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Super-High-Strength Bolt, “SHTB®”

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Abstract

Super-high-strength bolt, “SHTB®”, is a new steel bolt product having a strength 1.5 times that of conventional F10T and excellent in resistance to delayed fracture. To study countermeasures against delayed fracture, a method for evaluating delayed fracture properties was developed, and on that basis, a new steel excellent in delayed fracture resistance and a new bolt shape to prevent delayed fracture were developed. Additionally, to confirm the delayed fracture resistance of the developed bolts, atmospheric exposure tests were conducted. Use of SHTB reduces the size of a structural joint to 2/3 that of conventional ones, reducing construction costs and time and enhancing work safety.

1. Introduction

Steel structural members are fastened together either by welding or with high-strength bolts; the latter method consists of forming joints by connecting steel members, using high-strength bolts, which are industrial product, and for this reason it is easier to secure desired fastening quality by bolt connection than by welding, the fastening quality of which depends significantly on the skill of welding workers. On the other hand, as the height and size of buildings increase and use of thicker and strong-er steel materials for their structural frames expands, more number of bolts are required for each joint, leading to bulky joint sizes and low work efficiency, as far as conventional F10T bolts (1,000-N/mm^2 class tensile strength) are concerned. For this reason, stronger connecting bolts have been eagerly looked for.

In consideration of the market need, Nippon Steel Corporation began development of a new super-high-strength bolt product of a F15T class aiming at (1) fastening heavy-gauge and high-strength steel members with high-strength bolts in a practical manner, and (2) reducing the number of bolts to make joints compact, save manpower and shorten construction period.

At an early stage of the development, however, use of F11T high-strength bolts was virtually banned for fear of delayed fracture, and it was widely thought that the strongest of high-strength bolts that could be used reliably was F10T. In such a situation, the development of high-strength bolts of a F15T class was quite a challenging attempt, and it required a comprehensive approach such as development of (1) a method for evaluating delayed fracture properties, (2) a steel excellent in resistance to delayed fracture and (3) a new bolt shape to prevent the occurrence of delayed fracture, and (4) confirmation of the delayed fracture resistance of fastening bolts through exposure test in real environments.

The super-high-strength bolt, “SHTB®”, having a 1,400-N/mm^2 class tensile strength, was developed as a result of these activities. A newly developed thread shape realized a bolt tension 1.5 times that of F10T bolts. In 1999, Nippon Steel and NS Bolten was granted a general approval of SHTB by the then Minister of Construction (now called the Minister of Land, Infrastructure and Transport) in their joint names, used for construction of a high-rise building for the first time in 2001, and its application has expanded steadily ever since.

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This paper describes the technologies incorporated in SHTB and presents some examples of its applications.

2. Countermeasures Against Delayed Fracture

2.1 Mechanisms for occurrence of delayed fracture

Delayed fracture is the toughest problem to overcome in increasing the strength of high-strength bolts. Such fractures are a kind of hydrogen embrittlement, wherein a steel material fails under a static load, abruptly and without premonitory events, after a certain period has elapsed. It occurs more often as steel strength increases: in the case of high-strength bolts, occurrences increase markedly when the tensile strength of the steel exceeds 1,200 N/mm^2. Japanese Industrial Standards (JIS) once included high-strength bolts up to F13T (1,300-N/mm^2 class tensile strength), but in consideration of frequent failures of F13T bolts due to delayed fracture in 1964, the grade F13T was crossed out from the JIS in 1967. Furthermore, use of F11T (1,100-N/mm^2 class tensile strength) was practically banned in 1979, lowering the maximum strength of usable fastening bolts to F10T. All this was because the possibility of delayed fracture could not be eliminated with regard to high-strength bolts of F11T and above.

Delayed fracture results from a very small amount of hydrogen that comes into steel during its production processes such as heat treatment, pickling, electrolytic plating, etc and by corrosion as well. In the case of high-strength bolts for civil and building construction use, the hydrogen that causes delayed fracture comes mainly from corrosion, and the processes that lead to the failure are considered as follows (see also the schematic illustrations in **Fig. 1**):

(1) A bolt corrodes and hydrogen enters the steel matrix through the surface;
(2) The hydrogen diffuses to material inside and accumulates at portions where stress and plastic strain concentrate such as threads and the transition from the head to shank;
(3) When the accumulated hydrogen content exceeds the permissible limit for the failure of the steel, a crack forms;
(4) The crack causes more stress to concentrate near it, and it develops even with a smaller amount of hydrogen; and
(5) When the crack develops to a certain size, the bolt fails.

Therefore, to prevent delayed fracture from occurring in the high-strength bolts in use, it is effective to stop any one of the above processes or retard their progress as much as possible. The improved delayed fracture properties of SHTB were obtained through the development of a steel having a large permissible hydrogen content and a bolt shape that inhibits delayed fracture.

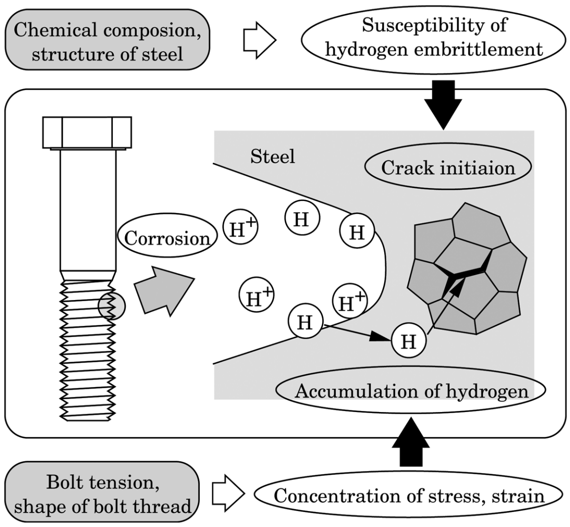


Fig. 1 Process of delayed fracture initiation

2.2 Development of evaluation method for delayed fracture properties

There are no commonly accepted methods for evaluating delayed fracture properties of steel, and thus, different research and evaluation institutes have used different evaluation methods of their own. Many of those methods evaluate delayed fracture properties in terms of the time to failure or rupture stress ratio of a steel material immersed in an acid solution. A major problem of these methods is that the behavior of hydrogen penetrating into steel in an acid solution is different from that in an atmospheric corrosion environment, in which the bolts are actually used. For this reason, there are some cases where evaluation results of delayed fracture resistance for some kinds of steel using one specific acid solution may be inversed with a different acid solution, or the delayed fracture properties observed in laboratories do not match with those in real environments. Therefore, it follows that to develop a new grade of steel resistant to delayed fracture, it is necessary first to develop a method capable of properly evaluating delayed fracture resistance of steel.

For this end, the authors developed a method of thermal desorption spectroscopy for measuring the amount of diffusive hydrogen in steel and a new evaluation method for delayed fracture properties of steel based on the measured amount of diffusive hydrogen[1, 2]. By the developed evaluation method based on the hydrogen amount, a critical hydrogen content $[H_C]$ not to cause delayed fracture is measured, it is compared with the amount $[H_E]$ of hydrogen that enters into and accumulates in steel from the environment, and a steel that has $[H_C]$ sufficiently larger than $[H_E]$ is judged not likely to fail by delayed fracture during use. Here, the value of $[H_C]$ is determined as follows: by cathodic electrolysis, hydrogen is made to penetrate, in different amounts, into a round-bar test piece having a circular notch simulating the stress concentration portion of a bolt; the test piece is then metal plated to prevent hydrogen from dissipating into the air; it is held at room temperature for a period of time to let the hydrogen diffuse homogeneously in the test piece; and then it is subjected to a static stress equivalent to an axial force applied to a bolt in actual use for tightening, and the time until its failure is measured. On the other hand, $[H_E]$ is determined by subjecting steel specimens to cyclic corrosion test (CCT) simulating real outdoor conditions and measuring the amount of hydrogen that penetrates into the specimens through corrosion and accumulates there.

By changing the chemical composition and heat treatment conditions, the authors prepared six kinds of specimen steels having tensile strengths ranging from 1,078 to 1,627 N/mm^2, and measured the values of $[H_C]$ and $[H_E]$ of the specimens in laboratories. Bolts were made from the same specimen steels and subjected to exposure tests at a coastal location in Okinawa, and the probability of delayed fracture was measured. **Fig. 2**[2] shows the relationship between the values of $[H_C]$ and $[H_E]$ and the probability of delayed fracture thus measured. The good correlation seen in the graph indicates that the developed evaluation method is usable for estimating the occurrence of delayed fracture in a real environment. A method like the above is, as far as it is based on hydrogen content of steel and the measurement conditions for $[H_C]$ and $[H_E]$ are properly selected, effective also in evaluating the probability of hydrogen embrittlement of structural members and mechanical components, even if they are used

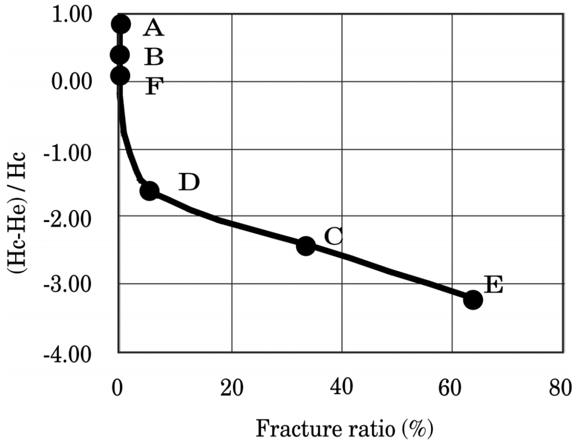


Fig. 2 Relationship between delayed fracture probability in exposure test and parameter [([H_C]–[H_E]) / [H_C]]

under conditions of stress loading (repeated stress, etc.) and hydrogen penetration very much different from those of high-strength bolts [3, 4].

2.3 Development of high-strength steel excellent in delayed fracture properties

Generally speaking, the strength of high-strength bolts is increased by quenching and tempering, and their structure is tempered martensite. Delayed fracture of a tempered martensite structure often starts in the form of an intergranular fracture between prior austenite grains, and accordingly, to improve the delayed fracture resistance of steel, it is essential to strengthen prior austenite grain boundaries. For this end, some papers proposed technique such as the following: (1) decreasing the contents of elements such as P and S that tend to segregate at grain boundaries[5]; (2) refining austenite grains by adding microalloying elements such as Nb, Ti and V[6]; and (3) preventing the precipitation of filmy cementite at austenite grain boundaries by tempering at high temperatures[7].

Since the delayed fracture of high-strength bolts results from a small amount of hydrogen that enters the steel by corrosion, delayed fracture resistance is expected to improve by rendering that hydrogen harmless. In this relation, carbides of Mo, V, Ti and Nb were found to trap hydrogen in steel[2, 8-11]. Carbides of Mo and V dissolve in comparatively large amounts in the steel matrix at temperatures of normal quenching of bolts, and by making them precipitate in fine particles during the tempering thereafter, it is possible to use them for precipitation hardening. In consideration of this, the authors examined the relationship between the hydrogen trapping behavior and delayed fracture properties of steel containing Mo and V in detail [12-16]. As a result, it became clear that, under a condition where corrosion proceeds (rainy weather, etc.), steel containing vanadium carbide traps hydrogen and renders it harmless, and under a condition where corrosion stops (fine, dry weather, etc.), vanadium carbide releases the trapped hydrogen harmlessly into the atmosphere[17].

Employing the above-said technique (1) to (3) to strengthen prior austenite grain boundaries as well as the technique to render hydrogen harmless, the authors developed a new steel for high-strength bolts; **Table 1** shows its chemical composition. Vanadium is added in a comparatively large quantity for the following reasons: during the heating for quenching, part of it forms insolute carbonitride, which pins austenitic grain boundaries to refine crystal grains, and during tempering at high temperatures, the part of it that dissolved in the steel matrix during the heating for quenching precipitates in the form of fine carbide to strengthen steel and trap hydrogen, thereby rendering it harmless.

The authors tempered the steel developed for SHTB to a tensile strength of 1,450 N/mm^2 and subjected it to delayed fracture test; **Fig. 3**[2] shows the results. The value of [H_C] of the developed steel is as large as 2.72 ppm. **Photo 1** compares a fractograph of SHTB after delayed fracture with another of conventional steel; whereas the fracture mode of the conventional steel is clearly intergranular fracture

Table 1 Chemical compositions of SHTB (mass%)

C	Si	Mn	P	S	Cr	Mo	V
0.40	Decrease	0.50	Decrease	Decrease	1.20	Addition	Addition

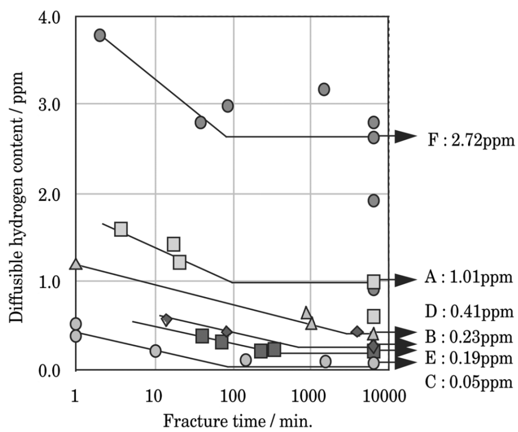
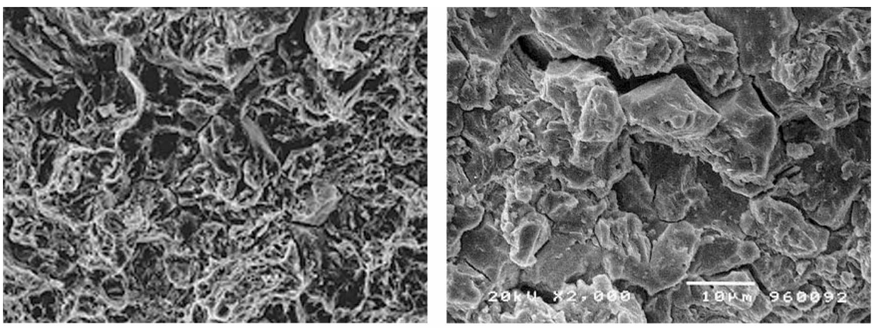


Fig. 3 Result of delayed fracture test



SHTB (Transegranular fracture) Conventional steel (Intergranular fracture)

Photo 1 Fractographs of delayed fracture surface

between prior austenite grains, that of SHTB is quasi-cleavage fracture, a type of transgranular fracture, evidencing that the developed steel effectively prevents intergranular fracture. With steels that trap hydrogen using fine precipitates, $[H_E]$ tends to increase. In consideration of the fact that the value of $[H_E]$ of the developed steel measured through the CCT was as low as 2.31 ppm[2] and as described in Sub-section 2.5, the largest value of its $[H_E]$ measured through the exposure test of bolts in Okinawa was as small as roughly 1 ppm, however, it is fair to conclude that the developed steel for SHTB has a good delayed fracture resistance to prevent delayed fracture from occurring during use in a real environment.

Another grade of steel was developed applying the technologies of the steel for SHTB and has been commercially used not only for civil and building construction applications but also for 12.9T bolts (1,200-N/mm^2 class tensile strength) for automobile engines.

2.4 Development of bolt shape to reduce stress and plastic strain concentration

Fig. 4[18] shows the frequency of delayed fracture of high-strength bolts by the position of fracture obtained through the exposure test conducted by the Bolt Strength Committee of the Japanese Society of Steel Construction (JSSC) from 1968 to 1972. It is clear from the graph that high-strength bolts fail most often by delayed fracture in the threaded portion, where the concentrations of stress and plastic strain are significant, especially at the portion of incomplete threads. In consideration of the above, to alleviate stress and plastic strain concentrations at various bolt portions while abiding by the basic dimensional regulations under JSS II 09-1981[19] and JIS B 1186-1979[20], the authors worked out the following new design features shown in **Fig. 5**, and applied them to SHTB: (1) a new thread shape (hereinafter called the SHTB thread); (2) improved shape of the transition from the shank to threaded part; (3) increased radius of the transition from the head to shank; and (4) a new nut shape. As a result, SHTB has shape and stress concentration properties quite different from those of conventional F10T bolts.

(1)SHTB thread

In the SHTB thread, which was newly developed based on shape study by the FEM analysis, the bottom shape was defined as a composite curve of three arcs[21]. **Fig. 6** is a sectional diagram of a groove of the SHTB thread; the radius of the arc at the beginning of the transition from the flank to the bottom was set at H/6 (H being the fundamental triangle height), equal to the bottom radius for the JIS metric coarse screw thread (hereinafter called the JIS thread) of conventional F10T bolts, and the radius at the bottom, where the concentration of stress and plastic strain is expected to be great, is set at 2H/3, four times that of the JIS thread. The pitch, fundamental triangle height, flank angle and outer diameter are the same as those of the JIS thread.

Fig. 7 shows an example of the FEM analysis results on the play thread portion of the SHTB and JIS threads; the diagrams show the distribution of stress concentration factors by elasticity analysis, the distribution of equivalent plastic strain under the design bolt tension

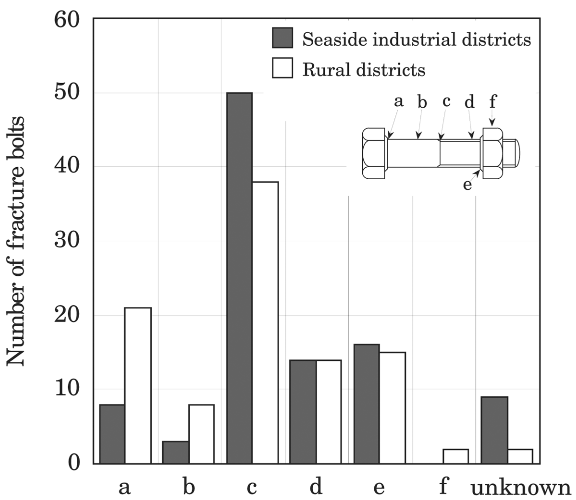


Fig. 4 Places of delayed fracture of HTB

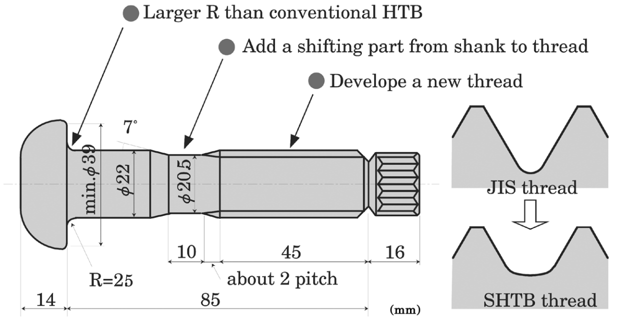


Fig. 5 Shape and dimension of SHTB

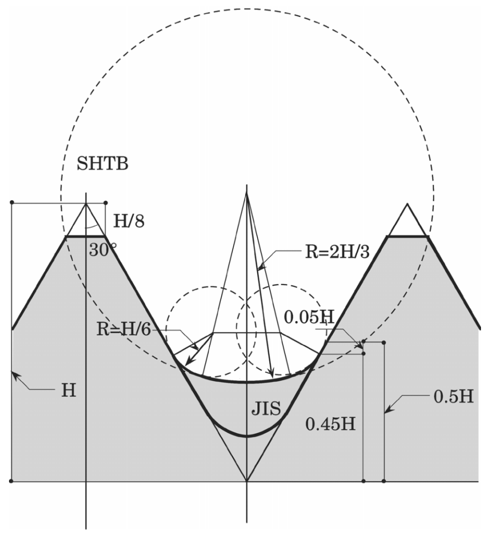


Fig. 6 Shape and dimension of SHTB thread

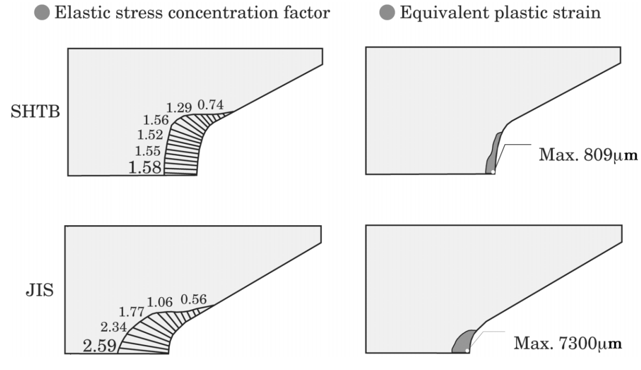


Fig. 7 Elastic stress concentration factor and equivalent plastic strain of thread bottom

estimated for F15T by elastic-plastic analysis (the hatched areas being plastic regions) and the maximum equivalent plastic strain. The stress concentration and maximum equivalent plastic strain are reduced in the SHTB thread to roughly 60 and 10%, respectively, of those in the JIS thread. It has to be noted in this relation that, as is understood from Fig. 6, the effective sectional area of the SHTB thread is larger than that of the JIS thread by several percents, which is advantageous for increasing bolt tension.

(2)Shape improvement of transition from shank to threaded part

In conventional F10T high-strength bolts, the shank, the diameter of which is equal to the nominal diameter, connects to the threaded part without any transition portion in between. SHTB has a parallel part, four thread pitches in length and having a diameter equal to the effective diameter, between the shank and threaded part so that imposed stress flows as smoothly as possible. **Fig. 8** shows an FEM analysis result of the maximum principal stress and maximum equivalent plastic strain at the incomplete threads, play threads and threads in nut under a standard bolt tension of 329 kN. Whereas, with the JIS thread, the stress and plastic strain increase conspicuously at the incomplete threads, their peak values there are significantly lower with the SHTB thread because of the combined effects of the new thread shape and improved transition between the shank and threaded part. The improved bolt shape is expected to be highly effective in improving the delayed fracture resistance of the incomplete thread portion, where delayed fracture occurred most frequently at the exposure test of the JSSC.

(3)Increase in radius below bolt head

The radius of the transition from the bolt head to the shank, which was 1.5 to 2.0 mm conventionally, has been increased to 2.5 mm for SHTB so as to decrease the stress concentration at the portion under a standard bolt tension to a level comparable to that at the threaded portion.

(4)New nut shape

As a result of the increase in the thread bottom radius described earlier, the shear strength of the contact between a bolt and nut per thread pitch is smaller with the SHTB thread than with the JIS thread by approximately 10%. To compensate this, the number of threads of a nut for SHTB was increased, with a safety margin, to 1.2 times that of a nut for the JIS thread. The increase in the number of threads decreases the stress borne by the bolt and nut per thread, and is effective also in lowering the maximum stress and plastic strain at each thread bottom.

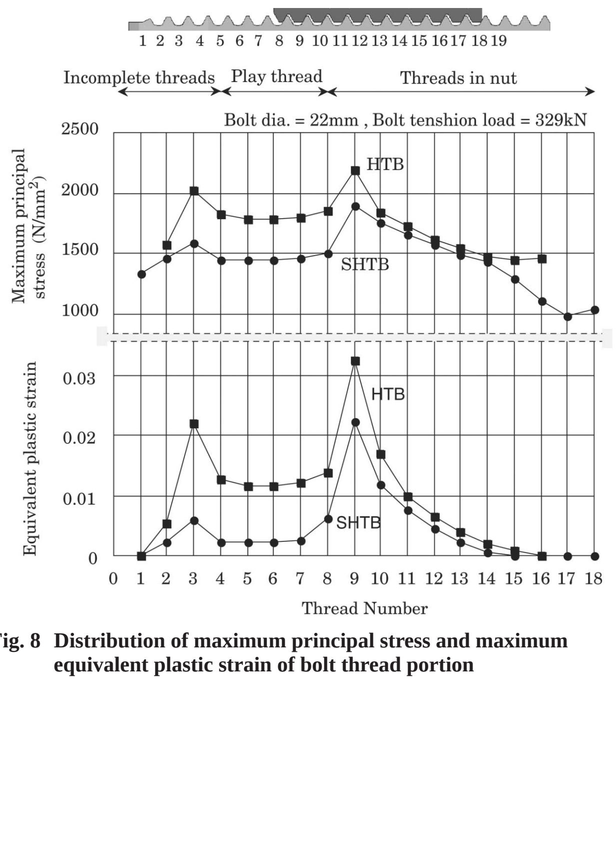


Fig. 8 Distribution of maximum principal stress and maximum equivalent plastic strain of bolt thread portion

2.5 Exposure test to verify delayed fracture resistance of SHTB

As explained in Sub-section 2.3, based on the understanding that a direct and effective measure to enhance delayed fracture resistance of steel is to increase its critical diffusible hydrogen content [H_C], the authors developed a new steel having [H_C] more than three times that of the steel for standard F10T high-strength bolts. The value of [H_C] of the steel for the version of SHTB that was finally launched to the market was yet higher than that of the steel used for the test shown in Fig. 3.

The amount of hydrogen that accumulates in bolts [H_E], on the other hand, varies depending on the environment in which they are used. To verify the delayed fracture resistance of SHTB and confirm the value of its [H_E], the authors subjected the developed bolts to accelerated laboratory exposure test and outdoor exposure test [22, 23].

2.5.1 Accelerated exposure test

Two steel plates, each 22 mm in thickness, were put together using a specimen of SHTB-M22 (hereinafter called SHTB22), and many such sets were placed on a Ferris-wheel type test equipment shown in **Fig. 9** for accelerated exposure test. As the wheels turn one revolution per hour, the specimen sets are immersed in a 3.5% salt solution. To allow the salt solution to contact the bolt shank, two grooves, each 10 mm wide and 5 mm deep, were cut into the steel plates, one on the side of the bolt head and the other on the side of the nut, and two grooves, 10 mm wide and 10 mm deep each, one on each of the two plate sides contacting each other, in a manner to cross each other in right angles at the bolt hole. The applied bolt tension was approximately 340 kN (75% of the tensile strength of SHTB).

A total of 128 bolts of different hot rolling and heat treatment lots were subjected to test batches at different times, each lasting for more than five years. None of them failed, although the specimen bolts rusted more heavily than was expected in normal use. The specimens were retrieved periodically at prescribed intervals to investigate the change in the amount of hydrogen accumulated in the steel [H_E]. The value of [H_E] reached saturation in about half a year of the test, but the maximum value was around 1.5 ppm, roughly a half of [H_C] of the SHTB steel.

2.5.2 Outdoor exposure test

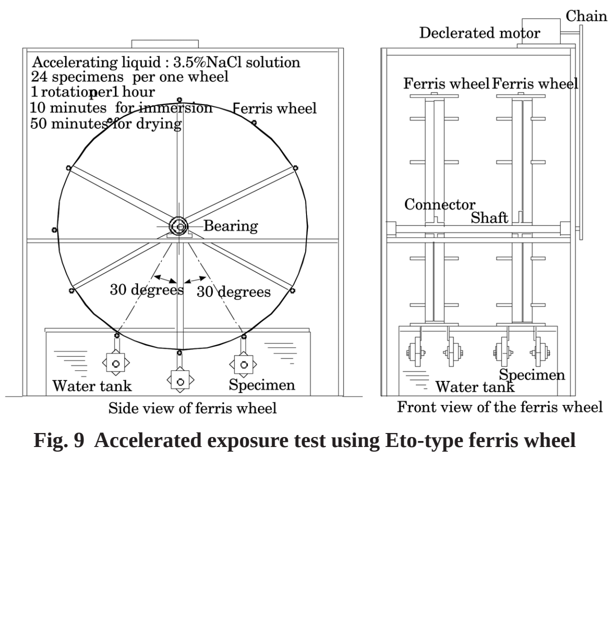


Fig. 9 Accelerated exposure test using Eto-type ferris wheel

Photo 2 Outdoor exposure test in Okinawa

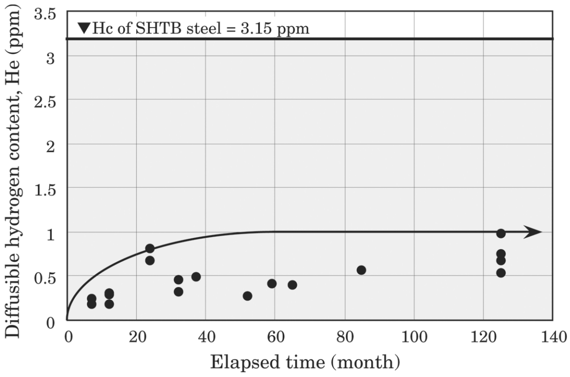


Fig. 10 Accumulated diffusible hydrogen content

The exposure test was conducted at two locations: in a typically corrosive environment in Gushikami Village, Okinawa, and in a typically urban environment in Yoyogi, Tokyo, using 800 test pieces of SHTB22 at each site; the test in Okinawa began in October 1995 and that in Tokyo in May 1996. More than 11 years had passed as of June 2007 and none of the bolts failed at either of the test sites.

Photo 2 shows the outdoor exposure test in Okinawa; the test site is some 100 m from a seashore and seawater droplets fall on the test pieces on windy days, and as a result, bolt heads and nuts exposed to the atmosphere are heavily corroded. **Fig. 10** shows the change of the hydrogen accumulation [H_E] in the bolts obtained through examination by retrieving the test pieces periodically. As seen here, [H_E] nearly reached saturation in about two years of exposure, and remained substantially stable at the level ever since. The maximum value of [H_E] is approximately 1 ppm, which is roughly 1/3 of [H_C] of SHTB. This well explains the reason for SHTB not failing during the exposure test.

3. Mechanical Properties and Design Bolt Tension of SHTB

3.1 Mechanical properties

(1)Mechanical properties of steel

Fig. 11 is an example of tensile test results using No. 4 test pieces specified in JIS Z 2201 cut out from SHTB. The average value of 0.2% yield stress of SHTB was 1345 N/mm^2, that of tensile strength 1452 N/mm^2, elongation 17.1%, and reduction of area 51.3%. The latter two satisfy the respective standard values for F10T under JIS, 14% or more and 40% or more.

(2)Maximum tensile force of bolt

Table 2 shows the results of tensile test of SHTB with a 10° tapered washer or plain washer on the bolt-head side. The mean value

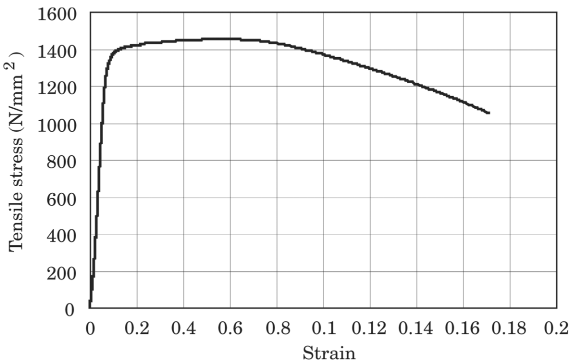


Fig. 11 Stress - strain curve of SHTB steel

Table 2 Results of tensile test of SHTB22

Washer type	Taper washer		Plain washer	
	Max. tensile force T (kN)	T/$_bA_e$ *1 (N/mm^2)	Max. tensile force T (kN)	T/$_bA_e$ *1 (N/mm^2)
Min.	450	1 427	451	1 427
Max.	461	1 458	463	1 464
Mean	457	1 445	457	1 447
SD	2.6	8.3	3.4	10.8
Number of spec.	81		17	

*1 $_bA_e$ = 316mm^2

of the maximum tensile force capacity, 457 kN, is 1.54 times the standard value of F10T-M22, which is 297 kN. The reason why the maximum tensile force capacity of SHTB was more than 1.5 times that of F10T in spite of its tensile strength being lower than the lowest standard tensile strength capacity for F15T of 1,500 N/mm^2 is that the effective sectional area of SHTB is larger than that of the JIS thread by about 4%, as explained earlier herein.

(3) Deforming capacity (relationship between bolt tension and nut rotation angle)

An initial tightening torque of 300 N·m was applied to SHTB22 specimens, and starting from this condition, the deforming capacity of the specimens was tested by tightened the nuts until the bolts broke. **Fig. 12** shows the relationship between the bolt tension and nut rotation angle thus obtained. The number of play threads was roughly eight including the incomplete threads. All the specimens failed at the play thread portion after two nut rotations or more, which is evidence of sufficiently high deforming capacity.

(4)Relaxation properties

Fig. 13 shows the results of relaxation test wherein SHTB22 specimens were used for tightening three JIS SS400 plates, 12, 22 and 12 mm in thickness (46 mm in total); the graph shows the residual bolt tension in percentage to the bolt tension at 1 min after nut tightening. The change of bolt tension was measured with a strain gauge attached to the bolt shank. The residual bolt tension of SHTB22 is roughly 95%; the tendency of its relaxation properties is substantially the same as that of F10T bolts measured so far.

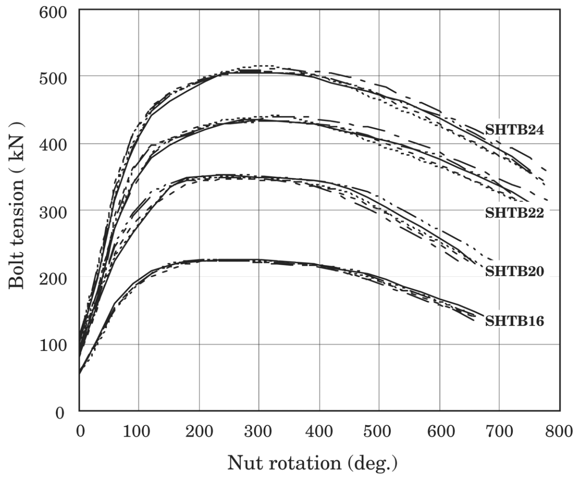


Fig. 12 Relationship between bolt tension and nut rotation

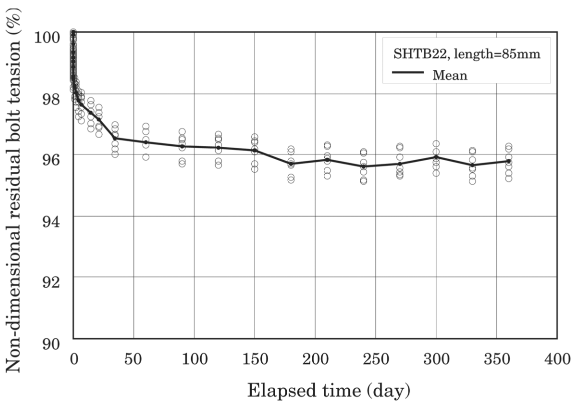


Fig. 13 Relaxation characteristic of SHTB

Table 3 Standard of mechanical properties of SHTB

	0.2% proof stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Reduction of area (%)
SHTB22	126 or over	140-149	14 or over	40 or over
F10T-HTB	96 or over	100-120	14 or over	40 or over

Table 4 Design bolt tension of SHTB

Name	Design bolt tension (kN)	Maximum tensile force (kN)
M16	155 (106)	230 (157)
M20	242 (165)	358 (245)
M22	299 (205)	442 (303)
M24	349 (238)	517 (353)

(F10T-HTB)

3.2 Design bolt tension capacity

SHTB, in nominal diameters of M16, 20, 22 and 24, has been approved by the Minister of Land, Infrastructure and Transport for structural applications. **Table 3** shows the standard mechanical property values of SHTB, and **Table 4** the values of its design bolt tension capacity and maximum tensile force capacity by nominal diameters; the corresponding values of F10T are given between the parentheses for reference purposes[24].

4. Application of SHTB

4.1 Joint design and field connection work using SHTB

Fig. 14 compares an example design of a beam joint using SHTB with another of a conventional joint using F10T. Use of SHTB makes it possible to reduce the size of a bolted joint to about 2/3 that of a conventional one, which leads to advantages such as reduced structure costs, shorter construction time and improved erection workability. However, the advantages of SHTB do not show in pin joints of secondary beams, etc. and there may be cases where SHTB and F10T are used for the same building. Even in such a case, there will be no problem of using one in place of the other because they can be easily distinguished from each other by markings of product name and manufacturer's emblem stamped on the bolt head and the difference in the height of nuts. The fasting work procedures for SHTB are substantially the same as those for conventional high-strength bolts of the torque shear type. It should be noted, however, that the torque for preliminary fastening of SHTB is about twice that of F10T and that for final tightening is also higher, and for this reason, a fastening device suitable for the tightening torque of SHTB must be

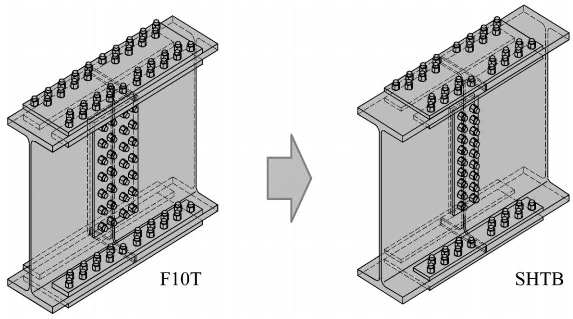


Fig. 14 Comparison of beam joint between using conventional F10T and SHTB

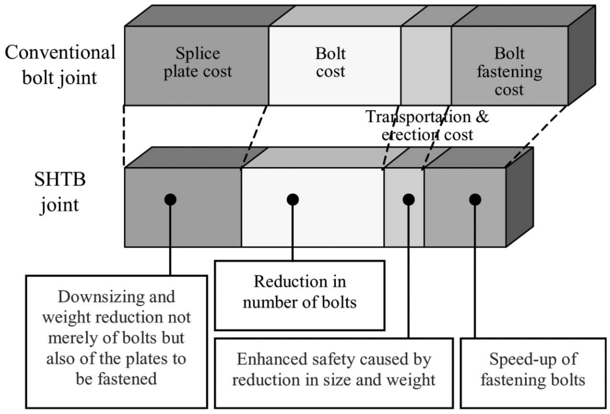


Fig. 15 Reduction of construction cost using SHTB

used. Specialists of Nippon Steel and NS Bolten Co., Ltd. are always ready to provide explanations and advice on the use of SHTB to customers who use it for the first time.

4.2 Examples of application of SHTB

SHTB was first used for the construction of the high-rise building of Hotel Nikko Bayside Osaka in 2001. Its application expanded ever since mainly for high-rise buildings and large-scale structures to count more than 250 buildings (about 10,000 metric tons, 15 million pieces) at present. **Fig. 16** plots the building projects for which SHTB was used in five years since it was launched to the market by the type of building; the size of circles corresponds to the weight of bolts used. The product has been applied mainly to building structures that use frame members of large sections such as high-rise office and multi-purpose buildings, commercial complexes of large column-to-column spans, and plant buildings and warehouses for heavy floor loads. Steel-framed reinforced concrete structure is used for most of medical facilities and hotels. Because of limited story height and other conditions, constant-outer-dimension, wide-flange sections, either rolled or welded, of 490-N/mm^2 class steels are often used for the beams of these types of buildings, and open sections such as of an H- or cross-shape for the columns. As these beams and columns are usually connected using bolt joints, this type of structure is suitable for enjoying the cost reduction effects of SHTB.

Photos 3 and 4 show erection work of a large shopping mall building of a composite structure having columns of concrete-filled, square hollow sections and steel beams. About 140,000 pieces of SHTB were used for beam joints, and the advantages of SHTB such as smaller number of bolts per joint, shorter fastening time, smaller and lighter splice plates, improved workability and work safety greatly contributed to the erection of the whole building frame weighing 7,000 tons in as short as 40 days. In addition to the above benefits, which were envisaged from the development stage, there were unexpected secondary benefits such as neat positioning of mounting pieces for outer wall panels. **Photo 5** shows an outer diaphragm plate for a beam-column joint using SHTB, designed to enhance seismic resistance with the use of continuous columns and reduce manpower for welding. Roughly 200,000 pieces of SHTB were used for this building to connect beams 900 to 1,200 mm in depth to joint diaphragms, which made it possible to reduce the projection of the diaphragms from the column surfaces, minimize required steel weight and improve transportation efficiency. As described above, SHTB is effective in promoting development and wider application of new design and erection methods.

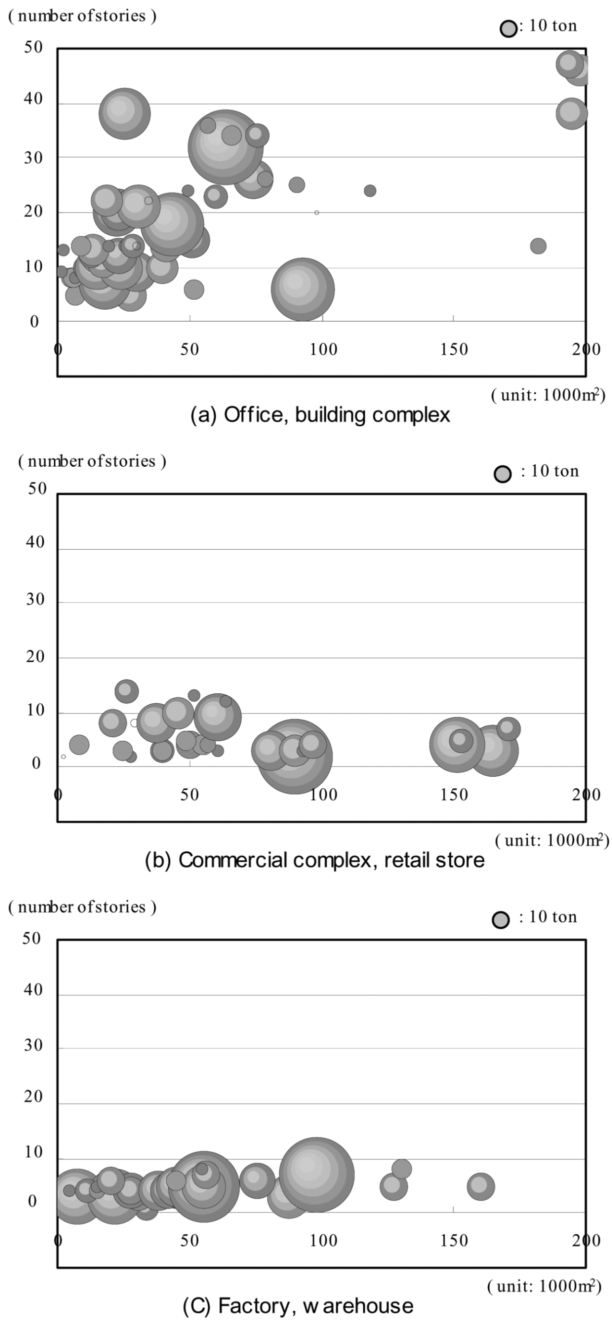


Fig. 16 Actual application of SHTB by building use

Photo 3 Building erection using SHTB

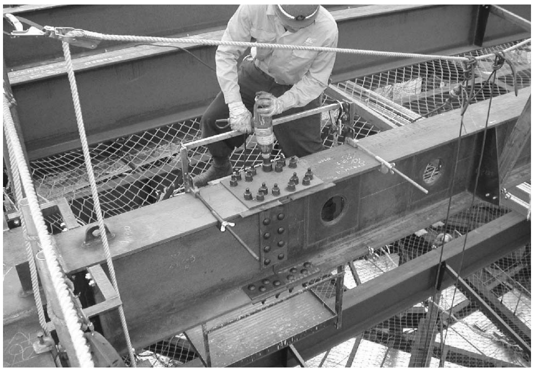


Photo 4 Beam joint of shopping mall using SHTB

Photo 5 Beam-column joint using SHTB

Photo 6 Field welding

Use of SHTB makes it easier to fasten ultra-heavy and high-strength sections together by bolt connection as shown in **Fig. 17**. As an alternative to site welding (see **Photo 6**), which requires skilled workers and high-level quality management systems, SHTB is expected to significantly contribute to quality assurance of steel structure. Although presently used mainly for building structures, SHTB is applicable, with hot-dip galvanizing or a primary rust prevention measure, to structures exposed to more demanding environmental conditions such as bridge structures and steel towers. Hot-dip galvanized SHTB (12GSHTB®) has been commercialized and was used

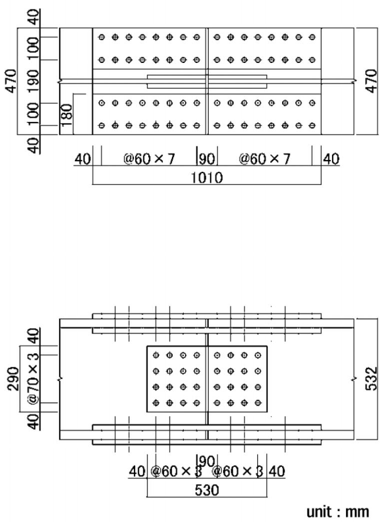
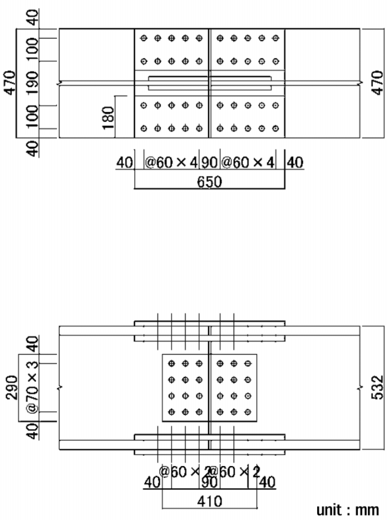
		Conventional bolt	SHTB
Bolt Joint			
High-strength bolt	Flange	S10T-M22 128bolts	SHTB22 80bolts
	Web	S10T-M22 32bolts	SHTB22 24bolts
	Total	S10T-M22 160bolts	SHTB22 104bolts
Splice plate	Flange (out)	PL-22×470×1010, 2plates	PL-22×470×650, 2plates
	Flange (in)	PL-25×180×1010, 4plates	PL-25×180×650, 4plates
	Web	PL-19×290×530, 2plates	PL-19×290×410, 2plates

Fig. 17 Column joint using jumbo shapes and SHTB

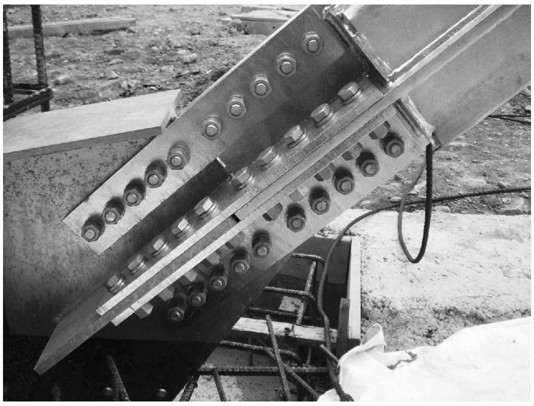


Photo 7 Bracing joint using 12GSHTB

for seismic reinforcement of steel towers for radio transmission as the first application. 12GSHTB is expanding its commercial use for applications such as building structures not covered by roofs and walls. **Photo 7** shows an example of 12GSHTB applications where it is used for bracing joints of a large warehouse.

5. Closing

This paper presented a new high-strength bolt product, super-high-strength bolt, "SHTB®", having a strength 1.5 times that of conventional F10T bolts and is excellent in delayed fracture resistance. The product makes it possible to reduce the size of a bolted joint to about 2/3 that of a conventional one leading to advantages such as reduced structure costs, shorter construction period and improved erection workability, and thanks to all these, its use is steadily expanding principally for high-rise and large-scale buildings. The product lineup of SHTB now includes corrosion-resistant and high-fatigue-strength bolts, and in addition, new types of building structures based on SHTB technologies have been proposed, triggering the development of new building structures. Its application is expected to further expand from the field of building structure to cover all types of steel structures such as civil construction and plant structures.

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