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Development of the structural system for thin-web steel beam reinforced with stiffener plates

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Abstract

The authors developed a structural system for steel structures in which an end of a beam is reinforced by stiffener plates. The system can retain the required plastic deformation capacities, for the entire beam with a thinner web plate, leading to reduction of the total amount of steel at the time of construction. Especially when these structural systems are applied to a high-rise building with large-sized beams, the effect of reducing the amount of steel is high by reducing the thickness of the web. Reducing the amount of steel can be expected to reduce the loads on the environment.

In this paper, the stiffening method outline is first shown, along with its design method for which the application range is extended for high strength steel (550N/mm^2 class steel). The simple stiffening method is proposed with horizontal stiffeners can improves factory manufacturability. Secondly, to confirm the plastic deformation capacity of a reinforced steel beam, a series of structural performance tests is carried out using 1/2 scale specimens. The specimens are quasi-statically loaded using displacement control loading. From the experimental results, the validity of the proposed structural system is shown. Finally, the finite element method (FEM) analysis is carried out on the specimens with proposed structural system. The effectiveness of the proposed structural system was verified by the structural performance test and FEM analysis.

Keywords: steel beam reinforced by stiffener plate, plastic deformation capability, cyclic loading test, FEM analysis

1. Introduction

For steel structures, various structural systems[1], [2] are proposed such as reducing the amount of steel by thinning large beam webs, or while the end of the beam is stiffened with a stiffener plate to ensure the required plastic deformation capacity of the entire beam. When these structural systems are applied to a high-rise building with large-sized beams, the effect of reducing the amount of steel is high by reducing the thickness of the web. However, it is still necessary to verify the applicability to the high strength steel material because the steel grade of the beam often needs to be specified as high strength steel materials. In addition, the stiffening methods are complicated with the existing construction methods, so further rationalization is possible.

This development project proposes a structural system that can be applied to high-strength steels, for which the system is streamlined by adopting a simple reinforcement method. This report first describes the outline of the proposed structural system and its design method. A structural test is conducted using a 1/2 scale specimen to verify the plastic deformation capacity of the reinforced steel beam. Regarding the specimen, high-performance 550N/mm^2 class steel for building structures is used as the specimen to verify the applicability of the proposed structural system. Furthermore, the finite element method (FEM) analysis is carried out on the specimens of structural performance test to verify the effectiveness the FEM analysis.

2. Outline of Proposed Structural System and Design Method

2.1 Outline of the Proposed Structural System

Fig. 1 shows the outline of the structural system. Although the target performance of the beam is the FA rank[3] (which means satisfying enough plastic deformation capacity) in the width-to-thickness ratio of the flange, the width-to-thickness ratio of the web is reduced so that the rank is specified as the FD rank[3] (which means not satisfying enough plastic deformation capacity). Two horizontal stiffeners are installed on one side of the web in the plasticized part at the beam end to improve the plastic deformation capacity of the web. While some of the existing similar structural systems also have vertical stiffeners and grid stiffeners, simple stiffening method with horizontal stiffeners can improves factory manufacturability.

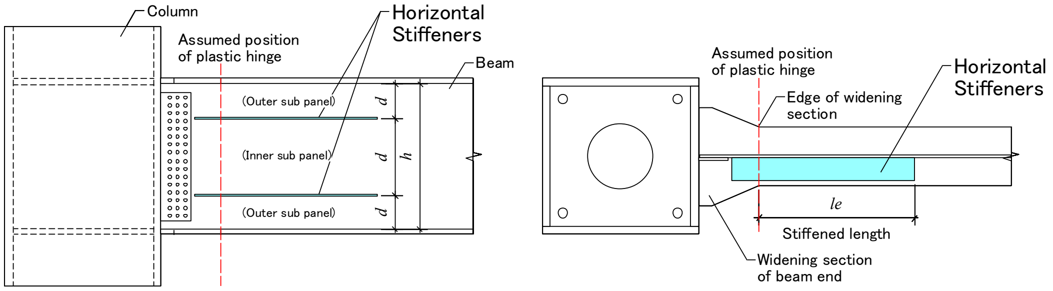


Fig. 1 – Schematic of structural system

2.2 Design Method

2.2.1 Equivalent Width-Thickness Ratio

This section explains the method to study an effective width-thickness ratio for sections (hereinafter referred to as sub panel) supported by stiffener plates to increase the rigidity of the webs. The equivalent width-thickness ratio calculation method in the previous study [2] is applied and the system is designed by applying a calculation method of the equivalent width-thickness ratio to satisfy the width-thickness ratio necessary to qualify the restrictions of the beam.

According to the previous study [2], the equivalent width-thickness ratio of the sub panel is obtained by the following formula. As shown in Fig. 2 (b), when stiffening with two stiffener plates, the equivalent width-thickness ratio is calculated for each of the divided outer subpanels and inner subpanel respectively to lead the larger ratio of the equivalent width. Therefore, width-to-thickness ratio restrictions can be evaluated based on the equivalent width-thickness ratio.

$$_{eq}\left(\frac{d}{t_w}\right)=\frac{d}{t_w}\cdot\sqrt{\frac{K_{cr}}{K'_{cr}}} \tag{1}$$

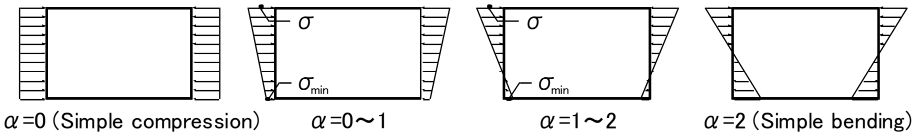
where
$$K_{cr},K'_{cr}=\frac{5.35}{\sqrt{1+\left(6\frac{Z_w}{Z_H}\cdot\frac{L}{h}\cdot\frac{5.35}{k(\alpha)}\right)^2}} \tag{2}$$

$$k(\alpha)=2.6\alpha^3-1.6\alpha^2+2.7\alpha+4 \tag{3}$$

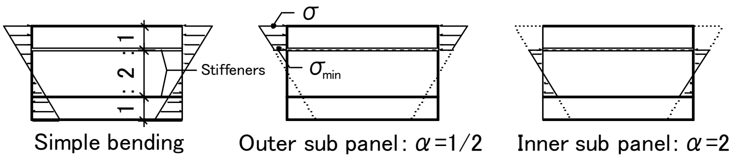
$$\alpha=1-\frac{\sigma_{min}}{\sigma} \qquad \text{(Fig. 2)} \tag{4}$$

Here,

d	: Height of subpanel	[mm]	h	: Height of web	[mm]
t_w	: Thickness of web	[mm]	L	: Length of shear span (Fig. 3)	[mm]
K_{cr}	: Buckling coefficient of non-stiffened steel		α	: Distributed coefficient of compressed stress	
K'_{cr}	: Buckling coefficient of sub panel		Z_H	: Section coefficient of H-shape beam	[mm^3]
Z_w	: Section coefficient of web	[mm^3]			



(a) α defined in AIJ Design Standard for Steel Structures [3]



(b) When the two stiffeners are in the ratio of 1:2:1

Fig. 2 – Distributed Coefficient of Compressed Stress

2.2.2 Stiffening Length of Stiffener Plate

The stiffening length by the stiffener plate is specified according to the design moment distribution of the beam. As shown in Fig. 3, it is confirmed that the local buckling limit strength M_C of the non-stiffened beam section exceeds the design moment M_D of the stiffening end. Here, the local buckling limit stress is calculated based on "The AIJ: Steel Structure Limit State Design Guidelines[4]". As for the thinned web, the local buckling limit strength is obtained by the following formula. For the design moment at the assumed plastic hinge position, the safety factor of 1.3 times the full plastic moment M_p, which is 1.2 times as the variation of the material and

1.1 times in consideration of the strain hardening, is desirable to consider. Similarly, for a web thickness that is not stiffened, a margin of shear strength is secured against a shear force equivalent to 1.3 × *Mp*.

$$M_c = {}_wF_{cr} \cdot Z_H \tag{5}$$

where

$${}_wF_{cr} = \left(5190 - 453 \cdot \frac{h}{t_w} \cdot \sqrt{\frac{F_{yw}}{E}}\right) \cdot 50 \cdot \frac{F_{yw}}{E} \tag{6}$$

Here,

M_c	: Local buckling limit stress of the web	[Nmm]	F_{yw}	: Yield strength of the webs	[N/mm^2]
${}_wF_{cr}$	: Buckling stress of the web	[N/mm^2]	E	: Young's modulus of steel	[N/mm^2]

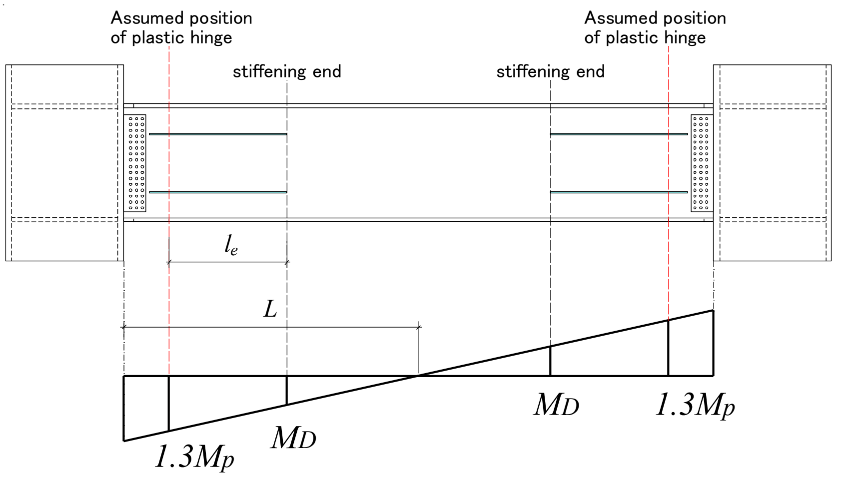


Fig. 3 – Distribution of the design moment of the beam and the stiffening length

2.2.3 Required Stiffness of Stiffener Plate

The required stiffness of the stiffener plate is studied based on “AIJ Design Standard for Steel Structures[5]”. This is to confirm that the stiffener cross-sectional secondary radius *i* (calculated with respect to the main axis in the web surface) is greater than or equal to the value obtained by the following formula.

$$\frac{i}{t_w} = C_m \cdot \{135(0.5 - \eta)^3 + 3\} \cdot \beta^{2/3} \tag{7}$$

$$C_m = 0.7 + \frac{1}{200(n+1)} \cdot \frac{i}{t_w} \cdot \frac{1}{\delta} \tag{8}$$

$$\eta = \frac{d_{min}}{h} \tag{9}$$

$$\beta = \frac{l_e}{h} \tag{10}$$

$$\delta = \frac{A_s}{h \cdot t_w} \tag{11}$$

Here,

i : Secondary radius of the cross-section of stiffeners [mm]

n : Number of stiffeners [piece]

d_{min} : Minimum height of the sub panel [mm]

A_s : Cross-section of stiffeners [mm^2]

3. Structural Performance Test

3.1 Specimens

In order to experimentally confirm the effectiveness of this structural system, a structural test is carried out using 1/2 scale specimens. Fig. 4, Table 1 and Table 2 show the specimen dimensions, the list of specimens, and the mechanical properties of the steel members respectively.

Specimen A-1 is a specimen of the standard case to which this structural system has been applied. H-576 x 216 x 9 x 19 (TMCP385B) is used for the beam. The beam end flange is widened, and the assumed position of the plastic hinge is the end of the widened portion. PL-6x84 (SM490A) is used as the horizontal stiffener, and the beam web was stiffened at a distance ratio of 1:2:1. The equivalent width-to-thickness ratio of the web is the FA rank. Specimen A-2 is a specimen that has not been stiffened. The width-to-thickness ratio of the web is the FD rank.

Specimen A-3 is a specimen in which a through hole (190.7mm in diameter) is created at a position of equal to height of beam +100 mm from the beam end. The through-hole reinforcement is with a conventional method (a backplate for reinforcement and the front plate + reinforcement pipe welding), which is designed to prevent yielding until the final state.

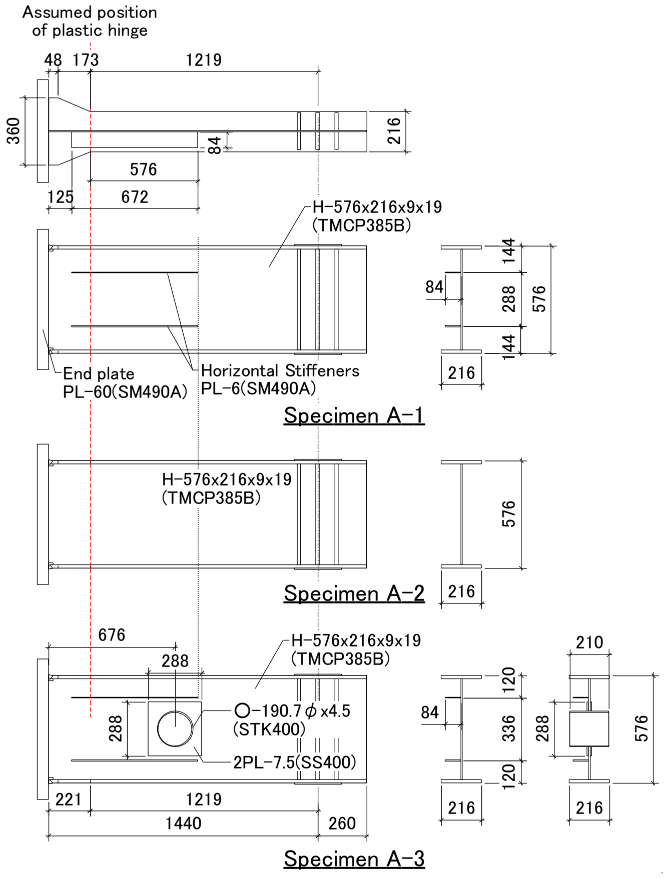


Fig. 4 – Specimen Configurations

Table 1 – Specimen List

No.	Type	Beam Section	$_{eq}(d/t_w)$	Width/Thickness Rank
A−1	Standard	Center: H−576x216x9x19 (TMCP385B) End: H−576x360x9x19 (TMCP385B)	32.0	FA
A−2	Non stiffened		59.8	FD
A−3	with a hole		32.0	FA

Table 2 – Mechanical Characteristics of Steel Members for the Test

Part	Thickness	Standard	Y.S [N/mm^2]	T.S [N/mm^2]	Elongation [%]
Beam Flange	PL−19	TMCP385B	425	568	22.7
Beam Web	PL−9	TMCP385B	435	563	20.4
Stiffener Plate	PL−6	SM490A	429	555	33.2
Hole reinforced Plate	PL−7.5	SS400	301	433	27.1
Hole reinforced Pipe	ϕ−190.7x4.5	STK400	424	559	29.4

3.2 Loading Sequence

Fig. 5 shows the loading equipment. The bottom end of the specimen is fixed, lateral force is applied to the other side of the specimen by a 2MN hydraulic jack. Adjacent to the applied point, the beam flange edge is restrained out-of-plane with a laterally stiffened beam.

Fig. 6 shows the loading program. In accordance with the loading program shown in the previous study [6], the positive and negative alternating forces are applied repeatedly and gradually. Based on the calculated angle of the plastic hinge at the assumed position of the plastic hinge (tip of widened portion) as a reference, a force is applied for one cycle at $\pm 1/2\theta_p$. After checking the elastic behavior, the load was applied for $\pm 2\theta_p$, $4\theta_p$, $6\theta_p$, $8\theta_p$ in two cycles, until the load was decreased to 90% or less of the maximum strength.

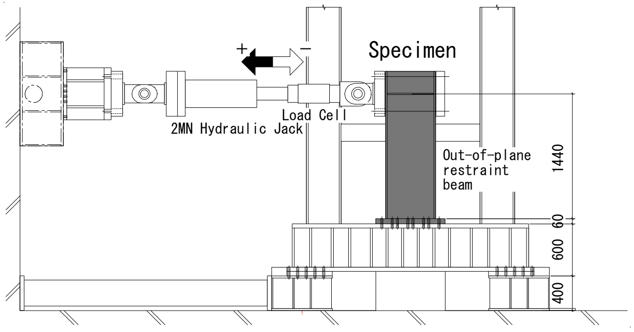


Fig. 5 – The Loading Equipment

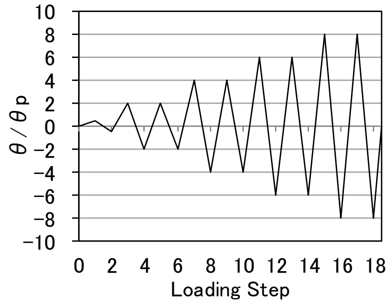


Fig. 6 – The Loading Program

3.3 Test Results

Fig. 7 shows the relationship between the beam shear force and the beam deformation angle obtained from the test. In the figure, the calculated stiffness and total plastic yield strength by beam theory are shown together with a bilinear curve (red line in the figure). Table 3 shows the test results.

For the specimens A-1 and A-3 stiffened by this structural system, the maximum strength is obtained in the first cycle of $+4\theta_p$. In the subsequent series of loading, out-of-plane deformation of the web appeared remarkably in the part where the stiffener is not installed. Eventually, the entire web, including the stiffening section, become buckled and the loading is then terminated. The ultimate strength of Specimen A-2 without stiffening reached the maximum strength during the first loading cycle of $+4\theta_p$, and out-of-plane deformation of the beam end web became outstanding at that point. With the subsequent loading, buckling progressed throughout the web, and then loading is terminated. Photo – 1 shows the deformation state in each specimen after the loading test.

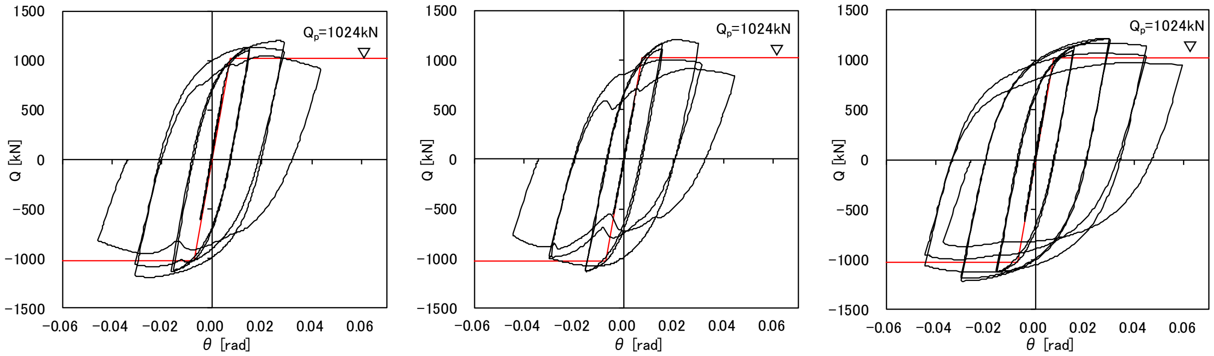


Fig. 7 – Relationship between beam shear force and angle of beam members

Table 3 – Test Results

Specimen		Initial Stiffness K [kN/rad]	Yeild Strength Q_y [kN]	Maximum Strength Q_u [kN]	Q_y/Q_p	Q_u/Q_p	Plastic Deformation Ratio $\mu_{90\%}$	μ_u	Cumulative Deformation Ratio η_A
A-1	+cycle	151203	970	1198	0.95	1.17	4.45	2.88	22.5
	−cycle	134640	−894	−1191	−0.87	−1.16	−5.27	−4.07	
A-2	+cycle	134269	990	1212	0.97	1.18	3.63	2.49	10.4
	−cycle	132750	−912	−1130	−0.89	−1.10	−4.08	−1.94	
A-3	+cycle	140459	964	1217	0.94	1.19	5.81	3.67	35.0
	−cycle	142861	−881	−1216	−0.86	−1.19	−7.42	−4.60	

3.4 Confirmation of Plastic Deformation Performance

This section is to study the plastic deformation performance of each specimen. The skeleton curve is extracted from the load deformation relationship shown in Fig. 7 to lead the plastic deformation ratio $\mu_{90\%}$, μ_u and the cumulative plastic deformation ratio η_A of the skeleton curve (Fig. 8). Here, the plastic deformation ratio $\mu_{90\%}$, μ_u and η_A are calculated using the formula (12) - (14). The "+" and "-" symbols indicate the +cycle side and -cycle side respectively in the load deformation relationship as shown in Fig. 8.

As shown in Fig. 9, regarding the specimens A-1 and A-3 stiffened by proposed method, the plastic deformation ratio $\mu_{90\%}$ in the skeleton curve exceeds the performance of 4.0 or more, which is a requirement for the beams in FA rank in design code[3]. In addition, the cumulative plastic deformation ratio improves more than about twice compared with Specimen A-2 without stiffening. The effectiveness of this structural system is confirmed.

$$\mu_{90\%+} = \frac{\theta_{90\%+}}{\theta_p} - 1,\ \mu_{90\%-} = \frac{\theta_{90\%-}}{\theta_p} - 1 \tag{12}$$

$$\mu_{u+} = \frac{\theta_{u+}}{\theta_p} - 1,\ \mu_{u-} = \frac{\theta_{u-}}{\theta_p} - 1 \tag{13}$$

$$\eta_A = \sum_{i=1}^{n_{90\%}} \left(\frac{\theta_{i+}}{\theta_p} + \frac{\theta_{i-}}{\theta_p} \right) \tag{14}$$

Here,

$\mu_{90\%+}$ $\mu_{90\%-}$	: The Plastic deformation ratio using $\theta_{90\%}$	
$\theta_{90\%+}$ $\theta_{90\%-}$	: The angle of the beam when the load drops to 90% of maximum strength after the maximum strength is reached	[rad]
μ_{u+} μ_{u-}	: The Plastic deformation ratio using θ_u	
θ_{u+} θ_{u-}	: The angle of the beam at maximum strength on the skeleton curve	[rad]
θ_p	: The angle of the beam at full plastic yield strength calculated by the beam theory	[rad]
η_A	: The angle of the beam at maximum strength on the skeleton curve	
$n_{90\%}$	: The cycle number when the load drops to 90% of maximum strength after the maximum strength is reached	[cycle]
θ_{i+} θ_{i-}	: The angle of the beam at "i" cycle loading step as shown Fig. 8	[rad]

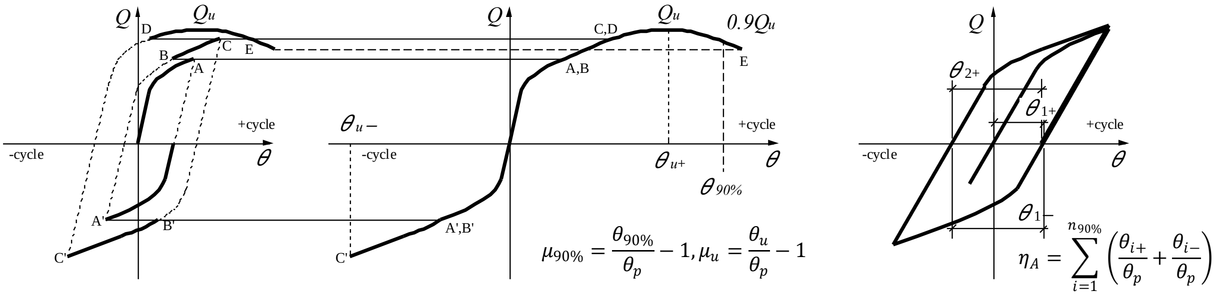


Fig. 8 – Definition of Skeleton Curve, Plastic Deformation Ratio and Cumulative Plastic Deformation Ratio

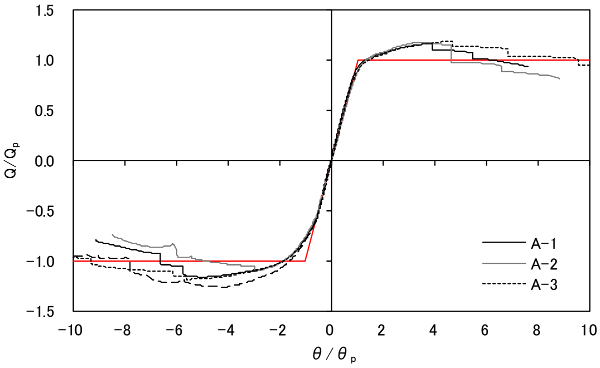


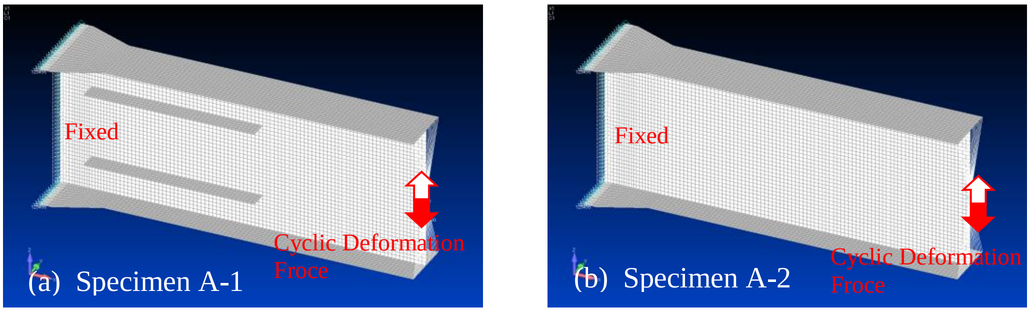
Fig. 9 – Skeleton Curve Dimensionless Using Q_p and θ_p

4. FEM Analysis

4.1 Analysis Model

To verify the effectiveness the FEM analysis, reproducibility analysis is carried out on the specimens of structural performance test. Analytical objects are specimen A-1 and A-2. The analysis mesh is illustrated in Fig. 10. Beams and stiffeners are modeled at the center of the thickness as SHELL elements.

The end plate position of specimen is fixed. And the loading position is fixed to avoid out-of-the-plane deformation, but exerting cyclic deformation for a static incremental analysis. For analysis, the nonlinear analysis and geometrical nonlinearity are considered. Fig. 11 shows the multi-linear model of the material. For the yield strength and tensile strength, the test results as shown Table 2 are used. And the combined hardening rule are used. In addition, the initial imperfection is given to facilitate the beam web to buckle. The shape of the initial imperfection is the deformation state of the first-order linear buckling eigenvalue analysis result in each model. The maximum deformation amount of the initial imperfection is designed as 1/1000 of the beam height, based on actual measurement results.



(a) Specimen A-1

(b) Specimen A-2

Fig.10 – FEM Analysis Mesh

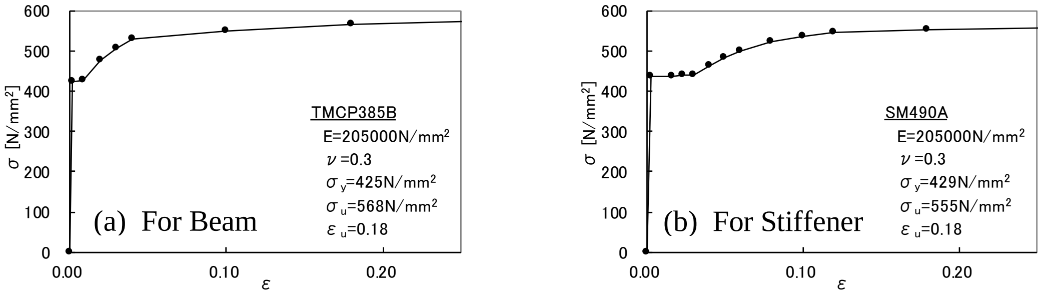


Fig. 11 – Multi-Linear Models of the Material

4.1.2 Results of Analysis

Fig. 12 shows a comparison of the load deformation relationship between the analytical results and the test results, Fig. 13 shows a comparison of the skeleton curves, and Fig. 14 shows a comparison of the deformation state of the test specimen and the analytical results at the corresponding time point.

As shown in Fig. 12 and Fig. 13, the analytical results of both test specimens A-1 and A-2 show a good correspondence to the test results. In addition, the buckling occurrence condition of the beam web shown in Fig. 14 can also be generally reproduced, and it is considered that a reasonable evaluation can be given by FEM analysis regarding the evaluation of plastic deformation capacity caused by buckling occurrence.

In the future, detailed examination by FEM analysis will be carried out, and further rationalization of the proposed structure method will be attempted.

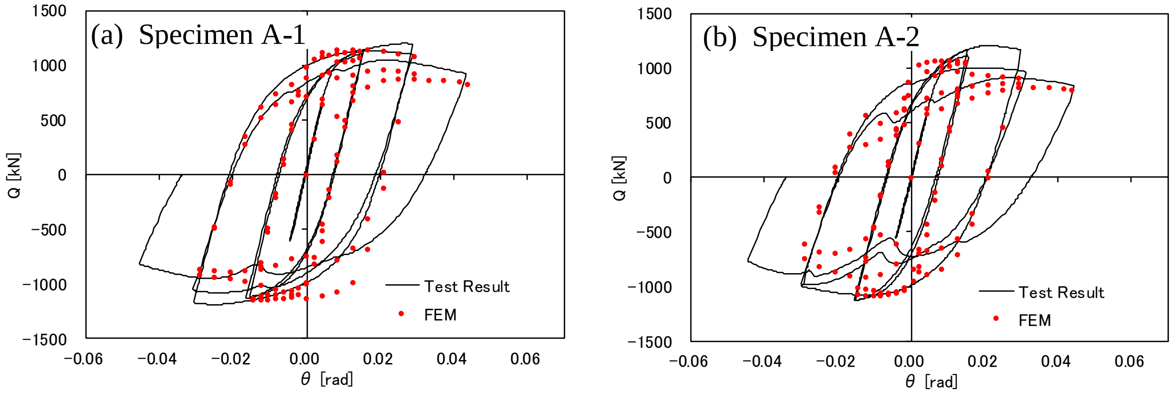


Fig. 12 – Comparison of the Load Deformation Relationship

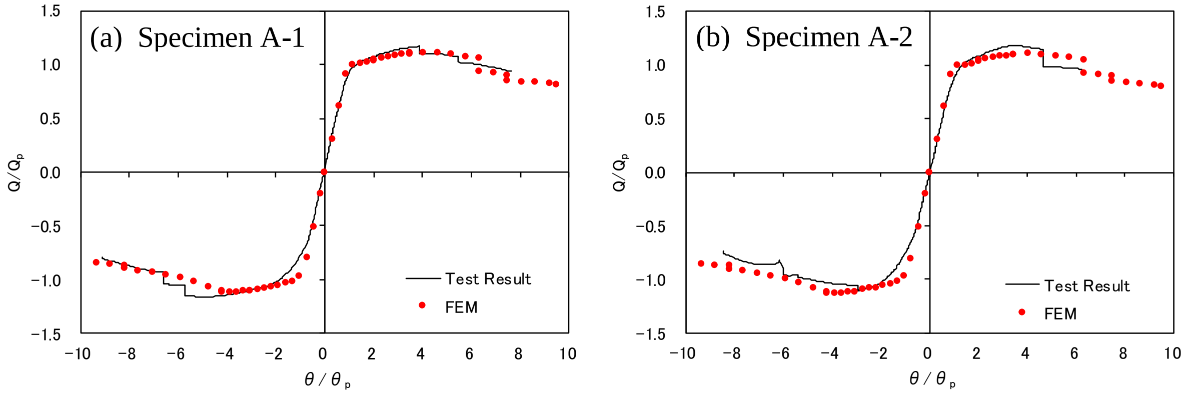
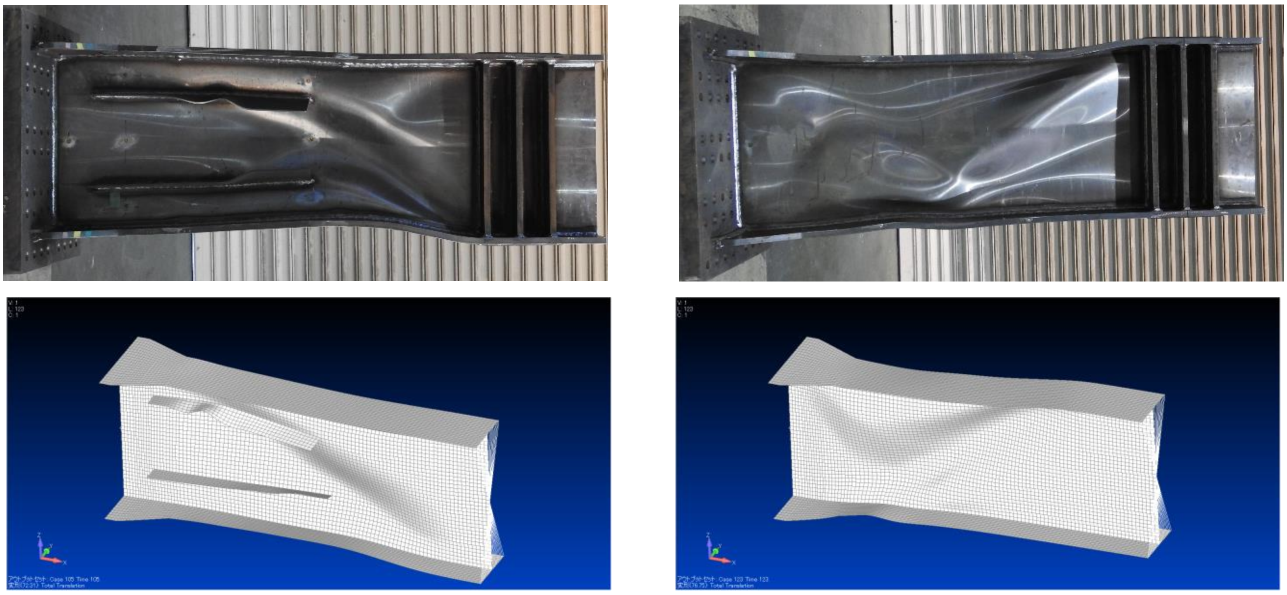


Fig. 13 – Comparison of the Skeleton Curves



(a) Specimen A-1 (b) Specimen A-2

Fig. 14 – Comparison of the Deformation State

5. Conclusion

The authors proposed a structural system with less steel by thinning the large beam webs in steel structure buildings. It also ensures the required plastic deformation capacities of the entire large beam by adding extra rigidity using stiffener plates at the end of the beam with stiffener plates. Furthermore, the effectiveness of the proposed structural system was verified by the structural performance test and FEM analysis.

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