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Development of Low Alloy Type YS785 MPa Class Shearing Reinforcement Contributing to High Strength in Buildings†

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Abstract:

The alloy composition, the manufacturing process, and the product shape were optimized in order to decrease the amount of the alloy element of the YS785 MPa class shearing reinforcement. Although the contribution of the Mo addition to the improvement of property balance was large, the target property was achieved without the addition of Mo by using the other alloy elements such as V. However, the lower alloy has been proved to need the stricter control of cooling process. A highly accurate cooling speed and the cooling stop temperature control was achieved by controlling the velocity of blast air and the amount of air blast cooling time after hot rolling. High strength has been united to excellent ductility by controlling the chemical composition and process condition.

1. Introduction

Reinforcing steel in reinforced concrete (RC) construction can be broadly classified as main reinforcement, which is arranged in the height direction of the structure, and shear reinforcement (hoop reinforcement), which is placed at approximately right angles to the main reinforcement. The role of the shear reinforcement is to prevent major deformation of the structure by constraining the bending of the main reinforcement. Against a background which includes changes in the residential environment, particularly in urban areas, recent years have seen the construction of increasingly higher RC structures. Accompanying this trend, high strength reinforcing steel has been adopted not only in main reinforcements, but also in shear reinforcements in an increasing number of cases, heightening the demand for high strength steel bars. As higher strength concretes are applied, it is known that cracks increasingly tend not disperse, but rather, the members cause brittle shear fracture. Adoption of higher strength shear reinforcements in combination with high strength concrete is an effective means of preventing brittle fracture when higher strength concretes are used[1)]. In response to this need, use of high strength welded type shear reinforcements with yield strength exceeding 490 MPa is increasing.

Construction methods for shear reinforcements can be divided into two types, namely, the spiral type, in which the hoops are wrapped around the main reinforcement in a spiral shape and secured with hooks on their ends, and the welded type, in which a series of individual hoops are arranged in parallel along the length of the main reinforcement, and are closed by welding.

Welded-type hoops offer various advantages from the viewpoint of workability, in that transportation of the reinforcing steel and construction of beams are both easy. However, when conventional high strength steel bars with strength exceeding 490 MPa are welded, a softened area is formed in the heat affected zone (HAZ), causing a phenomenon in which the strength of the welded joint is reduced to less than that of the base material. As a result, reduced ductility due to concentration of deformation on this softened area becomes a problem. These steel materials are required to achieve a

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high strength-ductility balance, including yield strength (YS) of 785 MPa, tensile strength (TS) of 930 MPa, and elongation (El) exceeding 5%, even in butt welding.

In response to this demand and related technical issues, JFE Steel and JFE Techno-wire developed a high strength shear reinforcement[2] which achieves high strength of the YS1275 MPa class by applying a quenching and tempering process, and also developed a high strength shear reinforcement which achieves YS785 MPa in the as-hot-rolled condition.

With the YS785 MPa class shear reinforcement steel produced by the JFE Steel Group, a non-heat treated microstructure consisting mainly of bainite is obtained by employing forced cooling after forming of rebar or round bars having diameters of 10–16 mm by rolling of hot-rolled wire rod materials. Conventionally, the JFE Steel Group had manufactured steel products which achieved these properties stably by adding Mo to the steel. However, the price of the alloying materials called “rare metals,” and among these, Mo, has risen dramatically in recent years because the available amount of these resources is small in comparison with the explosive growth of demand accompanying global economic development[3]. Under these circumstances, a change to an alloy composition which enables more stable use was required.

This paper describes a new steel which was developed in response to the background and problems described above.

2. Outline of Technology

2.1 Study of Optimum Chemical Composition

2.1.1 As-rolled tensile properties

One of the features of the steel used conventionally in this application was the fact that high strength of YS785 MPa or higher was achieved by securing a bainite microstructure by forced cooling of 0.19mass%C-Mo-added steel.

With the target of eliminating Mo addition, the effects of various elements on the required properties were investigated in order to clarify the possibility of achieving those properties by forced cooling of a steel with addition of a substitute element(s). The main chemical composition of the test steels is shown in **Table 1**. Using 0.19 mass% C steel as the base composition, the amounts of added Cr, Si, Mn, Mo, V, and B were varied in order to investigate the effects of these elements on properties. These test steels were prepared by vacuum melting and casting 100 kg ingots. As materials for evaluation, plates with a thickness of 20 mm were obtained by 2 heat hot rolling. These materials were then machined into round bars with a diameter of 13 mm × length of 300 mm, heated to 900°C, and cooled by forced-air cooling to obtain steels for investigation of properties.

Table 1 The chemical composition of steel examined

(mass%)

C	Si	Mn	Cr	V	Mo	Others
0.19	0.20–0.50	1.20–1.80	0.60–1.00	0.01–0.30	0.01–0.70	B, Nb

The effects of the alloying elements on the tensile properties of the test steels are shown in **Fig. 1**. This figure shows the change in the properties of YS and total El in case of addition of 0.1% of the individual alloy elements. In all cases, YS showed an tendency to increase when the alloying elements were added. In comparison with addition of Cr, Mn, and Si, addition of Mo had the advantage of maintaining the balance of properties, in that the decrease in El was small relative to the increase in YS. No remarkable increase in YS was observed accompanying increased addition of V; however, a slightly increasing tendency in El was confirmed.

Photo 1 shows the microstructures of 0.7% Mo-added steel, which achieved a bainite microstructure most stably among the test steels, and 0.15 mass% V-added steel, which showed substantially the same strength as the 0.7% Mo-added steel. Virtually the entire section of the Mo-added material displayed a bainite microstructure, and no clear formation of ferrite could be detected. In contrast to this, ferrite existed in mixed form in the bainite in the 0.15 mass% V-added material when cooled under the same cooling conditions. Photo 1(c) shows the results of transmission electron microscope (TEM) observation of this ferrite portion. The existence of fine V-type carbides could be observed in the ferrite. It is considered that there was little change in the strength of the 0.15 mass% V-added material because addition of V caused strengthening by precipitation of V-based

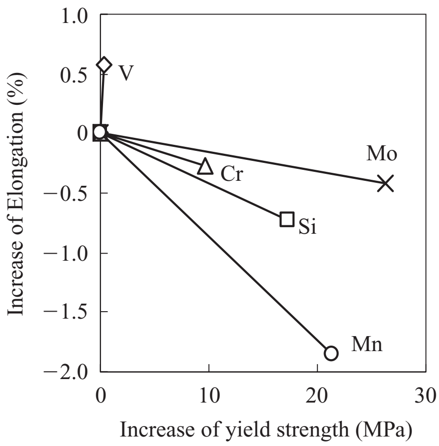
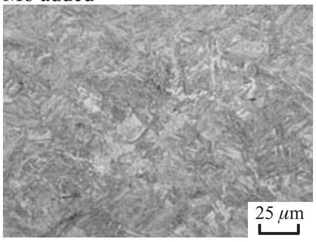


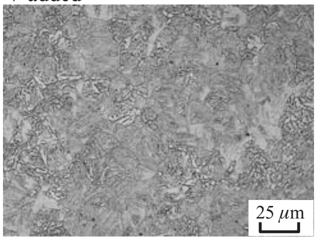
Fig. 1 Tensile property change with the addition of 0.1 mass% alloy elements

Mo added

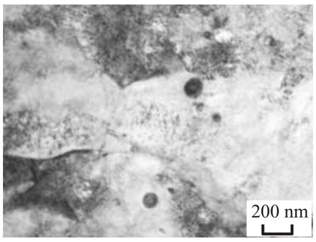


(a) Optical micrograph of steel with addition of 0.7 mass% Mo

V added



(b) Optical micrograph of steel with addition of 0.15 mass% V



(c) Transmission electron micrograph of steel with addition of 0.15 mass%V

Photo 1 Microstructure of the steel after air blast cooling

carbides simultaneously with promoting formation of ferrite, and these two effects were mutually offsetting.

2.1.2 Tensile properties after welding

In order to satisfy both high strength and high ductility after welding, it is important to suppress concentration of deformation on the softened area due to softening of the HAZ during welding. Therefore, the actual surface temperature of the steel during welding was measured in order to investigate the softening characteristics of the HAZ during welding of the steel. Based on the results, the heat histories of respective parts were arranged as shown in **Fig. 2**.

The area where softening progressed the furthest in this welding was the part located approximately 15 mm from the bonding interface.

In order to reproduce these heat cycles experimentally, test pieces with a diameter of 3 mm × length of 8 mm were prepared by machining from the forced-air cooled experimental steel bars (13 mm diameter) obtained in the previous section. The heat cycle corresponding to the part 5–20 mm from the bonding interface was reproduced with these test pieces using a heat treatment simulator (Formastor, manufactured by Fuji Electronic Industrial Co., Ltd.). The hardness where the greatest softening occurred in each steel was obtained as the most softened hardness, and the softening characteristics before and after welding were evaluated. The effects of the respective alloying elements on the amount of softening when a heat cycle corresponding to welding was applied are shown in **Fig. 3**.

With elements such as Mo, V, etc., it was found that both hardness before welding and hardness after welding tend to increase and the amount of softening

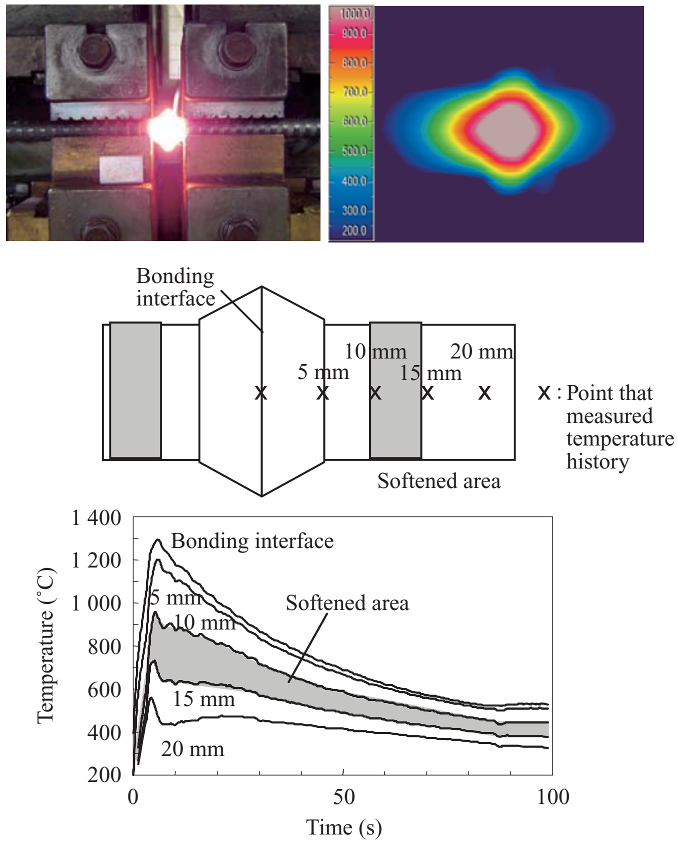


Fig. 2 Heat cycle during welding of shear reinforcement

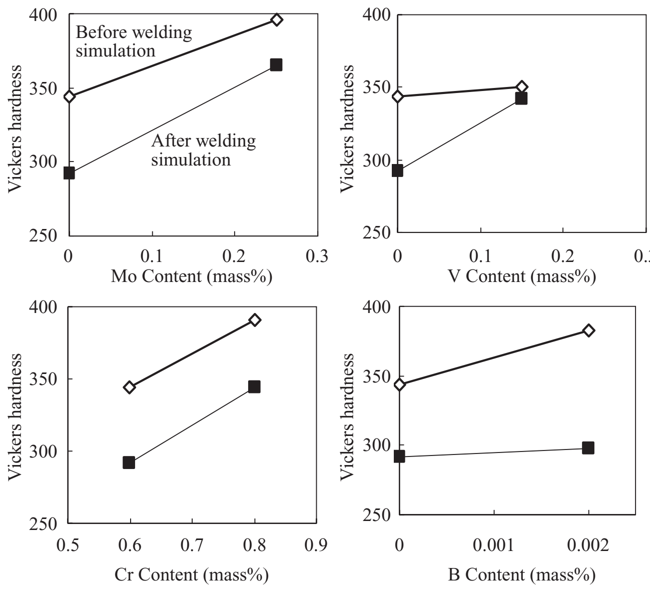


Fig. 3 Effect of alloying elements on the hardness of the steel before and after the welding heat treatment simulation

tends to decrease as the addition of these elements is increased. Within this general tendency, addition of V had a remarkable effect in suppressing softening accompanying the welding heat cycle. On the other hand, with addition of B, an increase in hardness before welding was confirmed, but no clear increase in the hardness of the most softened area after welding could be detected, and it was found that the amount of softening accompanying the welding heat cycle tends to increase as a result of addition.

There are many examples in which B addition is used as a means of obtaining high strength in the as-hot-rolled condition without quenching and tempering. However, in applications preconditioned on welding like that adopted with shear reinforcements, it was concluded that the use of a composition system without B addition is advantageous from the viewpoint of the balance of properties.

In spite of the large contribution of Mo addition to improvement of the balance of properties, based on the knowledge on the effects of alloying elements obtained in the study described above, it became clear that the target properties are not necessarily associated with the addition of Mo and can in fact be achieved by composite use of the effects of other elements, beginning with V.

2.2 Controlled Cooling

In manufacturing the high strength shear reinforcement under discussion here, controlled forced-air cooling is performed while transporting rebar material coiled in a spiral form on the “STELMOR” bed[4] after hot rolling. As an example of the control parameters, **Fig. 4** shows the effect of the air blast pressure and cooling time on the “STELMOR” bed on the temperature of the steel at the end of cooling. In this figure, the forced-air cooling time and blast velocity are shown using indexes in which their respective maximum values are defined as 1.0.

Microstructure control is performed in accordance with a guideline of suppressing the ferrite-bainite transformation in the high temperature region by accelerated cooling using forced-air cooling, and promoting the bainite transformation by stopping accelerated cooling at the proper temperature. Adoption of a system for measurement of the temperature of the steel over its full length when forced-air cooling is stopped has made it possible to control the cooling rate and the cooling stop temperature with high accuracy.

Figure 5 shows examples of the continuous cooling transformation diagrams of 0.7 mass% Mo-added steel

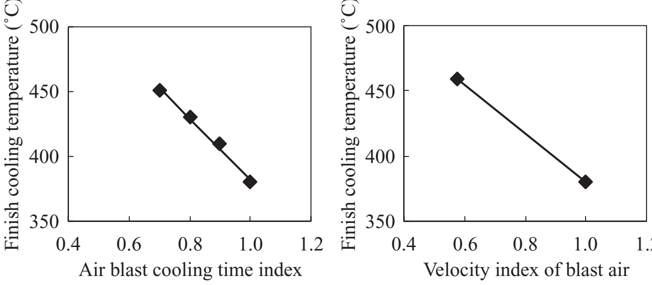


Fig. 4 Effect of cooling time and velocity of blast air on the finish cooling temperature

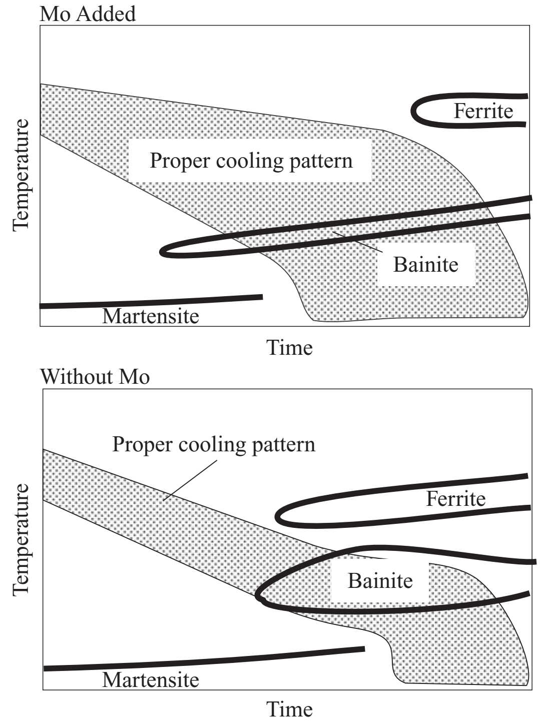


Fig. 5 Continuous cooling transformation diagrams of steels with or without Mo adding

and non-Mo-added steel. With the 0.7 mass% Mo-added steel, the effect of Mo addition suppresses ferrite formation in the high temperature region down to low cooling rates, making it possible to obtain the bainite transformation stably over a wide range of cooling rates. In contrast to this, with the non-Mo-added composition system, the bainite transformation can be obtained only within a limited range of cooling rates.

Based on the controlled cooling technology described above, JFE Steel established “STELMOR” operating conditions for stably realizing the bainite transformation without addition of a large amount of Mo.

2.3 Development of 4-Rib Shear Reinforcement with Excellent Balance of Concrete Bond Strength and Bending Ductility

In order to secure the strength of reinforced concrete structures, in addition to the strength of the steel materials themselves, bond strength between the steel and the concrete is important. Bond strength is determined by the deformed shape of the steel used as reinforcement. In steel bars for use with reinforced concrete, bar shapes with lugs (transverse deformations) are widely used. For YS235 MPa to YS490 MPa class materials, JIS G 3112 (JIS: Japanese Industrial Standards) specifies not only the mechanical properties of each strength class, but also the details of the product shape, including the interval between the lugs, height of the lugs, and other features for each rebar diameter[5].

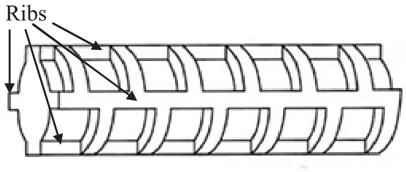


Fig. 6 Shape of developed shear reinforcement

Basically, increasing the concrete bond strength by imparting this kind of deformed shape to the steel and securing fracture resistance in the bending process are fundamentally mutually contradictory, and it becomes even more difficult to satisfy both properties as the strength of the steel material is increased.

In order to solve this problem, in addition to improving the strength-ductility balance of the steel by optimization of the chemical composition and controlled cooling, JFE Steel developed a 4-rib shape for high strength shear reinforcements, in which four longitudinally-continuous convex deformations called “ribs” are arranged at 90° intervals around the circumference of the bar, as illustrated in **Fig. 6**. This product is produced using a 4-roll type finishing mill. In the conventional bars in general use, two longitudinal ribs were provided at intervals of 180°. However, in this case, the fracture resistance of the bar varies greatly, depending on whether the two ribs are arranged in the same plane as the bending direction or in the plane perpendicular to the bending direction. Adoption of a design in which four ribs are spaced at 90° intervals greatly reduced deviations in bending resistance due to the bending angle, and thereby realized high bending resistance in a stable manner.

3. Features of Developed Steel

3.1 Main Properties

3.1.1 Tensile properties

The tensile properties of the developed non-Mo-added steel in the as-rolled condition and after welding are shown in **Fig. 7** in comparison with the properties of Mo-added steel. The developed steel shows tensile properties equal or superior to those of the conventional Mo-added steel in both the as-rolled condition and after welding, without requiring addition of Mo.

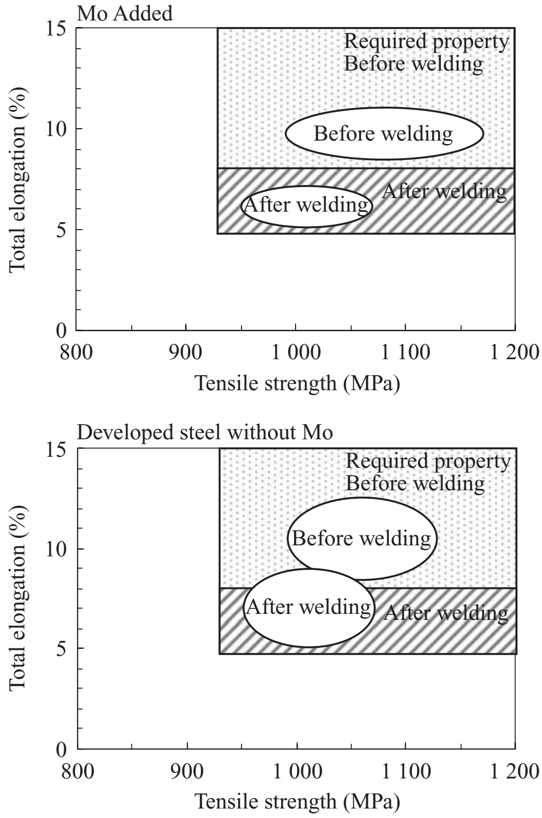
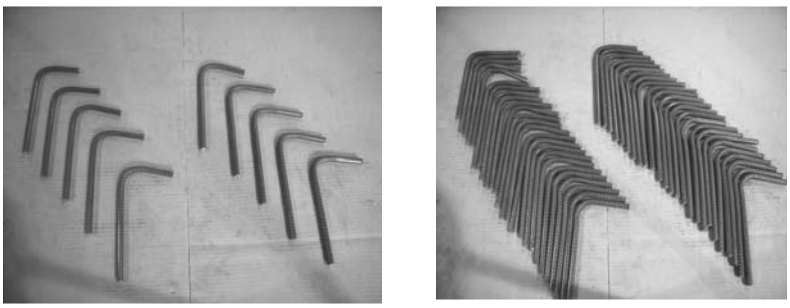


Fig. 7 Tensile properties of developed steel

3.1.2 Bending formability

Photo 2 shows the appearance of the developed steel after a test in which 180° bending at a radius of curvature 3 times the diameter of the respective specimens was performed at room temperature (20°C) and –20°C, followed by return bending to 90°. No fracture or cracking was observed in any of the specimens, showing satisfactory bending formability.



Bent at room temperature　　Bent at −20˚C

Photo 2 Bending test results of developed steel (The steel bar was bent back 90˚ after it was bent 180˚.)

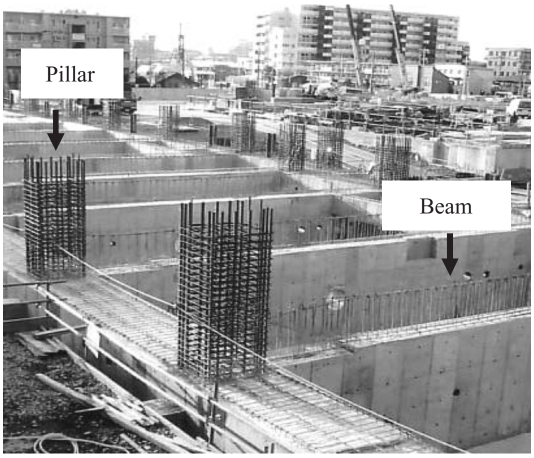


Photo 3 The multistory apartment house construction situation in which the development steel is used

3.2 Examples of Application

Photo 3 shows a view of a construction project using the YS785 MPa class high strength shear reinforcement "Riverbon 785" developed based on the study described above.

JFE Steel has developed high strength shear reinforcement products with two levels of yield strength, "Riverbon 785" and "Riverbon 1275," enabling JFE Techno-wire to respond to a diverse design and construction needs by taking advantage of the respective features of these products. Both high strength shear reinforcements, "Riverbon 785" and "Riverbon 1275," which are suitable for use with high strength concrete, have received individual certification by the Minister of Land, Infrastructure, Transport and Tourism (MLIT),[6] and possess yield strength of 785 N/mm^2 and 1 275 N/mm^2, respectively. The design and construction methods have been certified by the Building Center of Japan[7] for an applicable range of concretes having strengths of 21–60 N/mm^2. It is also possible to use these products with a variety of hoop shapes, including the spiral type, hook type, and welded type.

The safety of "Riverbon 785" is confirmed using a plasticity theory equation[1] proposed in the design and construction guidelines certified by the Building Center of Japan. The superiority of these products can be fully demonstrated when used with high strength concrete, and application in a wide range of structures from mid-to-high-rise buildings to super high-rise buildings is possible.

4. Conclusions

Various studies were carried out with the aim of reducing the amount of Mo addition in YS785 MPa class shear reinforcements. As a result, the following knowledge was obtained.

(1) Addition of Mo makes a large contribution to improving the property balance. However, it is possible to achieve the target properties without addition of Mo by composite use of the effects of other alloying elements, beginning with V.

(2) When adopting a low alloy design, controlled cooling is necessary, beginning with a higher accuracy cooling stop temperature. The effect of the cooling conditions after hot rolling on the heat history of the steel were clarified, and a technology which enables control of the cooling rate and cooling stop temperature with high accuracy was developed.

(3) Although the said application had conventionally assumed addition of Mo as a precondition, a study based on the above-mentioned knowledge clarified the fact that the required properties can be achieved without necessarily adding Mo.

As higher strength concretes are used, it is known that cracks increasingly tend not disperse, but rather, the members cause brittle shear fracture. In order to prevent brittle fracture when using higher strength concretes, it is effective to use higher strength shear reinforcement in combination with the concrete. In the future, JFE Steel and JFE Techno-wire will continue to study and develop high strength shear reinforcements matched to higher strength concretes.

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