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# Development and Commercialization of Steels for Construction Use

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**Abstract:**

*In recent years, buildings have been increasing in height and span to more effectively utilize limited land space and to more efficiently use interior space. To meet these requirements, steels for building frames must have higher strength and performance, and be heavier in gage, and larger in size. The thermal effect on such steels from welding with high heat input must also be studied. Manufacturing and application technologies have been developed for achieving the higher performance of conventional grades of plates, H-shapes, and pipes with tensile strengths of up to 490 N/mm². Also discussed are the development and commercialization of high-performance high-strength 590 and 780 N/mm² steels and extraheavy H-shapes for construction use, and low-yield point steels for seismic response control dampers.*

## 1. Introduction

Buildings can be classified into the following main types of construction: steel frame construction, steel-encased reinforced concrete construction, reinforced concrete construction, and wood construction. In recent years, the percentage of steel frame buildings has surpassed that of wooden frame buildings. To supply an expanding steel frame market and meet technological needs for increasing height and span of buildings, new steels for construction use have been developed and applied to the construction of steel frame buildings[1]. This paper describes Nippon Steel's development and commercialization of high-strength steels and high-performance steels for construction use.

As shown in **Fig. 1**, development has centered on construction steels with higher strength and performance, heavier gage, and in larger sizes. Steels with tensile strengths of 490 to 590 and 780 N/mm² have been exclusively developed for buildings (steels with tensile strengths of 490, 590, and 780 N/mm² are hereinafter

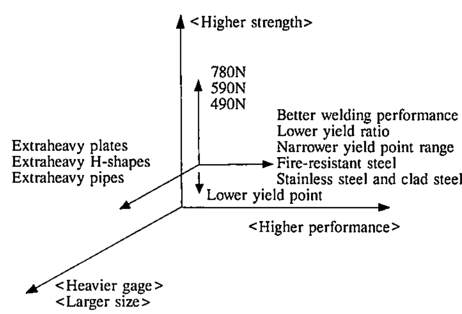



**Fig. 1** Development directions of steels for construction use

*1 Structural Group
*2 Plate Sales Div.
*3 Pipe & Tube Sales Div.
*4 Technical Development Bureau

abbreviated to 490N, 590N, and 780N steels, respectively). The progress of manufacturing technology has made it possible to produce steels capable of meeting performance requirements at the strength levels of 490N and 780N by achieving higher performance, that is control variability of the yield ratio (YR), yield point or yield strength, which is claimed indispensable for steels for construction use, and by improving through-thickness performance and welding performance. (Steels provided with necessary properties to assure the seismic performance and welding performance of building structures are hereinafter called high-performance steels.) Rolled steels for construction use covered by JIS G 3136 (SN steels), a Japanese Industrial Standard established in June 1995, are 400N and 490N high-performance steels. For heavier gages and larger sizes, the commercialization of extraheavy plates and H-shapes by the thermomechanical control process (TMCP) has been completed, and manufacturing technology has also been established for 590N and 780N steel plates up to 100 mm thick. Functional steels, such as fire-resistant (FR) steel and extralow-yield point steel used in seismic response control dampers, are extensively being put to practical use.

Nippon Steel can now meet advanced specifications. One example is 100-mm thick 590N steel plates that can be bent into pipes that satisfy the yield point and other property requirements characteristic of buildings.

## 2. High-Performance Steels for Construction Use

Manufacturing and application technologies have been developed to enhance the performance of conventional plate, H-shape, and pipe steel products with tensile strengths of up to 490 N/mm². The present product development and commercialization of these types of steels are described below. The service performance properties of 590N and 780N steels meet the requirements of high-performance steels. They will be discussed in detail in Chapter 3.

### 2.1 TMCP steels for construction use

2.1.1 TMCP steel plates for construction use (trade named BT-HT325, 325B, 325C, 355, 355B, 355C; numbers refer to yield point or strength)

(1) Features

Conventional extraheavy high-strength steels are produced with a high enough carbon equivalent (an index of weldability) to provide the desired strength. This, however, reduces their weldability. With TMCP steel plates for construction use, the weaknesses of the conventional plate steels were solved by the water-cooling TMCP manufacturing technology. **Fig. 2** shows the effect of carbon equivalent on the tensile strength of TMCP steel plates. The most striking feature of the TMCP steels is that they are stronger than conventional steels despite their low carbon equivalent. For this reason, TMCP steel plates are strong and

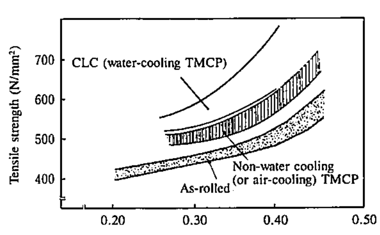



**Fig. 2** Effect of carbon equivalent on tensile strength

**Table 1** Chemical compositions

| Type designation | Thickness | Chemical composition (%) | | | | |
|---|---|---|---|---|---|---|
| | | C | Si | Mn | P | S |
| BT-HT325 | ≦50 mm | ≦0.18 | ≦0.55 | ≦1.60 | ≦0.035 | ≦0.035 |
| | >50 mm | ≦0.20 | | | | |
| BT-HT325B | ≦50 mm | ≦0.18 | ≦0.55 | ≦1.60 | ≦0.030 | ≦0.015 |
| | >50 mm | ≦0.20 | | | | |
| BT-HT325C | ≦50 mm | ≦0.18 | ≦0.55 | ≦1.60 | ≦0.020 | ≦0.008 |
| | >50 mm | ≦0.20 | | | | |
| BT-HT355 | >40 mm ≦100 mm | ≦0.20 | ≦0.55 | ≦1.60 | ≦0.035 | ≦0.035 |
| BT-HT355B | > 40 mm ≦100 mm | ≦0.20 | ≦0.55 | ≦1.60 | ≦0.030 | ≦0.015 |
| BT-HT355C | >40 mm ≦100 mm | ≦0.20 | ≦0.55 | ≦1.60 | ≦0.020 | ≦0.008 |

**Table 2** Mechanical properties

| Type designation | Yield point or strength (N/mm²) | Tensile strength (N/mm²) | Yield ratio (%) | Elongation | |
|---|---|---|---|---|---|
| | | | | Specimen | (%) |
| BT-HT325 | ≧325 | 490-610 | ≦80 | Thickness ≦ 50 mm No. 1(A)<br>Thickness > 40 mm No. 4 | ≧21<br>≧23 |
| BT-HT325B<br>BT-HT325C | 325<br>-445 | 490-610 | ≦80 | Thickness ≦ 50 mm No. 1(A)<br>Thickness > 40 mm No. 4 | ≧21<br>≧23 |
| BT-HT355 | ≧355 | 520-640 | ≦80 | Thickness ≦ 50 mm No. 1(A)<br>Thickness > 40 mm No. 4 | ≧19<br>≧21 |
| BT-HT355B<br>BT-HT355C | 355<br>-475 | 520-640 | ≦80 | Thickness ≦ 50 mm No. 1(A)<br>Thickness > 40 mm No. 4 | ≧19<br>≧21 |

Notes:

1. $\text{Yield ratio} = \frac{\text{Yield point or strength}}{\text{Tensile strength}} \times 100$

2. Specified values in longitudinal or transverse direction are given above.

have excellent weldability even when they exceed 40 mm in thickness. **Tables 1** and **2** give the chemical compositions and mechanical properties of construction use TMCP steels (generally approved by the Minister of Construction), respectively. The letter C at the end of some of the type designations, such as BT-HT325C, for example, refers to a steel that meets the through-thickness properties specified.

The construction use TMCP steel plates have high strength and excellent weldability as extraheavy gages, and are generally approved by the Minister of Construction for specified design strength (F value) of the base metal and weld metal. They require no strength reduction in the thickness range of 40 to 100 mm, a great design advantage.

(2) Application technology development

The TMCP steel plates for constructions use are mainly used in the four-side welded box-section columns of high-rise buildings. **Fig. 3** shows an example of a column-beam joint. The performance of such column-beam joints is verified by conducting many tests on the strength and toughness of the weld joints and by their high-heat input weld softening that becomes a problem with the TMCP steels. A full-scale model as illustrated in **Fig. 3** was made and tested for weld joint performance. The tension test results of cruciform weld joints of beam flanges and diaphragms across column skin plates are shown in **Fig. 4** and **Table 3**. Heat from welding increases the grain size of the heat-affected zone (HAZ) and slightly softens the HAZ. The tension test results, however, show that joint strength fully meets the base metal spec-

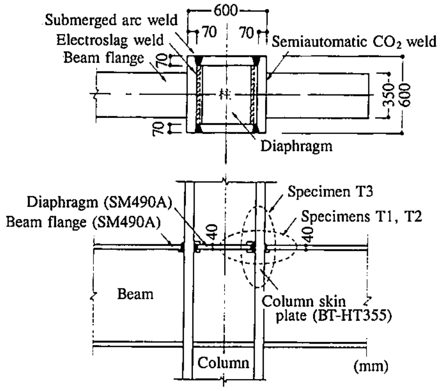



**Fig. 3** Column-beam joints of box-section column

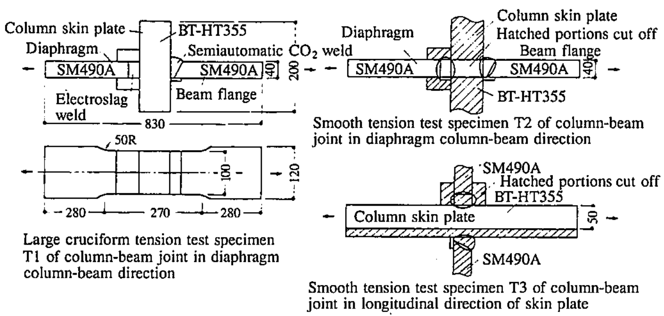



**Fig. 4** Weld joint tension test specimens

**Table 3** Tension test results of weld joints

| Specimen symbol | Specimen size: Thickness (mm) | Specimen size: Width (mm) | Gage length (mm) | Load: Yield point*1 (kN) | Load: Tensile strength (kN) | Stress: Yield point*1 ($N/mm^2$) | Stress: Tensile strength ($N/mm^2$) | Fracture position | Uniform elongation*2 (%) | Total elongation (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 39.6 | 100.1 | 270 | 1,294 | 2,117 | 326 | 534 | Base metal (SM490A) | 10.6 | 18.6 |
| T2 | 40.1 | 100.1 | 270 | 1,284 | 2,107 | 319 | 525 | Base metal (SM490A) | 16.8 | 26.5 |
| T3 | 50.2 | 100.3 | 200 | 1,744 | 2,646 | 347 | 525 | Center (deposited metal, HAZ, base metal) (BT-HT355) | 14.2 | 29.1 |

*1 0.2% offset yield strength at each gage
*2 Uniform elongation determined from load-elongation curve

ifications.

Since their development and commercialization, the construction use TMCP steel plates have been used for the columns of almost all high-rise buildings, recording a total production volume of about 50,000 tons at Nippon Steel.

2.1.2 Extraheavy TMCP steel H-shapes for construction use (trade named NSGH325B, 325C: numbers refer to yield point or strength)

(1) Features

The extraheavy TMCP steel H-shapes for construction use are made by a new rolling process, called the non-water-cooled TMCP, according to the same standards as applied to the TMCP steel plates (see **Tables 1** and **2**). Since they are manufactured by the TMCP, they are weldable and are strong enough to require no strength reduction of the base metal and weld metal. Being of open section, they also greatly simplify column-beam joint fabrication and quality inspection as compared with the box section.

**Table 4** Chemical compositions

| | Thickness (mm) | C | Si | Mn | P | S | Ceq | *P*cm |
|---|---|---|---|---|---|---|---|---|
| Specified value | >50 | ≦0.20 | ≦0.55 | ≦1.60 | ≦0.020 | ≦0.008 | ≦0.40 | ≦0.26 |
| Analysis value | 70 | 0.11 | 0.16 | 1.44 | 0.007 | 0.004 | 0.37 | 0.20 |

Ceq = C + Mn/6 + Si/24 + 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

**Table 5** Tension test results

| Division | Test location | Thickness (mm) | Direction | Yield strength ($N/mm^2$) | Tensile strength ($N/mm^2$) | YR (%) | Elongation (%) | Reduction of area (%) | |
|---|---|---|---|---|---|---|---|---|---|
| Specified value | 1/4F | >50 | L | 325-445 | 490-610 | ≦80 | ≧23 | Average ≧ 25 | Individual ≧ 15 |
| Test value | 1/4F | 70 | L | 395 | 508 | 78 | 38 | | |
| | | | Z | 364 | 512 | 71 | 33 | 79 | min.78 |
| | 1/4W | 45 | L | 360 | 502 | 72 | 38 | | |
| | | | Z | 373 | 513 | 73 | 32 | 77 | min.76 |

*L : longitudinal, Z : through-thickness, F : flange, W : web

**Table 6** Impact test results

| Division | Test location | Thickness (mm) | Direction* | vEo (Average): Absorbed energy (J) | vEo (Average): Brittle fracture ratio (%) |
|---|---|---|---|---|---|
| Specified value | 1/4F | | L | ≧27 | |
| Test value | 1/4F | 70 | L | 298 | 7 |
| | | | T | 253 | 9 |
| | 1/4W | 45 | L | 326 | 0 |
| | | | T | 228 | 17 |

*L : longitudinal, T : transverse, F : flange, W : web

**Table 4** gives the specified and analyzed chemical compositions of the extraheavy TMCP steel H-shapes. The carbon equivalent (Ceq) and weld cracking sensitive composition (*P*cm) are reduced to enhance the ease of welding and hot straightening, among other fabricating operations. The specified and tested mechanical properties are given in **Table 5**, and the impact test results are given in **Table 6**. The extraheavy TMCP steel H-shapes exhibit excellent earthquake resistance, lamellar tearing resistance, and impact resistance (prevention of brittle crack propagation) in each part and direction.

(2) Application technology development

The building structural TMCP steel H-shapes are mainly used in the columns of high-rise buildings and are predominately welded in the form of column-column butt joints and column-beam T-joints as shown in **Fig. 5**. These weld joints made under the conditions of **Table 7** were tension and impact tested. The tension and impact test results are given in **Tables 8** and **9**, respectively. The weld joints have strength and toughness comparable to those of the base metal.

To confirm their performance as columns, the construction use TMCP steel H-shapes were simple bend tested as shown in **Fig. 6**. Their load-deformation relationship is shown in **Fig. 7**. The simple bend test results show that the extraheavy TMCP steel H-shapes have the yield strength and plastic deformation capacity required of steels for construction use.

The building structural TMCP steel H-shapes are provided with such strength that there is no need to reduce the F value specified in the Building Standards Law of Japan (Notification

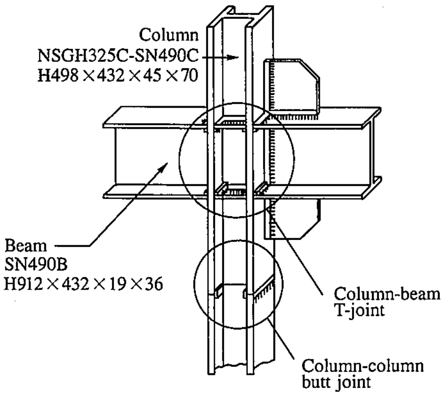



**Fig. 5** Extraheavy H-shape column-beam weld joints

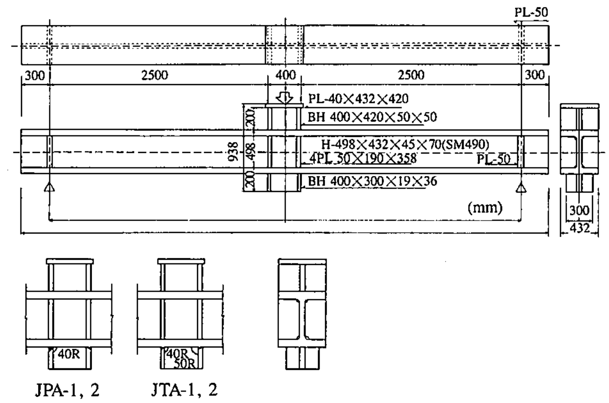



**Fig. 6** Schematics showing test columns

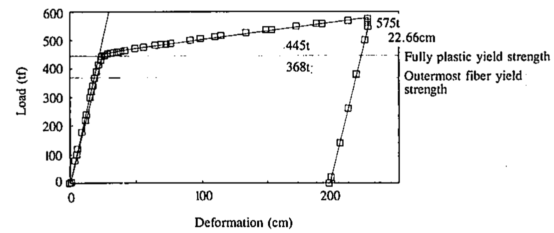



**Fig. 7** Load-deformation curve of extraheavy H-shape (specimen JTA1) in simple bend test

**Table 7** Welding conditions

| Test column | Weld position | Assumed welding place and position | Groove shape | Welding conditions: Number of passes | Current (A) | Voltage (V) | Speed (cm/min) | Heat input (J/cm) |
|---|---|---|---|---|---|---|---|---|
| Column-beam joint | Flange | On-site Flat | 35°, 7mm | 20 | 290 | 37 | 23 – 45 | 14,310 – 27,990 |
| | Web | Shop Horizontal | | 27 | 270 | 39 | 22 – 76 | 8,310 – 28,710 |
| Column-column joint | Flange | On-site Horizontal | 9 mm, 25° | 68 | 270 | 33 | 30 – 40 | 13,370 – 17,820 |

Welding process : Semiautomatic $CO_2$, Welding material : YM-26, 1.2mm$\phi$, Interpass temperature : ≦ 250℃

**Table 8** Tension test results of weld joints

| Test column | Column-column joint | | Column-beam joint | | |
|---|---|---|---|---|---|
| Item / Part | Tensile strength ($N/mm^2$) | Fracture location | Yield point ($N/mm^2$) | Tensile strength ($N/mm^2$) | Fracture location |
| 1/4 flange | 536.4 | HAZ | — | 562.9 | Bond |

**Table 9** Impact test results of weld joints (J)

| Test column | Column-column joint | | | | Column-beam joint | | | |
|---|---|---|---|---|---|---|---|---|
| Direction | Longitudinal direction | | | | Through-thickness direction | | | |
| Location | Base metal | Weld metal | Bond | HAZ | Base metal | Weld metal | Bond | HAZ |
| 1/4F(1/2t) | 152 (52) | 83 (33) | 198 (38) | 140 (51) | 141 (52) | 114 (28) | 118 (50) | 47 (86) |

Values in parentheses: Brittle fracture ratio (%), Test temperature: $_vE_{0℃}$ F=flange

**Table 10** Press-bent TMCP steel pipes

| No | Type | Size (D/t) (mm) | Before or after SR |
|---|---|---|---|
| ① | BT-HT325 | 750$\phi$×70×750 (10.7) | Before |
| ② | BT-HT325 | 750$\phi$×70×750 (10.7) | After |
| ③ | BT-HT355 | 850$\phi$×70×750 (12.1) | Before |
| ④ | BT-HT355 | 850$\phi$×70×750 (12.1) | After |

Note 1: SR stands for stress relieving
Note 2: SR conditions as per JIS Z 3700
(Holding temperature: 595℃, Holding time: 1 h/25 mm or more)

No. 1906 of the Ministry of Construction). At present, however, they must be appraised and approved for specific projects. Citing their performance results in several projects, we will work to have the building structural TMCP steel H-shapes generally approved by the Minister of Construction.

2.1.3 Press-bent TMCP steel pipes

The diversification of their designs is increasing the number of buildings where extraheavy steel pipes are used, such as 900-mm diameter and 90-mm wall SM570Q steel pipes (with the outside diameter-to-wall thickness ratio of D/t = 10.0) used in the Yokohama Landmark Tower[2]. The building structural TMCP steel plates BT-HT325 and BT-HT355 were press bent into pipes and tested to verify their performance by taking stress relieving (SR) as a parameter. The test results are briefly discussed below.

The press-bent TMCP steel pipes used in the test are listed in **Table 10**. The pipes measured 750 mm diameter by 70 mm wall (D/t = 10.7) for BT-HT325 and 850 mm diameter by 70 mm wall (D/t = 12.1) for BT-HT355. They were stress relieved at the holding temperature of 595°C for the holding time of 1 h/25 mm or more as per JIS Z 3700-Method of Postweld Heat Treatment. The TMCP steel plates before being formed into pipes were subjected to chemical analysis, acoustic anisotropy, tension, and impact testing. The TMCP steel pipes were subjected to tension, weld tension, and impact testing before and after they were stress relieved. The test results each satisfied the specified values (guaranteed values). The tension test results of BT-HT325 are given in **Table 11**. The test results show the effect of stress relieving in improving the mechanical properties and meet the specified values except for the yield ratio before stress relieving.

The TMCP steel plates for the press-bent TMCP steel pipes are guaranteed for their low yield ratio, weldability (represented by carbon equivalent and weld crack sensitive composition), and Charpy absorbed energy, among other properties, as already described in Section 2.1.1. The press-bent TMCP steel pipes

**Table 11** Tension test results of BT-HT325

| Before or after SR | | Thickness (mm) | Specimen | Location | Direction | Yield point or strength (N/mm²) | Tensile strength (N/mm²) | Yield ratio (%) | Elongation (%) | Reduction of area (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Specified value | | >40 | No.4 | — | L,T | ≧325 | 490-610 | ≦80*2 (85*3) | ≧23 | — |
| Plate | — | 70 | No.4 | 3/4t | L | 383 | 527 | 73 | 36 | — |
| | | | No.5 | Full thickness | L | 400 | 541 | 74 | 59 | — |
| | | | | | | 396 | 541 | 73 | 58 | — |
| | | | WES 1106 | — | Z | 392 | 533 | 74 | 28*4 | 75 |
| | | | | | | 398 | 533 | 75 | 28*4 | 75 |
| | | | | | | 386 | 532 | 73 | 28*4 | 75 |
| Pipe | Before SR ① | 70 | No.4 | 1/4t | L | 491*1 | 556 | 88 | 30 | — |
| | | | | | | 493*1 | 556 | 89 | 30 | — |
| | | | | | T | 431*1 | 533 | 81 | 30 | — |
| | | | | | | 443*1 | 534 | 83 | 30 | — |
| | | | No.5 | Full thickness | L | 489*1 | 579 | 85 | 51 | — |
| | | | | | | 494*1 | 581 | 85 | 50 | — |
| | After SR ② | 70 | No.4 | 1/4t | L | 440 | 540 | 81 | 34 | — |
| | | | | | | 429 | 542 | 79 | 33 | — |
| | | | | | T | 400 | 523 | 76 | 34 | — |
| | | | | | | 384 | 522 | 74 | 33 | — |
| | | | No.5 | Full thickness | L | 429 | 554 | 77 | 53 | — |
| | | | | | | 424 | 557 | 76 | 53 | — |

*1: Yield point or strength is yield point when not marked by a symbol and is 0.2% offset strength when marked by *1.
*2: ① and ② are numbers for pipes in Table 10.
*3: *2 and *3 are target and guaranteed values of yield ratio, respectively.
*4: *4 is reference value of elongation in through-thickness direction tension test.

meet the service performance requirements specified for the TMCP steel plates.

### 2.2 Rolled steels for construction use (designated SN)

An important factor in the new seismic design methods put into practice in 1981, is ensuring the deformation capacity of steel frames. Post-yield redundant force and plastic deformation capacity are consequently required of steel members. General-purpose steels, designated SS and SM, were traditionally used in large amounts for building structures. These steels have no service performance requirements as noted above. For this reason, JIS G 3136-Rolled Steels for Construction Use was established for a new family of construction steels, designated SN, in June 1994. The outline and manufacturing results of the SN steels are introduced with H-shapes as examples.

The standard for the SN steels is characteristic in that the upper and lower limits of the yield point or strength, the yield ratio, Charpy absorbed energy and through-thickness performance (for type C) are specified as mechanical properties, that seismic design requirements are added, and that the assurance of weldability (Ceq) and the limitation of impurity elements like phosphorus and sulfur are intensified.

The specified and actual chemical composition and mechanical properties of an SN steel are given in comparison with a conventional steel (SS400) in **Tables 12** and **13**, respectively. SN400A is intended for members and parts that do not undergo plastic deformation, and are not subject to full-fledged welding. SN400B is intended for general members and parts. SN400C is designated for parts subject to force in the thickness direction and is a grade that is through-thickness performance specified.

In September 1994, Notification No. 1794 of the Ministry of Construction was revised to Notification No. 1906 to legally permit the use of SN steels. SN steels are destined to become a predominant family of construction steels.

**Table 12** Chemical composition (thickness: 16 < t < 40 mm, 400N steel) (%)

| Type designation | Carbon equivalent (Ceq) | C | Si | Mn | P | S |
|---|---|---|---|---|---|---|
| SN400B | ≦0.36 | ≦0.20 | ≦0.35 | 0.60-1.40 | ≦0.030 | ≦0.015 |
| SN400B (measured) | 0.29 | 0.16 | 0.14 | 0.71 | 0.018 | 0.007 |
| SS400 (specified) | – | – | – | – | ≦0.050 | ≦0.050 |

**Table 13** Mechanical properties (thickness: 16 < t < 40 mm, 400N steel)

| Type designation | Yield point (N/mm²) | Tensile strength (N/mm²) | Yield ratio (%) | Elongation (%) | Charpy absorbed energy(℃(J)) |
|---|---|---|---|---|---|
| SN400B (specified) | 235-355 | 400-510 | ≦80 | ≧22 | 0 ≧27 |
| SN400B (measured) | 281 | 437 | 64 | 34 | 131 |
| SS400 (specified) | ≧355 | 400-510 | – | ≧21 | – |

### 2.3 Round steel pipes for construction use (UO steel pipes for construction use)

(1) Features

The diversification of building designs and the spread of concrete-filled steel pipe composite structures has been increasing the demand for round steel pipe columns. Formerly, small- and medium-diameter steel pipes were frequently used in truss members, and centrifugally cast steel pipes were mainly used as building columns. UO pipes or press-bent pipes, both cold formed from plates, are optimum materials for concrete-filled steel pipe structures in terms of wall thickness and external diameter. If UO pipes and press-bent pipes traditionally used for pipelines are to be employed as building columns, they must be provided with appropriate properties for construction use, such as a low yield ratio and axial performance, and must also meet close dimensional tolerances.

Press-bent pipes have been already introduced in Section 2.1.3 and are omitted here. UO pipes[3] are discussed below. **Table 14** shows the typical mechanical properties of UO pipes made to have the same properties as SM490A. **Fig. 8** shows the changes in the mechanical properties of the UO pipes in the thickness direction. There is some work hardening on the inside and outside surfaces, but the effect of work hardening over the full thickness is judged to be practically negligible in the available range of present UO pipes (with the D/t ratio of about 20 or more). **Fig. 9** shows the distributions of yield point or strength, tensile strength, and yield ratio among the mechanical properties of UO pipes (SM490A) produced for construction use. The yield ratio is 80% or less for most of the UO pipes. The UO pipe's mechanical properties are satisfactory for construction use.

**Table 14** Tension test results of base metal in UO pipes

| | Direction | Yield point (N/mm²) | Tensile strength (N/mm²) | Yield ratio (%) | Elongation (%) |
|---|---|---|---|---|---|
| Specified value | — | ≧315 | 490-610 | — | ≧21 |
| ①812.8mmφ×28mm (D/t=29.0) | L | 406 | 559 | 73% | 25% |
| | T | 454 | 573 | 79% | 42% |
| ②711.2mmφ×28mm (D/t=25.4) | L | 415 | 592 | 70% | 26% |
| | T | 454 | 608 | 75% | 41% |
| ③711.2mmφ×25mm (D/t=28.4) | L | 431 | 599 | 72% | 25% |
| | T | 418 | 598 | 70% | 40% |

Note: Yield point is 0.2% offset strength, and D/t is outside diameter-to-wall thickness ratio.

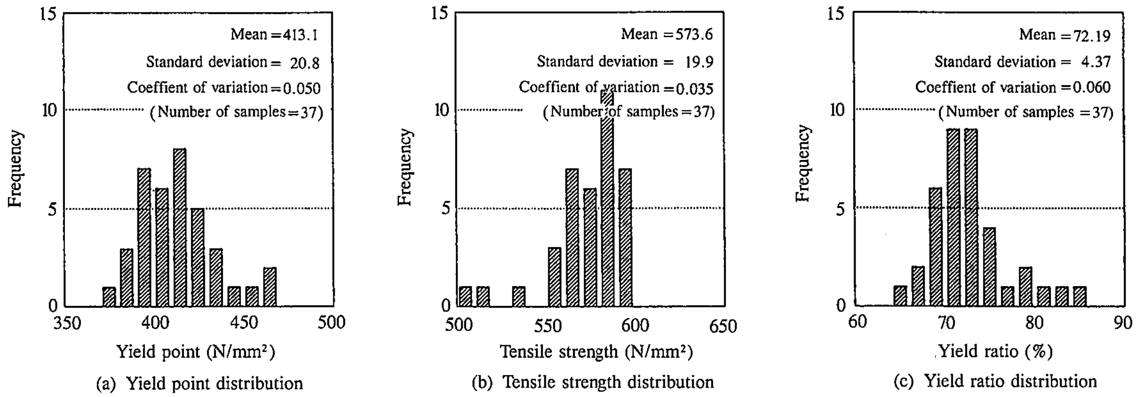



**Fig. 9** Measured mechanical properties of UO pipes (SM490A, longitudinal direction of base metal)

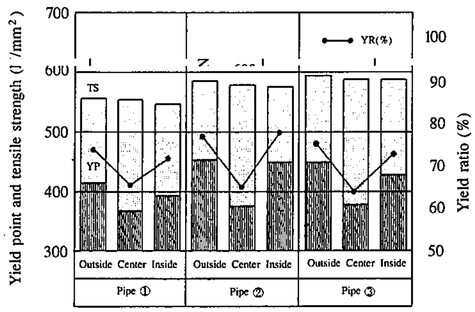



**Fig. 8** Through-thickness distributiones of tension test results of base metal in UO pipes

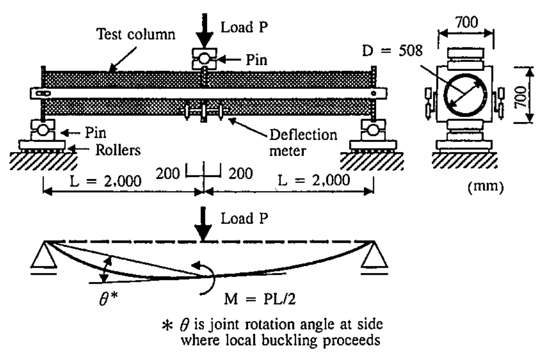



**Fig. 10** Test column, and loading and measuring methods

**Table 15** Test results

| Test column | Maximum strength $M_{max}$ (tf·m) | Calculated strength $M_p$ (tf·m) | $\frac{M_{max}}{M_p}$ | Elastic limit deflection at $M_p$ $\theta_p$(%) | Deflection at local buckling $\theta_{LB}$(%) | Deflection at maximum strength $\theta_{max}$ (%) | Plastic deformation capacity $\frac{\theta_{max}}{\theta_p}-1$ |
|---|---|---|---|---|---|---|---|
| C20-85 | 301.0 | 250.4 | 1.20 | 0.71 | 3.99 | 5.69 | ≧7.03 |
| C20-75 | 326.0 | 260.4 | 1.25 | 0.73 | — | 6.18 | ≧7.45 |
| C32-85 | 184.4 | 144.9 | 1.27 | 0.62 | 2.44 | 4.89 | 6.86 |
| C32-75 | 202.0 | 159.0 | 1.27 | 0.66 | 2.43 | 6.14 | 8.25 |
| C42-85 | 140.5 | 116.5 | 1.21 | 0.64 | 2.17 | 2.81 | 3.41 |
| C42-75 | 149.5 | 122.2 | 1.22 | 0.67 | 2.44 | 3.70 | 4.56 |
| C56-85 | 105.8 | 105.0 | 1.01 | 0.75 | 1.56 | 2.13 | 1.84 |
| C56-75 | 103.2 | 92.9 | 1.11 | 0.67 | 1.59 | 2.49 | 2.73 |

(2) Application technology development

To verify their performance as columns, full-size steel pipes were simple bend tested as shown in **Fig. 10**. The test pipes are listed in **Table 15**, and some of their load-deformation curves are shown in **Fig. 11**. **Fig. 12** shows the effect of the D/t ratio on the rate of yield strength increase and the plastic deformation factor. The test results confirm that the yield strength and plastic deformation capacity of the UO pipes are high enough to meet the properties required for construction steels.

### 2.4 Low-yield point and extralow-yield point steels (trade named BT-LYP235 and 100; numbers refer to yield point or strength)

(1) Features

Rapid technological progress has resulted in the improvement of building seismic performance by incorporating seismic response control devices to counter earthquake energy and by causing their seismic response control effect to absorb most of the earthquake energy. Commercial dampers for this purpose are made of viscous material, such as oil dampers, or of viscoelastic material like lead, or make use of friction. As far as ferrous

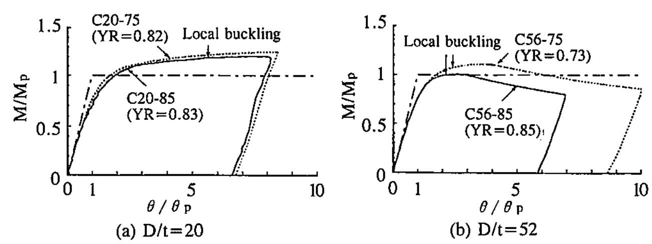



**Fig. 11** Load-deformation curves

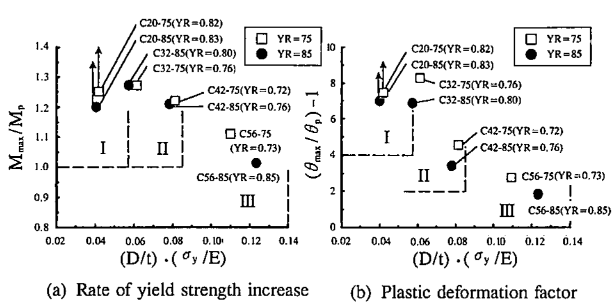



**Fig. 12** Effect of outside diameter-to-wall thickness (D/t) ratio on rate of yield strength increase and plastic deformation factor

materials are concerned, seismic response control techniques of the hysteresis energy absorption type are attracting attention because they use a low-yield point steel of low strength or extralow-yield point steel of even lower strength[4-7].

The seismic design method that incorporates such seismic response control dampers involves the damper yielding prior to the main structural members, such as columns and beams, in the event of an earthquake. For the damper to yield prior to main structural members made of 490N steel, for example, the damper must be low in yield strength, as well as properly shaped and installed. The variability of yield strength must also be controlled to cause the damper to yield at the load assumed in the design

**Table 16** Chemical compositions (%)

| Steel | Test column | | Thickness (mm) | C | Si | Mn | P | S |
|---|---|---|---|---|---|---|---|---|
| LYP235 | Target value | | — | ≦0.18 | — | — | ≦0.035 | ≦0.035 |
| | Test value | No.1 | 12 | 0.05 | 0.03 | 0.27 | 0.021 | 0.012 |
| | | No.2 | 20 | 0.04 | 0.02 | 0.24 | 0.018 | 0.008 |
| | | No.3 | 40 | 0.04 | 0.01 | 0.27 | 0.018 | 0.009 |
| LYP100 | Target value | | — | ≦0.03 | — | — | ≦0.035 | ≦0.035 |
| | Test value | No.1 | 6 | 0.003 | 0.02 | 0.14 | ≦0.007 | 0.012 |
| | | No.2 | 9 | | | | | |
| | | No.3 | 12 | | | | | |

Chemical analysis was conducted as specified in JIS G 3106.

**Table 17** Mechanical properties

| Steel | Test column | | Thickness (mm) | Test orientation | Yield point or strength*3 (N/mm²) | Tensile strength (N/mm²) | Elongation (%) | Specimen geometry |
|---|---|---|---|---|---|---|---|---|
| LYP235 | Target value | | | | 215-245 | 300-400 | ≧40 | JIS No.5 |
| | Test value | No.1 | 12 | L*1 | 238 | 335 | 55 | |
| | | | | T*2 | 229 | 332 | 55 | |
| | | No.2 | 20 | T | 224 | 325 | 62 | |
| | | No.3 | 40 | T | 215 | 313 | 71 | |
| LYP100 | Target value | | | | 90-130 | 200-300 | ≧50 | JIS No.5 |
| | Test value | No.1 | 6 | L | 123 | 255 | 58 | |
| | | | | T | 116 | 251 | 59 | |
| | | No.2 | 9 | L | 123 | 253 | 63 | |
| | | | | T | 112 | 253 | 61 | |
| | | No.3 | 12 | L | 103 | 260 | 64 | |
| | | | | T | 100 | 263 | 66 | |

*1: L or longitudinal direction: Specimen was removed parallel to rolling direction of steel and tested.
*2: T or transverse direction: Specimen was removed normal to rolling direction of steel and tested.
*3: Yield point or strength for LYP100 is 0.2% offset yield strength.

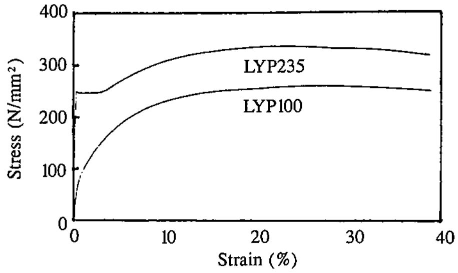



**Fig. 13** Stress-strain curves (LYP235: t=12, LYP100: t=6)

stage and to ensure the reliability of the damper. The damper material cyclically deforms over the plastic range at the time of an earthquake and must possess excellent ductility and low-cycle fatigue strength as well.

The chemical compositions and mechanical properties of the low-yield point steel BT-LYP235 and extralow-yield point steel BT-LYP100 developed and commercialized by Nippon Steel are given in **Tables 16** and **17**, respectively. Their stress-strain curves are shown in **Fig. 13**. The two steels have the following features. The yield point or strength is low at 235 N/mm² for BT-LYP235 and 100 N/mm² for BT-LYP100, and the range of variability is small in absolute terms. The total elongation is 40 to 50% or more, attesting to excellent elongation performance. In terms of fabrication properties, such as weldability, the two steels are equal to conventional mild steels.**Fig. 14** shows the low-cycle fatigue test results of BT-LYP235, BT-LYP100, and SS400. BT-LYP100 is somewhat inferior to SS400 in low-cycle fatigue strength, probably due to grain coarsening.

(2) Application technology development

**Figs. 15** and **16** show the test results of seismic response control panels made of low-yield point steel and extralow-yield point steel. In this example, BT-LYP100's shear yield indicates stable energy absorption performance. **Fig. 17** shows an example in which BT-LYP235 is fabricated into a honeycomb form and used as a seismic response control wall. In this way, the technol-

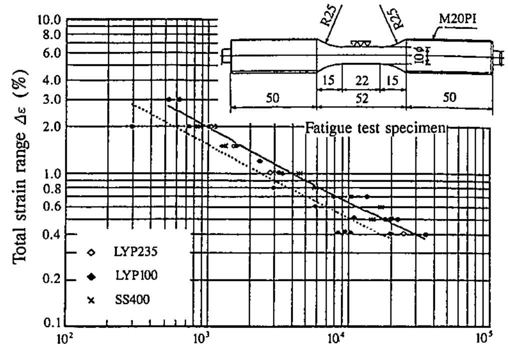



**Fig. 14** Low-cycle fatigue test results

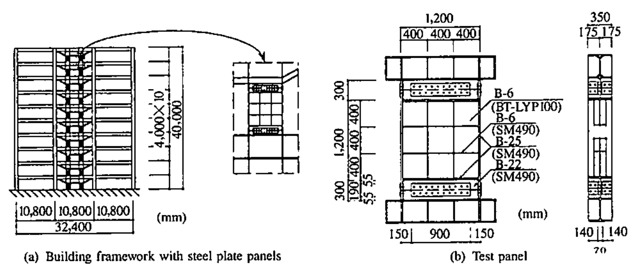



**Fig. 15** Building framework with steel plate panels and test panel

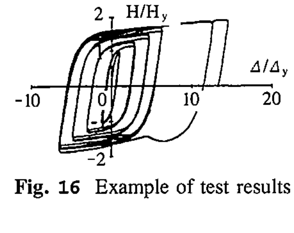



**Fig. 16** Example of test results

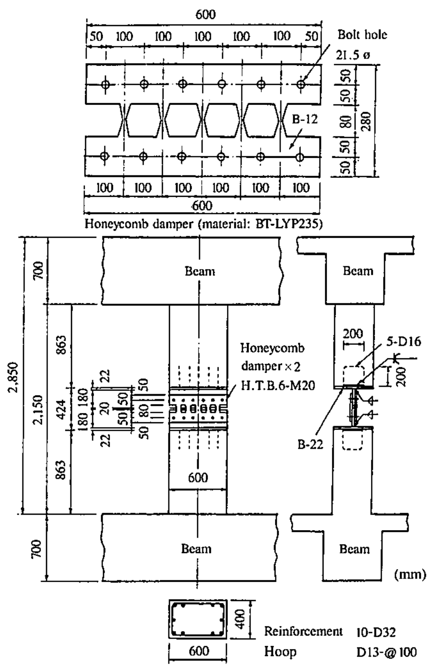



**Fig. 17** Use of seismic response control wall of honeycomb type

ogy of concentrating seismic energy onto seismic response control devices of low-yield point or extralow-yield point steel is put to practical use, thereby reducing damage to main frames.

## 3. 590N and 780N Steels for Construction Use

With the increasing height and span of buildings, high stresses develop in the columns of some high-rise or long-span structures. Steels of the 490N class used to counter these high stresses are nearly 100 mm in thickness and difficult to fabricate and weld. Building structural steels have been developed that have a tensile strength of 590 or 780 N/mm², and satisfy high-performance steel specifications. Use of the new construction steels reduces construction costs by lowering steel weight, prevents the plate thickness from becoming excessive, and enhances the reliability of the products themselves.

### 3.1 590N steels for construction use (trade named BT-HT440B, 440C; numbers refer to yield point or strength)

(1) Development history

The Ministry of Construction carried out a comprehensive technology development project "Development of New Materials and New Material Application Techniques in the Construction Industry" for five years from 1988. As part of the project, the "High-Performance Steel Application Technique Subcommittee", established in the Kozai Club, worked on the research and development of 590N high-performance steels, and prepared such guidelines as those on techniques for effective use of high-performance steels[8], on welding procedures of 60 kgf/mm² class high-performance steels[9] and on design and installation of high-strength bolts made of high-performance steels[10].

Before they are used, the 590N steel plates must be approved by the Minister of Construction under the Building Standards Law. Nippon Steel is preparing for 590N steel plates approval from the Minister of Construction within fiscal 1995, regarding the material standards, design and construction, F value, width-to-thickness ratio by structural type, and other provisions of the guidelines mentioned above. Some modifications are made, as shown in **Table 18**, so that the requirements of the above-mentioned guidelines conform to those specified for SN steels.

(2) Features

Nippon Steel's construction use 590N steel BT-HT440 is quenched and tempered, and is made by a process composed of hot rolling and heat treatment. The standards for the BT-HT440 steel plates are shown in **Table 18**. The applicable thickness range is 19 to 100 mm. The yield ratio is controlled to a maximum of 80%, the difference between the upper and lower limits of the yield point or strength is controlled to a maximum of 100 N/mm², and the Charpy absorbed energy value is specified at a minimum of 47 J at 0°C.

The F value is set at the lower limit of 4.5 t/cm² (440 N/mm²) of the yield point or strength and is 0.4 t/cm² greater than the F value[11] of 4.1 t/cm² for the conventional SM570Q steel. The material strength required to obtain the horizontal load carrying capacity is the F value multiplied by 1.05.

(3) Applied technology development

To verify the weld joint performance of steel pipe columns with penetrated diaphragms, full-size test columns having col-

**Table 18** Standard for BT-HT440 steel plates

(a) Chemical composition (wt%)

| | Type | Thickness (mm) | C | Si | Mn | P | S | Ceq | *P*cm |
|---|---|---|---|---|---|---|---|---|---|
| Comprehensive project specification | SA440I<br>SA440II | 19-100 | ≦0.18 | ≦0.55 | ≦1.60 | ≦0.035 | ≦0.008 | ≦0.47(0.44) | ≦0.30(0.28) |
| Minister of Construction approval | BT-HT440B | 19-100 | ≦0.18 | ≦0.55 | ≦1.60 | ≦0.030 | ≦0.008 | ≦0.47(0.44) | ≦0.30(0.28) |
| | BT-HT440C | | | | | ≦0.020 | | | |

Ceq and *P*cm assume values enclosed in parentheses for thickness range of 19 to 40 mm and values given outside of parentheses for thickness range of 40 to 100 mm.

(b) Mechanical properties

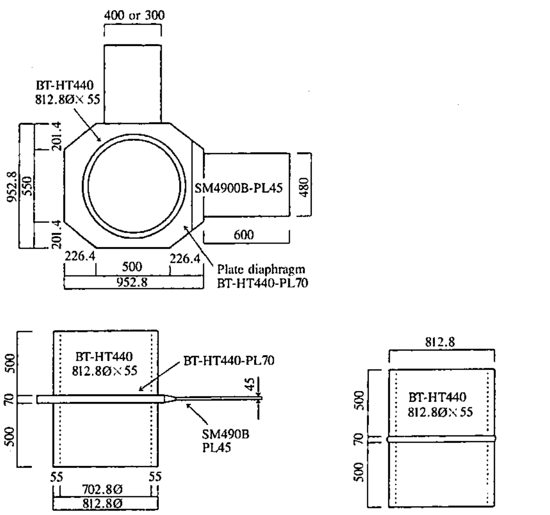
| | Type | Thickness (mm) | Yield point or strength (N/mm²) | Tensile strength (N/mm²) | Yield ratio (%) | Elongation (%) | Absorbed energy (0°C) (J) | Reduction of area in through-thickness direction(%) |
|---|---|---|---|---|---|---|---|---|
| Comprehensive project specification | SA440I | 19-100 | ≧440 | 590-740 | ≦80 | ≧20(26) | ≧47 | — |
| | SA440II | | 440-540 | | | | | |
| Minister of Construction approval | BT-HT440B | 19-100 | 440-540 | 590-740 | ≦80 | ≧20(26) | ≧47 | — |
| | BT-HT440C | | | | | | | ≧25 |

Elongation shall be equal to or greater than value enclosed in parentheses for No. 5 specimens when thickness is 19 mm or more, and shall be greater than value given outside of parentheses for No. 4 specimens when thickness is greater than 20 mm.

umn-beam and column-column joints as shown in **Fig. 18** were made from BT-HT440 steel pipes with 812.8 mm external diameter and 55 mm wall (D/t = 14.8), and were tension, impact and weld joint hardness tested[12]. The tension, impact, and weld joint hardness test results are shown in **Figs. 19** to **21**, respectively. The weld joints were confirmed to fully meet all of the strength, toughness, and weld heat effect requirements.

(4) Applied examples

BT-HT440 has been practically applied in the Landmark Tower (70 stories above ground, total floor area of about 230,000 m², individual appraisal acquired in September 1989) in block 25 of the central district of the Minato Mirai 21 project in Yokohama; building B (28 stories above ground, total floor area of about 70,000 m², individual appraisal acquired in June 1993) in block 24 of the central district of the Minato Mirai 21 project; and the head office building of East Japan Railway (28 stories above ground, total floor area of about 60,000 m², individual appraisal acquired in February 1994). It is used in the steel pipe columns and four-side welded box-section columns of lower floors in these buildings.




(a) Column-beam joint (b) Field column-column joint

**Fig. 18** Full-size test column with weld joints

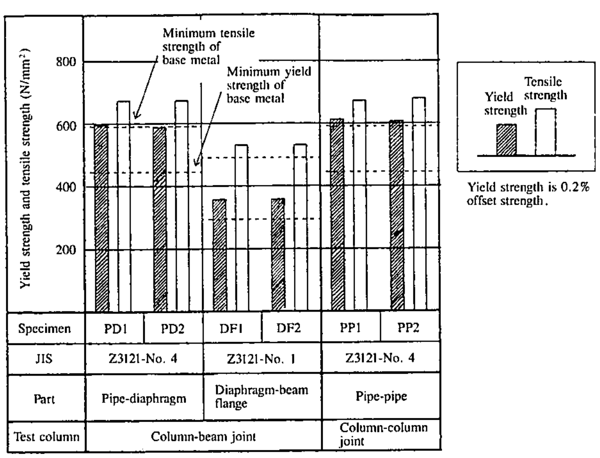



**Fig. 19** Tension test results of weld joints

### 3.2 780N steel for construction use (trade named BT-HT620; number refers to yield point or strength)

(1) Development history

Not only 590N, but also 780N steels have been traditionally utilized in civil engineering structures, but their use has been limited in the elastic region. Although based on elastic design columns in superhigh-rise buildings are very likely to locally plasticize at the base and in other parts. Such locally plasticized parts require a sufficient plastic deformation capacity of 780N steels. Conventional 780N steels were poor in plastic deformation capacity as represented by a yield ratio of 90% or more, calling for research to cope with high-heat input welding that was becoming popular for building steel frames.

After much research and development, Nippon Steel commercialized the 780N steel BT-HT620 for construction use and has summarized the material standards, design and construction pro-

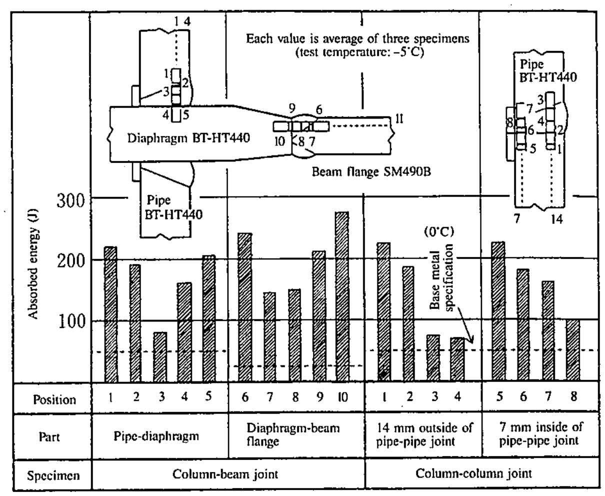
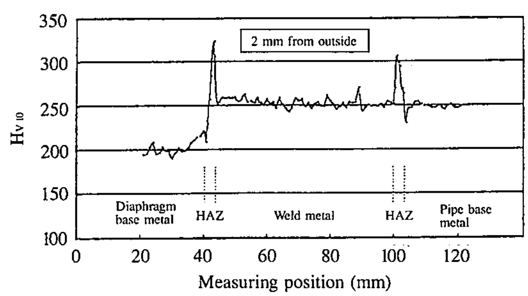
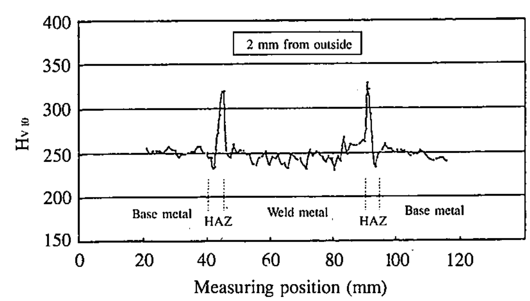



**Fig. 20** Charpy impact test results




(a) Column-beam (pipe-diaphragm) joint




(b) Column-column (pipe-pipe) joint

**Fig. 21** Hardness test results

cedures, F value, width-to-thickness ratio by structural rank and other details for the new 780N steel. Some of the results are introduced here. Prior to its use, the 780N steel BT-HT620 must be approved by the Minister of Construction in the same way as for the 590N steel BT-HT440.

(2) Features

The construction use 780N steel BT-HT620 is produced with high strength and a low yield ratio by the TMCP manufacturing process that comprises quenching, dual phase heating, rapid cooling, and tempering. In order to lower the preheat temperature for prevention of weld cracking (or to minimize the hardness of the HAZ) the carbon content is held low and boron is not added. Copper is added to ensure adequate strength, as is nickel to improve impact toughness of the HAZ. Nippon Steel's company standards for BT-HT620 steel plates appears in **Table 19**. The applicable thickness range is 25 to 100 mm. The yield ratio is controlled to a maximum of 85%, and the Charpy absorbed energy value is specified at a minimum of 47 J at 0°C.

The F value is the lower limit of 6.3 t/cm² (620 N/mm²) of the yield point or strength and is about twice as large as the F value of 3.3 t/cm² for the 490N steel[13]. The material strength required to obtain the horizontal load carrying capacity is the F value multiplied by 1.05.

**Fig. 22** shows the y-groove weld cracking test results of BT-HT620. The weldability of 100-mm thick plates was verified for steel A of such chemistry as to assure the desired low-temperature impact toughness of the HAZ of welds made with high heat input (nickel is added to the conventional grade that has boron added to impart hardness) and steel B (BT-HT620) mainly designed to lower the preheat temperature for prevention of weld cracking. The preheat temperature for prevention of weld cracking is 75°C for steel A and 50°C or less for steel B. This means that steel B is superior in weld cracking resistance.

**Table 19** Standard for BT-HT620 steel plates

(a) Chemical composition (wt%)

| C | Si | Mn | P | S | Cu | Ni | Cr | Mo | Nb | V | Ceq |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ≦0.16 | ≦0.35 | 0.60-1.60 | ≦0.030 | ≦0.015 | 0.15-1.50 | 0.70-2.00 | 0.30-0.80 | 0.20-0.60 | ≦0.05 | ≦0.60 | ≦0.60 |

Ceq=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14
Other alloying elements are added as required.

(b) Mechanical properties

| Tension test | | | | Impact test | |
|---|---|---|---|---|---|
| Yield point or strength (N/mm²) | Tensile strength (N/mm²) | Yield ratio (%) | Elongation (%) | Test temperature (℃) | Absorbed energy (average of 3specimens)(J) |
| ≧620 | 780-930 | ≦85 | ≧16 | 0 | ≧47 |

JIS No. 4 specimens removed normal to plate rolling direction are used in tension test.
JIS No. 4 specimens (2-mm V notch) removed parallel with plate rolling direction are used in impact test.

Welding conditions

| Welding process | Electrode | Current | Voltage | Speed | Heat input |
|---|---|---|---|---|---|
| Covered electrode arc welding | L-80EL | 170A | 25V | 15cm/min | 17kJ/cm |

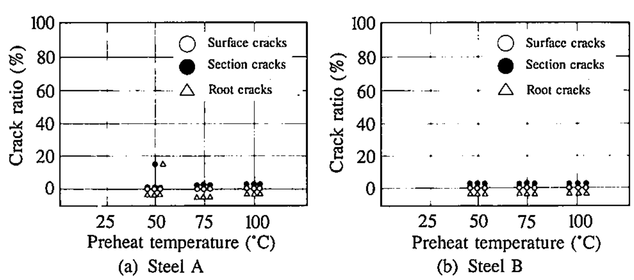



**Fig. 22** Results of y-groove weld crack test

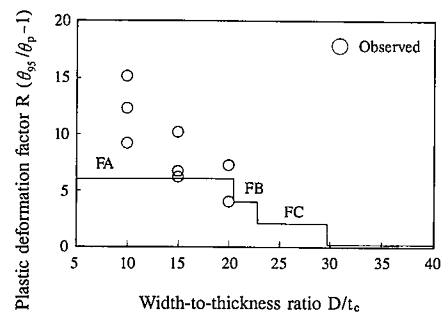



**Fig. 23** Plastic deformation capacity of box-section columns

(3) Application technology development

The compressed bend test results of box-section columns fabricated from BT-HT620 steel plates are shown in **Fig. 23**[14]. The plastic deformation factor R is defined as the deformation of a box-section column at 95% of the maximum strength that is divided by the yield deformation of the column minus 1. The solid line indicates the width-to-thickness ratio[12] of 490N steel plates that is multiplied by

$$\sqrt{\{(\text{F value of 490N steel})/(\text{F value of BT-HT620})}$$

The test results show that the plastic deformation capacity of box-section columns made of BT-HT620 steel plates can be evaluated by the critical width-to-thickness ratio indicated by the solid line.

## 4. Future Trends and Conclusions

High-strength steels, high-performance steels, and functional steels, all developed for construction use, have been described above. In recent years, work has proceeded on the research and development of technology for making the best use of these steels. One example is the design technique that incorporates extralow-yield point steel dampers in a high-strength steel framework to keep the framework within the elastic range in the event of an earthquake and to dramatically improve the seismic performance of the framework. Another is the practical application of 590N or 780N steel pipes filled with high-strength concrete. The creation of applied technology for new steels to be developed will improve the seismic performance of steel frame buildings and reduce their construction cost.

### References

1) Ohashi, M. et al.: Nippon Steel Technical Report. (44), p. 8 (1990)
2) Hagiwara, K. et al.: Journal of the Japan Welding Society. 61 (2), 113 (1992)
3) Nagata, M. et al.: Summaries of Technical Papers of Annual Meeting, Structure, Architectural Institute of Japan. September 1994, p. 1071
4) Kobori, T. et al.: Summaries of Technical Papers of Annual Meeting, Structure, Architectural Institute of Japan. October 1989, p. 643, 645, 647; October 1990, p. 951, 953; August 1992, p. 1041
5) Saburi, K. et al.: Summaries of Technical Papers of Annual Meeting, Structure, Architectural Institute of Japan. September 1994, p. 1341
6) Yamaguchi, T. et al.: Summaries of Technical Papers of Annual Meeting, Structure, Architectural Institute of Japan. September 1994, p. 1067

7) Onishi, K. et al.: Concrete Journal, Japan Concrete Institute. 31 (10), 28 (1993)
8) Building Research Institute of the Ministry of Construction, Kozai Club: Guidelines on Techniques for Effective Use of High-Performance Steels. 1994
9) Kozai Club: Guidelines on Welding Procedures of 60 kgf/mm²-Class High-Performance Steels. 1993
10) Kozai Club: Guidelines on Design and Installation of High-Strength Bolts with High-Performance Steels. 1993
11) Architectural Institute of Japan: Standards for Structural Calculations of Steel Structures. 1973
12) Okada, T. et al.: Summaries of Technical Papers of Annual Meeting, Structure, Architectural Institute of Japan. September 1994, p. 1235
13) Building Center of Japan: Structural Provisions of Buildings. September 1994
14) Suzuki, T. et al.: Summaries of Technical Papers of Annual Meeting, Structure, Architectural Institute of Japan. September 1994, p. 1173