strength due to local buckling or shear buckling before the beam end yields and exerts deformability, stiffener cross section needs to be designed taking into consideration the influence of unavoidable imperfections, variation of yield strength of steel material, welding residual stress, and so on. To cope with these, in the method, based on the results of tests and analysis, moment of inertia of area of the stiffener I_h is prescribed so that the calculated elastic values of local buckling stress intensity and the shear buckling stress intensity of the stiffened web become two times or higher than the compression yield stress intensity and the shear yield stress intensity of the web (**Fig. 4**).

Namely,

$$\sigma_{cr} = \frac{4+\xi}{1+\xi}\,\frac{\pi^2 E}{12\,(1-\nu^2)}\left\{\frac{t_w}{d}\right\}^2 \geq 2F \tag{1}$$

$$\tau_{cr} = \left\{9.34 + 2\sqrt{\frac{4}{3}\xi}\right\}\frac{\pi^2 E}{12\,(1-\nu^2)}\left\{\frac{t_w}{d}\right\}^2 \geq 2\,\frac{F}{\sqrt{3}} \tag{2}$$

$$\xi = \frac{I_h}{I_0}\,,\quad \zeta = 2\,\frac{t_h \cdot b_s}{t_w \cdot d}\,,\quad I_0 = \frac{t_w^3 \cdot d}{24\,(1-\nu^2)} \tag{3, 4, 5}$$

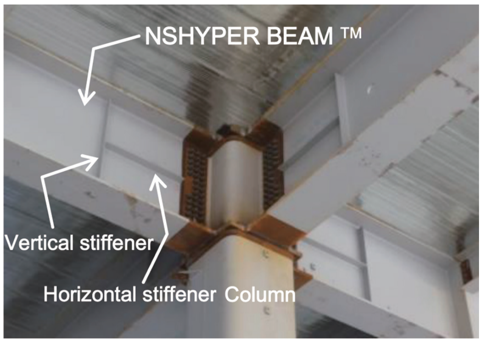


Photo 2 Application of stiffened beam-end web construction method

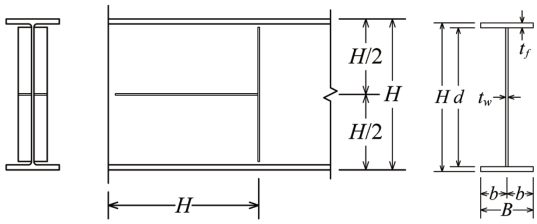
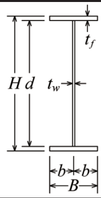
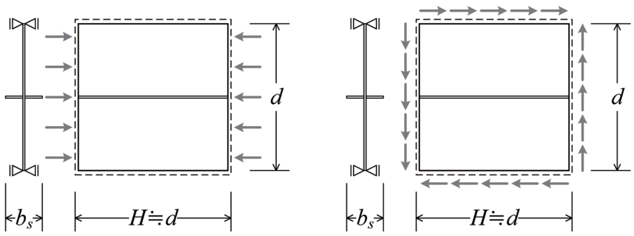


Fig. 3 Beam-end web stiffener

Table 3 Classification of a beam with beam-end web stiffener

Division	Width-thickness ratio		Classification	
	Flange b/t_f	Web d/t_w		
I	$\leq 9\sqrt{235/F}$	$\leq 84\sqrt{235/F}$	FA	
II	$\leq 11\sqrt{235/F}$		FB	



(a) $\sigma_{cr} \geq 2F$ (b) $\tau_{cr} \geq 2F/\sqrt{3}$

Fig. 4 Design criterion of beam-end web stiffener

$$I_h = E\,\frac{t_h \cdot b_s^3}{12} \tag{6}$$

where

σ_{cr}: Local buckling stress intensity of the stiffener reinforced web
τ_{cr}: Shear buckling stress intensity of the stiffener reinforced web
F: Standard strength of the web material strength
E: Young's modulus of steel material (= 205 000 MPa)
ν: Poisson's ratio (= 0.3)
b_s: Width of stiffener
t_h: Thickness of stiffener
t_w: Thickness of web
d: Distance between the thickness centers of upper and lower flanges

Furthermore, the cross-sectional area of the stiffener obtained with the above designing is small and practically stiffeners made of a flat bar PL-9×75 (SS400) are used for all sizes of NSHYPER BEAM of slender web cross section.

3.3 Welding test

When welding a stiffener plate to a slender web, deformation in cross-sectional shape of the beam due to welding heat is concerned about. For this reason, a welding test was conducted using slender web cross section NSHYPER BEAM of HY-1 000×400×16×32 (**Photo 3**). In the test, stiffener plates (flat bars: PL-9×75) were fillet-welded with leg length of 7 mm to the web and the effect of welding heat strain was measured studied by measuring the cross-sectional shape of the beam before and after the welding. After confirming that the bending of the web was suppressed by welding after clamping the web end with angle steel, and that the beam cross-sectional shape after welding complies with the control tolerance specified in the "Japanese Architectural Standard Specification JASS 6 Steel Work" [1] (**Table 4**), the result of the test has been arranged as welding operation procedures of the method.

3.4 Beam bending test

The deformability of the beam end determined by local buckling is known to be influenced by imperfections, welding residual stress, and so on. For this reason, a beam bending test was conducted, using slender web cross section NSHYPER BEAM of HY-1 000×400×16×32 (SN490B). A flat bar of PL-9×75 (SS400) was used for the stiffener plates that were welded to the web of the specimen under the same welding condition with the one adopted in the welding operation test stated in the foregoing section. In the test, both ends of the test piece were supported by pin rollers and the monotonic loading was applied in the manner of monotone force application of concentrated load to the center position of the specimen with an oil jack (**Fig. 5**).

3.5 Test result

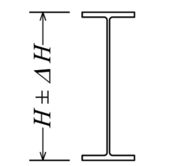
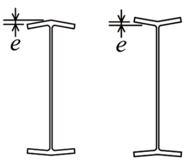
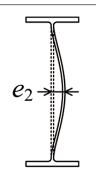
In **Fig. 6**, the relationship between the beam-end moment and rotation angle of the specimen obtained as a result of the test and in **Photo 4**, deformation after the experiment is shown, respectively. Maximum strength is determined when the local buckling at the beam end becomes apparent in the experiment. After the local buckling of the web between the flange and the horizontal stiffener plate is confirmed after the yielding of the beam end, the local buckling of the flange was developed and the buckling of the entire web is stopped by the stiffener.

As shown in **Table 5**, η_{max}, the plastic ductility ratio, calculated from the rotation angle at the maximum strength point in the test exceeds the aimed performance of 6.0 and steady load-deformation relation without rapid drop of strength even after the maximum strength are obtained.

(a) Before welding (b) After welding (c) Enlarged view

Photo 3 Full-scale welding test of beam-end stiffener

Table 4 Actual dimension of the specimen after welding (unit: mm)

Measurement items		Measured value	Tolerance (JASS6 [1])
Height ΔH		1.1	≤ 3.0
Squareness e		0.6	≤ 3.0
Turning e_2		1.7	≤ 4.0

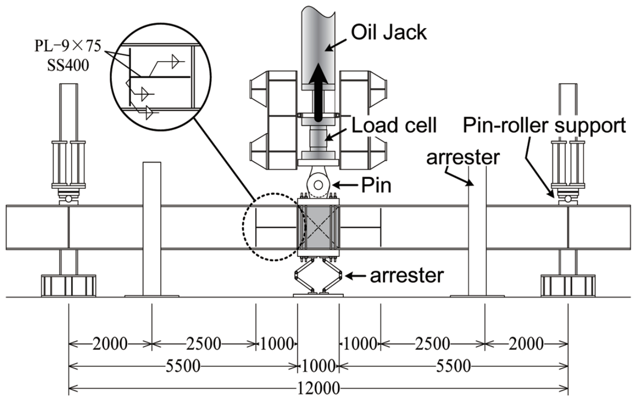


Fig. 5 Test setup of the full-scale beam bending test

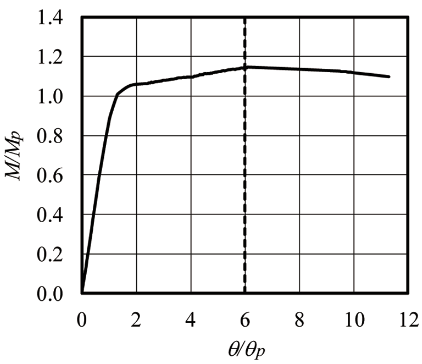


Fig. 6 Beam-end moment-rotation relationship

Photo 4 Deformation of specimen after the test

Table 5 Results of the full-scale beam bending test

Cross-sectional dimensions (steel)	Maximum load	Plastic ductility ratio	Failure mode
	M_{max}/M_p	η_{max}	
HY-1 000 × 400 × 16 × 32 (SN490B)	1.15	6.1	Local buckling

M_{max}: Maximum load, M_p: Full plastic moment
η_{max}: Plastic ductility ratio $\eta_{max} = \theta_{max}/\theta_p - 1$
θ_{max}: Deformation capacity of maximum load
θ_p: Deformation of full plastic moment

4. "Innovative Lateral Torsional Buckling Design Method for Composite Steel Beams" for Narrow-width Cross-sectional Beam

"Innovative lateral torsional buckling design method for composite steel beams" is a method that enhances narrow-width NSHYPER BEAM usability, and the Architectural technology performance certificate of the General Building Research Corporation of Japan (a general incorporated association) was obtained in July 2014.

4.1 Innovative lateral torsional buckling design method

In case of a steel structural beam with floor slab installed thereon and fixed thereto with share connecters (headed stud), lateral buckling strength is enhanced by the restrained lateral displacement of the upper flange. Then, in the method, taking into consideration the restraining effect, the following new formula of M_e of elastic lateral buckling strength has been developed for an H-shaped beam of which both ends are rigidly connected to columns, being exerted upon by double curvature bending moment.

$$M_e = 3.1\frac{4\pi^2 EI_f}{l^2}d_b + \frac{GJ}{d_b}\left(1 + 17\sqrt{\frac{EI_f}{GJ}}\frac{d_b}{l}\right) \qquad (7)$$

where
E: Young's modulus of the steel material
G: Shear modulus
I_f: Second moment of area of flange ($= t_f \cdot B^3/12$)
J: Saint-Venant's torsion constant of H-shaped cross section
l: Length of beam
d_b: Distance between the upper and lower flange thickness centers

Formula (7) is an approximate expression of the elastic lateral buckling strength (analytical solution) developed based on the assumption of the buckling mode as shown in **Fig. 7** for the case where bending moments and shearing forces are working on the both ends of a beam, of which lateral displacement of the upper flange being restrained and each of either of the forces and the moments working in adverse direction to each other.

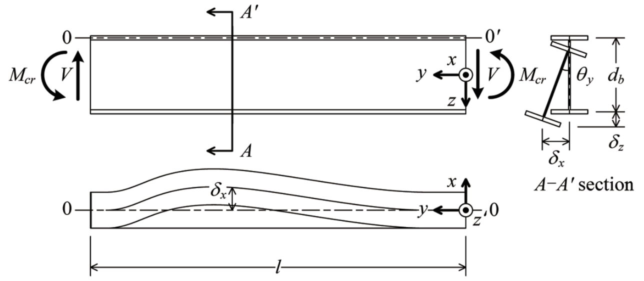


Fig. 7 Lateral buckling mode of H-shaped beam restrained side-sway displacement of top flange

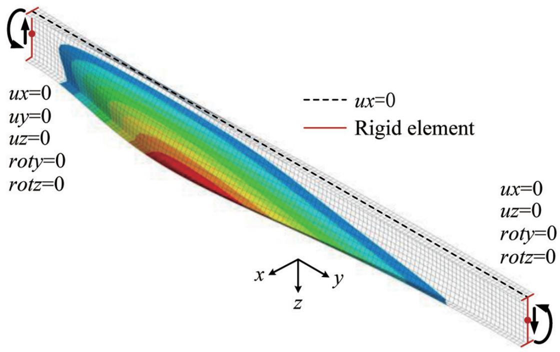


Fig. 8 Result of finite element linear buckling analysis

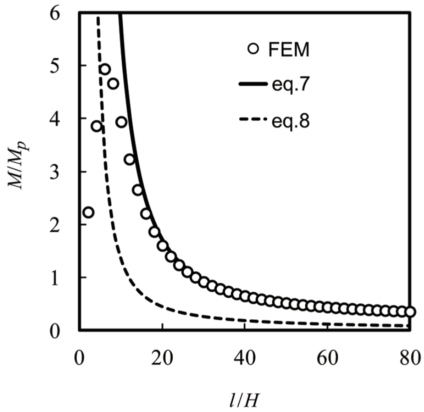


Fig. 9 M/M_p - l/H relationships

In order to verify Formula (7), elastic buckling analysis by means of FEM was conducted (**Fig. 8**). In the analysis, the relationship between the elastic lateral buckling strength and the beam length has been studied for a narrow-width cross section NSHYPER BEAM of HY-700×200×12×22 for the case of the lateral displacement of the upper flange being restrained. As **Fig. 9** shows, as opposed to the assessment result on safe side provided by the conventional elastic lateral buckling strength formula (Steel Structure Limit State Design Guideline, Formula (8))[2)] that does not take into account the restraining effect rendered by the floor slab, Formula (7) follows with high accuracies the result of the analysis with FEM.

$$M_e = 2.3\sqrt{\frac{\pi^4 E^2 I_y I_W}{(0.75l)^4} + \frac{\pi^2 EI_y GJ}{l^2}} \qquad (8)$$

where

I_y: Second moment of area of cross section of beam around weak axis

I_w: Wagner's torsion bending rigidity

4.2 Proposal of new lateral buckling curve

Due to the influence of imperfections, residual stress and so on, it is known that the actual lateral buckling strength of a beam exhibits its nonlinear behavior from the neighborhood of $M_e/M_p = 0.6$ and falls below the elastic buckling curve. Furthermore, in the method, through the tests and numerical analysis, it is confirmed that the beam endcan reach full plastic moment without developing lateral buckling in the below 0.6 range of λ_b. Based on these, the buckling curve shown in **Fig. 10** is adopted as ultimate strength for designing. In the figure, λ_b is defined by the following formula. It is meant that the smaller the λ_b is, the higher the lateral buckling strength of a beam and the plastic deformability become.

$$\lambda_b = \sqrt{M_p / M_e} \quad (9)$$

where M_p represents the entire plastic bending strength of a beam.

In Fig. 10, the result of elasto-plasticity analysis by FEM is shown. The analysis shows the result of study on the relationship between λ_b and deformability of a beam studied for narrow-width cross section NSHYPER BEAM of HY-700×200×12×22 (SN490B). The shorter a beam length becomes, the smaller λ_b becomes, and along with, beam deformability is improved. In this construction method, $\lambda_b \leq 0.45$ is set to secure the aimed performance of plastic ductility ratio of over 4.0 and $\lambda_b \leq 0.60$ is set to secure the aimed performance of plastic ductility ratio of over 2.0, respectively. In the figure, buckling curve specified in the past steel structure limit state design guideline is also shown. In the new buckling curve, the upper limit value of the slenderness ratio for $M/M_p = 1$ (M: lateral buckling strength) is about two times of the conventional value, and economically rational designing has become possible.

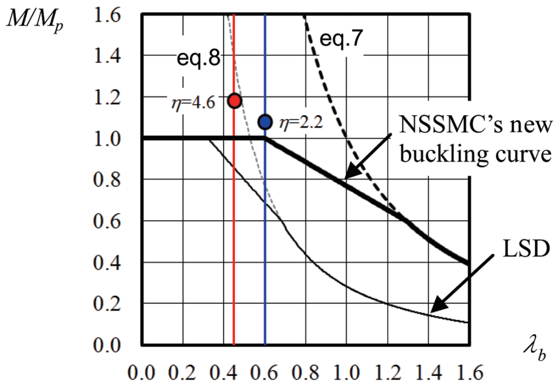


Fig. 10 New design curve of lateral buckling

4.3 Loading tests on beam-column assemblies

To confirm the restraining effect of floor slab on upper flange of a beam, loading tests on beam-column assemblies with floor slab were conducted. The specimens were 1/2 scale model and a welded built-up H-shape of BH-500×150×9×12 (SN490B) was used for the each specimens (**Table 6**, **Fig. 11**). The floor slab was RC slab of 70 mm in thickness with flat deck (molding deck) and weld-meshed metal nets (6 mmϕ-@100) arranged in up and down two stages. The headed stud share connecter for the floor slab on the upper flange was 10 mm in diameter and 50 mm in length and 27 pieces were arranged on the upper flange of the beam at the separation of 200 mm. Concrete of ordinary quality (aimed strength of 18 N/mm^2) was used.

The column heads and the column feet are pin-supported and each of the column heads is connected to an oil jack installed horizontally via a load cell. The pin-supported column foot on one side is supported by horizontal rollers below the column foot and connected to a load cell. A pantograph is installed to each column to restrain the deformation of the column to outside of the experiment sphere. Proper horizontal loading is supplied by controlling the oil jacks so that the angles of deformation of the left side and the right side columns become equal. Horizontal loading was applied in a single direction (compressing direction of the jack) after two cycles

Table 6 Specimens description

Mark	Cross-sectional dimensions (steel type)	λ_b	Floor slab
No. 1	BH-500 × 150 × 9 × 32 (SN490B)	1.03	Non
No. 2		0.55	RC

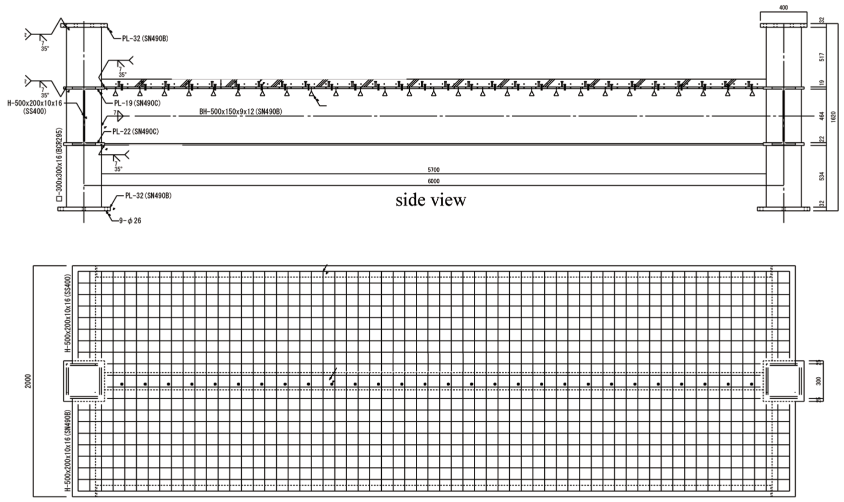


Fig. 11 Specimens

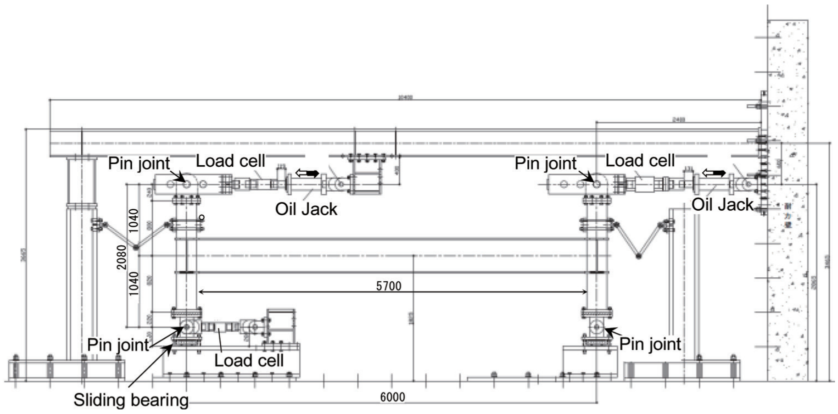
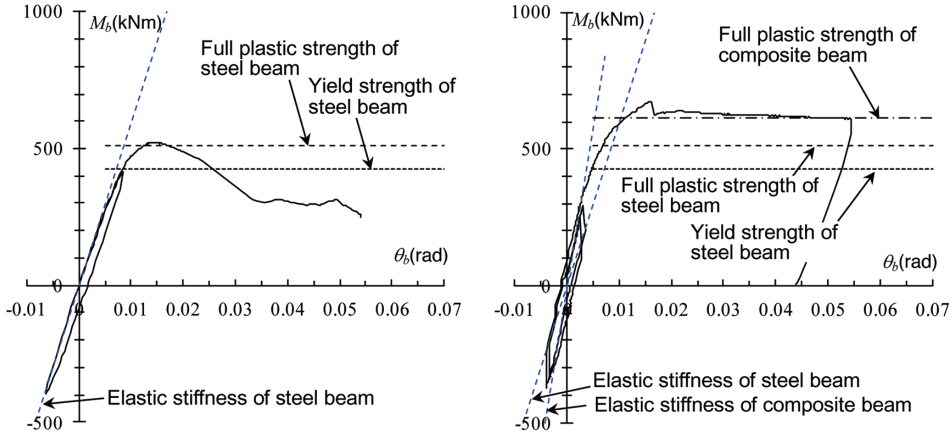


Fig. 12 Test setup of half-scale frame test



(a) No.1 (b) No.2

Fig. 13 Beam-end moment-rotation relationship

(a) No.1 (b) No.2

Photo 5 Deformation of specimens after the test

within an elastic range had been repeated (**Fig. 12**).

4.4 Test results

In **Fig. 13**, the relationships between the beam-end bending moment and rotation angle of the specimens and, in **Photo 5**, the condition of fracture of the specimens are shown respectively. In case of No. 1 without floor slab, lateral buckling is dominant and in No. 2 with floor slab, local buckling near the beam end becomes dominant and the maximum strength in the experiment is determined thereby. As opposed to the case of No. 1 without floor slab where rapid deterioration in strength accompanied by the lateral deflection of upper and lower flanges was developed right after the beam end reached the entire plastic bending moment strength, in the case of No. 2 with floor slab, steady load deformation curve is demonstrated.

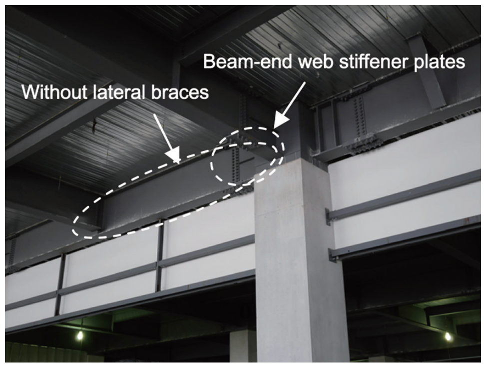


Photo 6 Application example

5. Effect of the Application Technology

Actual examples of the application technology are shown. The subject building is four-storied with RC column and steel beam structure and is a logistic warehouse of floor space of 40000 m^2 in total (**Photo 6**). In **Table 7**, cross-sectional dimension of the large beam and in **Fig. 14**, basic planar grid plan is shown. For the large cross-sectional beam, slender web, narrow-width cross section NSYP345 is used. By applying the "design and construction method for steel beams with stiffened slender web," steel weight saving by more than 10% has been realized. Furthermore, as to the large cross-

Table 7 Cross-sectional dimension of beams

Direction		Cross-sectional dimension	d/t_w	Steel type	Weight ratio*
X	Alternative	HY900×250×14×19	61.6	NSYP345B	0.88
	Original	H-900×250×16×22	53.5	SM490A	1.00
Y	Alternative	HY900×250×16×22	53.5	NSYP345B	0.84
	Original	H-900×300×19×22	45.1	SM490A	1.00

* Ratio of alternative beam weight to original beam weight.
Lateral stiffener omission construction method is applied to Y-direction beam and stiffened beam-end web construction method is applied to X-direction beam.

sectional beam on the X structure plane, it was confirmed that lateral braces were made unnecessary up to the inner beam span length of 10.9 m by applying the "Innovative lateral torsional buckling design method for composite steel beams" and therefore lateral braces were omitted. Though it is not long since performance assessment was obtained for these technologies, applications have reached 17 in total with total amount of floor space of 630000 m^2, expanding its application results mainly in warehouse projects.

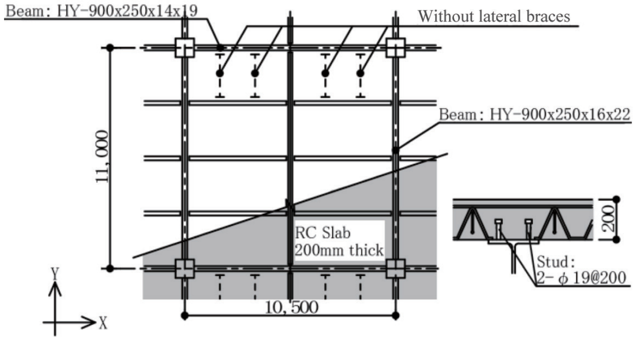


Fig. 14 Application example of the construction method

6. Conclusion

Outlines of the "design and construction method for steel beams with stiffened slender web" and the "Innovative lateral torsional buckling design method for composite steel beams" that take advantage of the features of slender web cross section and narrow-width cross section, respectively, have been introduced. With these application technologies, use of NSHYPER BEAM with greater economic rationality becomes possible. To cope with the demand for cost rationalization of building material that is growing increasingly stronger, the authors are determined to continue henceforth to further develop application technologies that take advantage of the features of NSHYPER BEAM.

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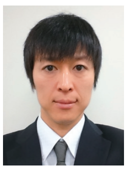
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