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Features of New High-Strength Steel Materials "550 N/mm^2 Class" for Building Frames†

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Abstract:

JFE Steel developed a new line of high-strength steel products with a lower limit tensile strength of 550 N/mm^2 for building frames using its advanced Super-OLAC (on line accelerated cooling)accelerated cooling technology. This product series currently consists of a steel plate, "HBL385," circular steel tube, "P-385," and square steel tube, "P Column G385." These products realize high strength and excellent earthquake resistance while maintaining the weldability of the conventional steel. The results of a test of members using the square tube confirmed that the cumulative ductility factor of 30, which is required in columns, can be sufficiently secured. A rolled H-shape steel, "HBL-H385," is also under development. A design trial was carried out to investigate the qualitative advantages and problems with these products. The results showed that it is difficult to guarantee the design criteria necessary to replace the beams in all stories as story drift increases by more than 20% due to reduced stiffness, but replacement of columns presents no problems for practical use. A further expansion of the applicable range is possible if designs are prepared using these products from the initial stage.

1. Introduction

The steel products used in high-rise buildings are generally SN materials or thermo-mechanical control process (TMCP) steels of the 490 N/mm^2 class. As a higher strength product, 590 N/mm^2 class steel is available, but for various reasons, this material has not reached the stage of general application. Among its disadvantages, addition of alloying elements and complicated heat treatment are necessary in the production process, and special controls such as preheating control and limitations on heat input are required in the welding process. Against this background, there was a need for high-strength steel products with a combination of good weldability and earthquake resistance. To meet this need, JFE Steel developed a new line of high-strength steel products for building frames with a lower limit tensile strength of the 550 N/mm^2 class by applying the *Super*-OLAC, which is the company's advanced on-line accelerated cooling device and satisfies both rapid cooling and uniform cooling requirements.

2. Features of Products

The newly-developed 550 N/mm^2 class high-strength steel for building frames has a design standard strength of 385 N/mm^2. Current products are a steel plate, "HBL385," circular steel tube, "P-385," and square steel tube, "P Column G385" (hereinafter referred to collectively as the 385 Series). A rolled H-shape steel, "HBL-H385," is currently in the development stage. The chemical composition of the 385 Series is shown in **Table 1**; mechanical properties are shown in **Table 2**.

2.1 Steel Plate "HBL385"

HBL385 is a TMCP plate which was approved by Japan's Minister of Land, Infrastructure and Transport in Feb. 2002 and achieves its maximum reference strength (385 N/mm^2) as an as-rolled material (without tempering and quenching). Examples of mechanical properties are shown in **Figs. 1** and **2** and **Table 3**. High strength and a low yield ratio (YR) are realized by optimal com-

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Table 1 Chemical compositions of 385 series

(mass%)

Grade	C	Si	Mn	P	S	N	C_{eq}	P_{CM}	f_{HAZ}
HBL385B	≦0.18	≦0.55	≦1.60	≦0.030	≦0.015	–	≦0.40*	≦0.26*	–
HBL385C				≦0.020	≦0.008		≦0.42**	≦0.27**	
P-385B	≦0.20	≦0.55	≦1.60	≦0.030	≦0.015	≦0.006	≦0.40*	≦0.26*	≦0.58
P-385C				≦0.020	≦0.008		≦0.42**	≦0.27**	
P column G385B	≦0.20	≦0.55	≦1.60	≦0.030	≦0.015	≦0.006	≦0.40	≦0.26	≦0.58
P column G385C				≦0.020	≦0.008				

*t ≦ 50, **t > 50
$C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$
$P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$
$f_{HAZ} = C + Mn/8 + 6(P + S) + 12N - 4Ti$

Table 2 Mechanical properties of 385 series

Grade	YS (N/mm^2)	TS (N/mm^2)	El (%)	YR (%)	$_vE_{0°C}$ (J)	RA$_Z$ (%)	
HBL385B, C	385–505	550–670	≧26*	≦80	≧70	C	≧25(average)
			≧20**				≧15(each)
P-385B, C	385–535	550–700	≧26*	≦85	≧70	C	≧25(average)
			≧20**				≧15(each)
P column G385B, C	385–505	550–670	≧26*	≦80	≧70***	C	≧25(average)
			≧20**				≧15(each)

* T.P.: JIS No. 5, ** T.P.: JIS No. 4, *** T.P.: At flat part
YS: Yield strength, TS: Tensile strength, El: Elongation, YR: Yield ratio
$_vE_{0°C}$: Charpy absorbed energy at 0°C
RA$_Z$: Reduction of area in through thickness tensile test (Z)

Table 3 Mechanical properties of HBL385

Thickness (mm)	YS (N/mm^2)	TS (N/mm^2)	El (%)	YR (%)	$_vE_{0°C}$ (J)	RA$_Z$ (%)
19	422	552	44	76	289	74, 70, 74
32	423	569	37	74	189	74, 72, 71
35	458	593	32	77	269	73, 73, 72
70	445	596	31	75	290	76, 74, 74
100	432	578	31	75	247	72, 69, 71

Tensile test: Full thickness (JIS No. 5)-C(19 t), 1/4t(JIS No.4)-C(32, 35, 70, 100 t)
Charpy test: 1/4t-C, RA$_Z$: Z

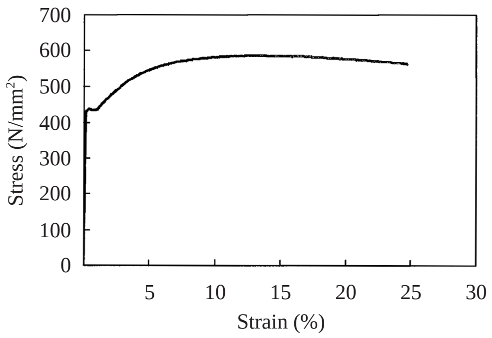

Fig. 1 Stress-strain relationship (t = 32 mm)

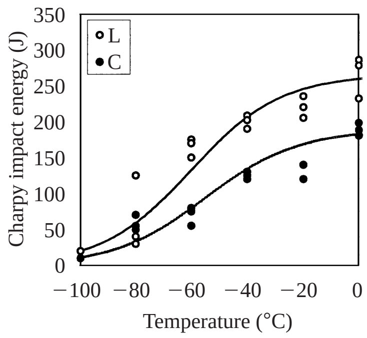

Fig. 2 Charpy impact property (t = 32 mm)

position design, taking advantage of the features of JFE Steel's *Super*-OLAC rapid cooling and uniform cooling technology. Excellent weldability is achieved by holding C_{eq} and P_{CM} to the 520 N/mm^2 steel level. (For detailed items, including welded joint performance, see Ref. 1). Because this product possesses a combination of excellent earthquake resistance and weldability, its superiority has been highly evaluated since the start of sales, and full-scale use in prestigious large buildings began in 2004.

2.2 Circular Steel Tube "P-385"

P-385 is a circular steel tube which was approved by the Minister of Land, Infrastructure and Transport in Aug. 2003 and can be manufactured by either of two pipemaking processes, the UOE process and press-bending. Because it is a circular tube (i.e., produced by bending plate), its yield strength (YS) range, tensile strength (TS) range, and YR provisions conform to the STKN standard in Japanese Industrial Standards (JIS), but all other material properties conform to HBL385.

2.3 Square Steel Tube "P Column G385"

P Column G385 is a cold press-formed square steel tube of the 550 N/mm^2 class which was jointly developed by JFE Steel and Seikei Corp. Ministerial approval was obtained by Seikei Corp. in Nov. 2004. Plates for the product are manufactured by JFE Steel, and pipemaking and marketing are by Seikei Corp. With the exception of corner parts, flat parts have the same performance as HBL385. Design requirements conform to the Manual for the Design and Fabrication of Cold-Formed Square Tubes[2)]. The product is applied by reading 385 N/mm^2 for the design standard strength of BCP325. The following introduces the structural performance of P Column G385 based on the results of member bending tests.

(1) Outline of Test

An outline of the test is shown in **Fig. 3** and **Table 4**. Using the standard displacement, δp corresponding to the plastic moment, Mp of the member, cyclical loading was applied for two cycles at each of 1 time, 2 times, 4 times, 6 times, 8 times, . . . , δp. The specimens have a through diaphragm welded in the center, as in Fig. 3. Using test specimen No. 3 in Table 4 as a standard specimen, No. 2 was prepared to investigate the effect of the load input direction; No. 4, the effect of the non-brittle fracture welding method (NBFW; welding method used to prevent brittle fracture; for details, see Ref. 2); and No. 5, the effect of the width-thickness ratio, respectively. All of the above are FA rank specimens in which the ultimate state is expected to be fracture. In addition, specimen No. 1, which is an FB rank specimen, was also prepared in order to consider an ultimate state due to local buckling. **Table 5** shows the mechanical properties of the respective specimens. In all cases, the specimens display high corner toughness. It may be noted that, because the maximum strength of the

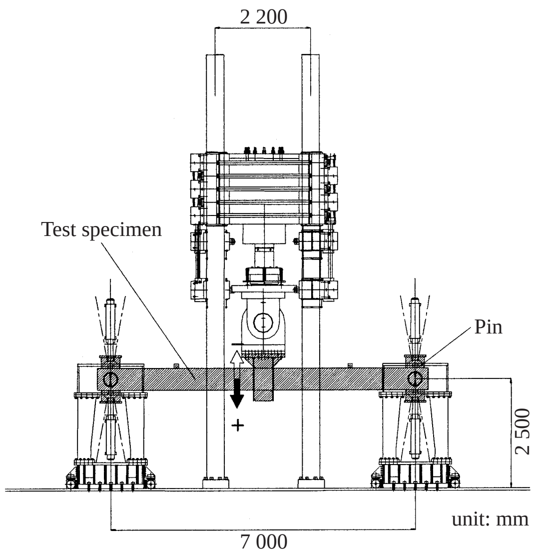

Fig.3 Test setup

Table 4 List of test specimen

Test specimen		Figure						Section performance			
		Load direction	*B* (mm)	*t* (mm)	*B*/*t*	Rank of *B*/*t*	Welding method	*A* (cm^2)	*I* (cm^4)	*Z* (cm^3)	Zp (cm^3)
No. 1	C50019-00-1	0°	500	19	26.3	FB	NBFW	347	129 554	5 182	6 131
No. 2	C50032-00-1	0°	500	32	15.6	FA	NBFW	546	186 845	7 474	9 206
No. 3	C50032-45-1	45°	500	32	15.6	FA	NBFW	546	186 845	6 083	8 920
No. 4	C50032-45-0	45°	500	32	15.6	FA	Normal	546	186 845	6 083	8 920
No. 5	C60032-45-1	45°	600	32	18.8	FA	NBFW	674	344 744	9 124	13 421

Table 5 Material properties

Test specimen	Flat part					Corner part				
	YS (N/mm^2)	TS (N/mm^2)	El (%)	YR (%)	$_vE_{0°C}$ (J)	YS (N/mm^2)	TS (N/mm^2)	El (%)	YR (%)	$_vE_{0°C}$ (J)
No. 1	431	567	36.5	76.0	327	534	580	40.5	92.1	292
No. 2	456	615	44.7	74.1	336	601	654	44.5	92.0	298
No. 3	454	591	46.1	76.8	298	564	639	49.5	88.4	311
No. 4	485	647	44.9	75.1	244	579	635	45.0	91.5	297
No. 5	456	615	44.7	74.1	336	590	651	45.0	90.5	298

column corner was 654 N/mm², YGW21 (JIS Z 3312) was used as the welding consumable for welding with the diaphragm.

(2) Experimental Results

Figure 4 shows the hysteresis loop of specimen No. 3 as a typical example. The specimen withstood deformation up to 6δp, and the hysteresis loop also displayed a stable spindle shape. **Photo 1** shows the weld in the area of the diaphragm after completion of the test. With specimen No. 3, which was welded by the NBFW method, the fracture line ran from the bead line into the column base material side. In contrast, with specimen No. 4, which was prepared by conventional welding, the fracture line ran into the column base material side, and also the HAZ on the bead line. Due to this difference, the plastic deformability of specimen No. 3 exceeded that of No. 4, confirming the effectiveness of the NBFW method. **Figure 5** shows the results for plastic deformability in comparison with those for conventional columns. The results of this test are shown together with the corresponding test specimen numbers. From these results, it is expected that the cumulative ductility factor of P Column G385 will be plotted in the region between the two dotted lines in Fig. 5. All of the FA rank test specimens, including the specimens which were not prepared by NBFW, exceeded the required cumulative ductility factor of 30, and thus have plastic deformation capacities equal to those of conventional columns. These results confirmed that the plastic deformability of P Column G385 presents no problems for practical use.

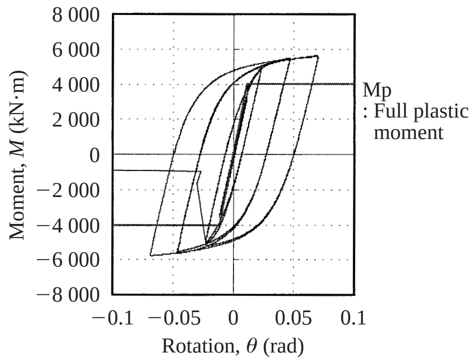

Fig. 4 Test result (Moment-rotation relationship)

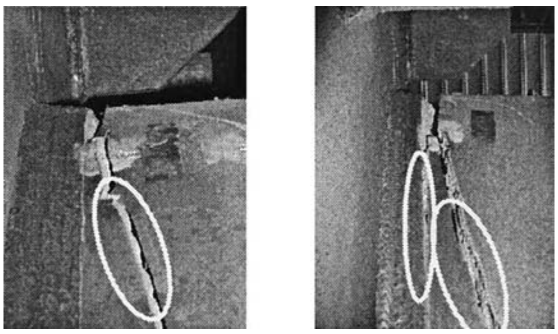

Photo 1 Fracture parts

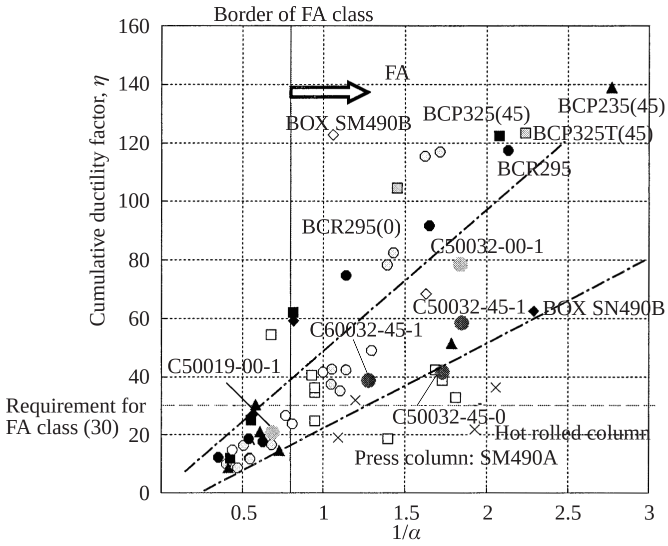

Fig. 5 Relationship between cumulative ductility factor, η and general width-thickness ratio, α

2.4 Rolled H-Shape Steel “HBL-H385”

HBL-H385 is a rolled H-shape steel produced using the *Super*-OLAC S with the aim of realizing material properties equal to those of HBL385. Because this product is currently under development, a detailed description will presented on some future occasion.

3. Design Trial

This chapter describes a design trial which was carried out in order to determine the qualitative merits and problems/tasks when applying the 385 Series to high-rise buildings.

3.1 Object Building and Design Trial Method

The object of the design trial was a 25-story high-rise building with a height of 122 m, as shown in **Fig. 6**. The plan is square, and the building is equipped with seismic dampers. Three column section profiles were used, a box-shaped section (hereinafter, BOX), H-shape section, and circular section (CFT). **Table 6** shows the maximum member sections used in the original design. The BOX section was □-600 × 80 (TMC325), the H-shape section was H-612 × 520 × 70 × 80 (TMC325), and the pipe section was ○-1200 × 50 (TMC325). As the design trial method, existing members were replaced with different sections based on the strength difference, and the characteristics of the building after replacement were confirmed. Member replacement was studied for a total of four cases: Case 1, in which the beams were replaced, Case 2, in which the columns were replaced, Case 3, in

Table 6 Maximum member section

	Original design	Interchange
BOX	□-600 × 70 “TMC325”	□-600 × 60 “HBL385”
H-shape	H-612 × 520 × 70 × 80 “TMC325”	H-592 × 510 × 60 × 70 “HBL385”
Pipe (CFT)	○-1 200 × 50 “TMC325”	○-1 200 × 40 “HBL385”
Beam (H-shape)	H-1 500 × 400 × 16 × 40 “SN490”	H-1 500 × 400 × 16 × 32 “HBL385”

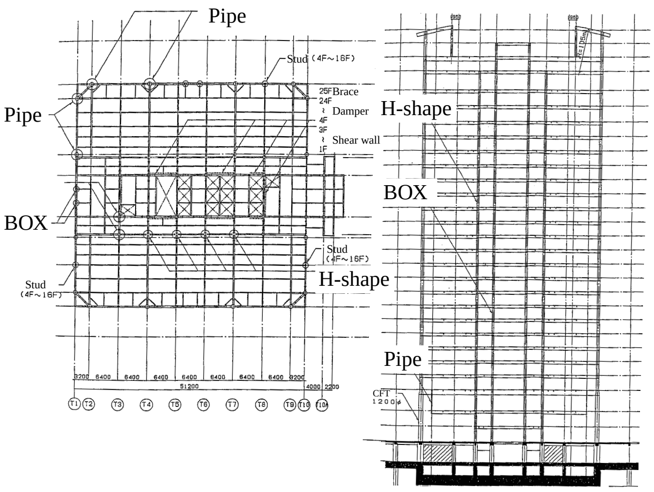

Fig. 6 Building for trying to design

which both the columns and the beams were replaced, and in Case 4, in which only the beams and columns in the lower 10 stories were replaced. In making these replacements, as shown in Table 6, only the thickness was changed, depending on the strength ratio, and the depth and width were left unchanged. The standard plate thickness was used as the plate thickness. When replacing beams, only the flange was considered.

3.2 Results of Design Trial

The quantity of steel after the design trial is shown in **Table 7**. In Case 1, the total weight of steel was reduced by 4.3% in comparison with the original design. The weight reduction in the other cases was 2.6% for Case 2, 6.9% for Case 3, and 4.3% for Case 4. By type of member, replacement of columns resulted in a 6% decrease from the original design, replacement of the beams in all stories resulted in a 10% decrease, and replacement of the beams limited to the lower 10 stories resulted in a 4% decrease. **Table 8** shows the primary natural period of the building for each case. In comparison with the original design, the natural period increases in Cases 1 and 3, in which the beams are replaced, but is basically unchanged in Case 2, in which only the columns are replaced. Case 4, in which the columns and beams in the lower 10 stories are replaced, shows an intermediate value between the above-mentioned results. **Figure 7** shows the story drift in first stage design and second stage design, assuming the value for the original design to be 100%. It should be noted that an extremely rare earthquake is assumed in the second stage design. In Case 1 and Case 3, in which the beams are replaced, the decrease in the stiffness of the upper stories is remarkable, and in the second stage design, the story drift from the mid-to-upper stories increases by more than 20% from the original design and it becomes impossible to satisfy the design criteria. In Case 2, where the columns are replaced, this change is amply possible. Likewise, criteria are also satisfied in Case 4, where the beams

Table 7 Quantity of steel as a result of trying to design

(unit:t)

Quantity of Steel	Original	Case 1	Case 2	Case 3	Case 4
Total	9 607 (100%)	9 194 (96%)	9 356 (97%)	8 943 (93%)	9 190 (96%)
Columns	3 881 (100%)	3 881 (100%)	3 630 (94%)	3 630 (94%)	3 630 (94%)
Beams	4 190 (100%)	3 777 (90%)	4 190 (100%)	3 777 (90%)	4 024 (96%)
Others	1 535 (100%)	1 535 (100%)	1 535 (100%)	1 535 (100%)	1 535 (100%)

Table 8 Primary natural period as a result of trying to design

(unit:s)

Natural period	Original	Case 1	Case 2	Case 3	Case 4
X direction	3.14	3.23	3.15	3.24	3.19
Y direction	3.02	3.09	3.03	3.11	3.08

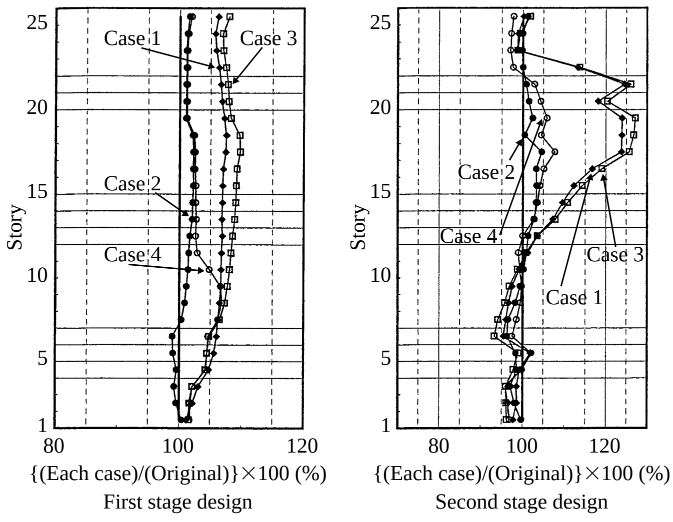

Fig. 7 Story drift

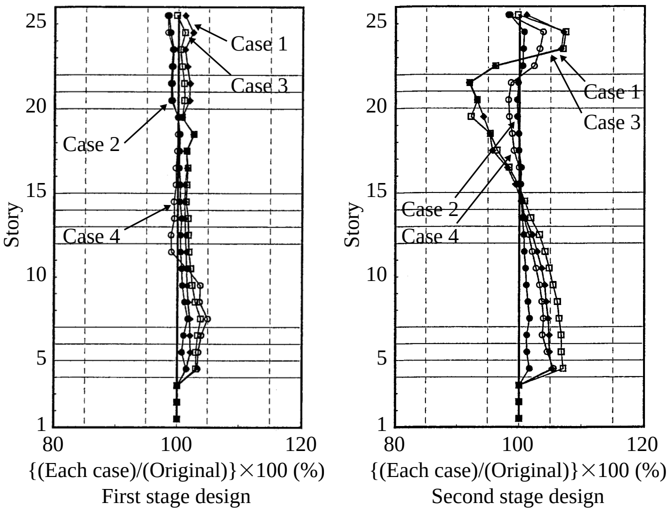

Fig. 8 Contributional ratio of damper

and columns in the lower 10 stories are replaced. Next, **Fig. 8** shows a comparison of the damper contribution ratio in first stage and second stage design. In the mid-to-upper stories, where the story drift criteria become severe, the damper contribution ratio decreases remarkably in the structures in which the beams are replaced, i.e., in Cases 1 and 3. Moreover, in Cases 1 and 3, even if the damper capacity is increased in order to guarantee the design criteria, it is difficult to reduce deformation because the stiffness of the frame itself is reduced.

Thus, in the case of this building, replacement of the beams in all stories results in a dramatic reduction in stiffness, making it difficult to guarantee the design criteria. In Case 2, in which the columns are replaced, criteria can be amply secured and there are no problems for practical use. Replacement of the beams in the lower 10 stories in Case 4 has a similar effect. Based on the results of this study, it is possible to reduce the weight of steel used by replacing 490 N/mm² columns with HBL385, and there are no problems from the viewpoint of design criteria. Furthermore, when replacement is limited to the lower stories, application of HBL385 to the beams is also sufficiently possible. Although the design trial in this work assumed a change from 490 N/mm² steel, if the design is prepared using HBL385 from the beginning, a further expansion in the applicable range would appear to be possible.

4. Conclusion

JFE Steel developed the 385 Series as a new line of 550 N/mm² class high-strength steels with excellent weldability for building frames. Commercialization of member sections mainly for building frames has been completed with plates, circular tubes, and square tubes, and high performance as products for building frames has been confirmed. A design trial showed that it is possible to reduce the weight of steel used in buildings by applying the 385 Series. Based on this, the 385 Series, as one of JFE Steel’s Only One products, is capable of responding to diversifying building design needs. Development of a rolled H-shape steel is now in progress and will complete the series, making it possible to supply the full range of building frame products.

References

1) Hayashi, K.; Fujisawa, S.; Nakagawa, I. JFE Steel Technical Report. no. 5, 2004, p. 45.
2) The Building Center of Japan. Manual for the Design and Fabrication of Cold-Formed Square Tubes. 2003.