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A STUDY ON THE SEISMIC REINFORCEMENT OF BUILT UP BEAM USING THE HIGH STRENGTH BOLTED JOINTS

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Abstract

Structurally weak points, such as the joints of beams and columns, must be reinforced in seismic design. The seismic reinforcement of joints has been researched in many studies. Welding has been used as a method of reinforcing joint parts because it offers high design flexibility and drilling a hole is not necessary. However, factories require strict fire curing to protect their machine equipment and products. Welding cannot be performed in factories that handle oil and flammable substances. In addition, welding technology is difficult and influences the strength of the weld. For these reasons, reinforcement is often accomplished by friction joints using high-strength bolts. High-strength bolting technology with high seismic performance is important because bolt connection is superior to welding in terms of building recycling and reuse.

The reinforcement method proposed in this research achieves high-strength bolt joints with high structural performance in buildings whose parts cannot be welded. Beams are designed as beam sideway mechanisms so that plastic hinges occur at the beam ends. Therefore, sufficient bending proof strength and flexural rigidity must be obtained since they play vital roles in earthquake proof. This experiment considered a deflection reinforcement of built-up beams in which H-shaped steels were stacked and jointed with high strength bolts. Friction joints were selected as the high-strength bolted joints because they are robust against breakage caused by partial area loss in the bolt holes and are resistant to cyclic loading. To improve the structural performance of the friction joint, the friction surface must be made slip resistant. For these reasons, the three friction surface with different friction properties such as shot blasting, mill scale and coating were verified in the experiments. The structural performance of the high-strength bolted joints was experimentally validated for different processing methods of the friction surface. In future work, we will investigate seismic reinforcement of other parts, such as the joints of beams and columns.

This research examined the friction joint of built-up beam with high strength bolt in the two experiments. The proof stress and structural performance of the friction joints were verified in tension and bending experiments. In the tension experiment, the performance of the shot-blasted friction surface was evaluated by the slip factor. The built-up beam bending test also clarified the structural performance of the specimen composed of stacked H-section steels and jointed with high-strength bolts. Consulting the two sets of experimental results, we examined the function and performance of the high-strength bolted joints and considered the seismic performance effect of the built-up beam joined by high-strength bolts.

This paper validated the structural performance of the built-up beam from the results of the two experiments and examined the deflection-reinforcement function of the beam. Moreover, the structural performance of the high-strength bolt friction joint was examined to explore the possibility of aseismic reinforcement in other parts.

Keywords: seismic reinforcement; *high strength bolt; built-up beam; slip factor; shot blast*

1. INTRODUCTION

Welding has high design flexibility and does not require the drilling of a hole, thus, it is used to reinforce joint parts. However, factories require strict fire curing to protect their machine equipment and products. Welding cannot be performed in factories that work with oil and flammable substances. Furthermore, welding technology is difficult and influences the strength of the weld. Therefore, friction joints are often used for reinforcement using high-strength bolts. High-strength bolting technology with high seismic performance is critical because bolt connection is superior to welding in terms of building recycling and reuse. The reinforcement method proposed herein creates high-strength bolt joints with high structural performance in buildings whose parts cannot be welded.

The experiment conducted herein considered the deflection reinforcement of built-up beams in which H-shaped steels were stacked and joined using high-strength bolts. The unification of joints in built-up beams is important to obtain sufficient bending strength and flexural rigidity. However, currently, little research has been conducted on such unified joints in the field of steel structures. Therefore, in this work we focused on friction joints creates using of high-strength bolts on built-up beams.

A friction joint tension experiment and a bending test of the built-up beam using the high-strength bolted joints were performed to verify the strength and structural performance of the friction joint. This article reports the results of the friction joint tension and bending experiment of the built-up beam using high-strength bolted joints.

2. EXPERIMENT OUTLINE

2.1 OVERVIEW OF FRICTION JOINT TENSION EXPERIMENT

In normal high-strength bolt friction joints, the standard hole diameter for M24 bolts or less is defined as the bolt nominal diameter (d) + 2 mm[1)]. The experiment conducted herein aimed to determine the standard slip factor of the friction surface with hole diameters of (d) + 3mm above the reference value.

Based on existing literature 1), a two-sided friction jointing method was used with F10T and M22 bolts. In the test specimen, two medium steel plates were sandwiched between two splice plates, and the joints on both sides were joined with two bolts each. The experiment used test specimens processing shot blasting, general painting and mill scale on the friction surface. Three specimens were used in one processing trial for a total of nine specimens.

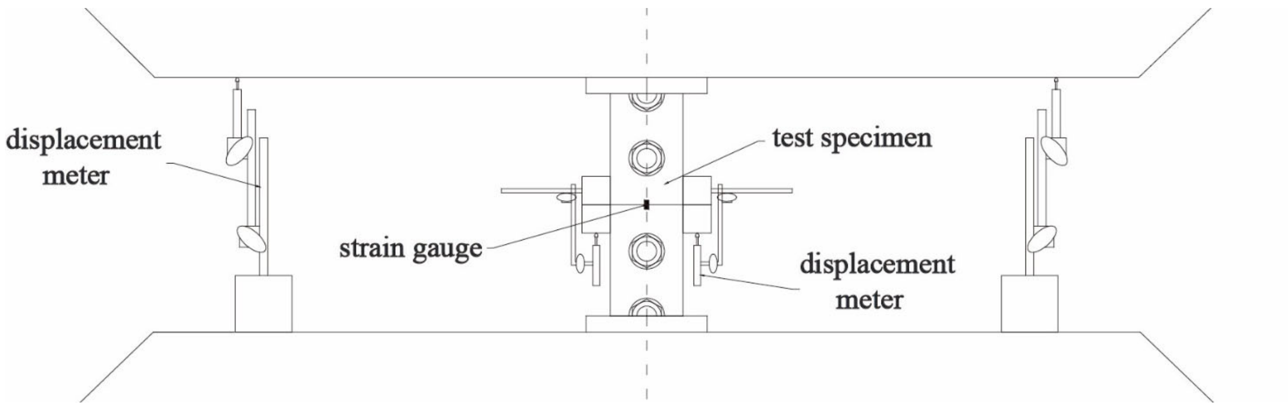


Fig.1. Situations of the friction joint tension experiment

A 2000 kN universal testing machine was used as the loading device. The loading was monotonous tension loading, and the test was performed until the main slip on the friction surface was confirmed. The experiment measured the relative displacement between the base metal and the splice plate, and determined the slip factor to understand the variation in structural performance due to the difference in the treatment method of the friction surface. Furthermore, strain gauges were attached to a specimen with each friction surface processing method to check the stress condition of the splice plate.

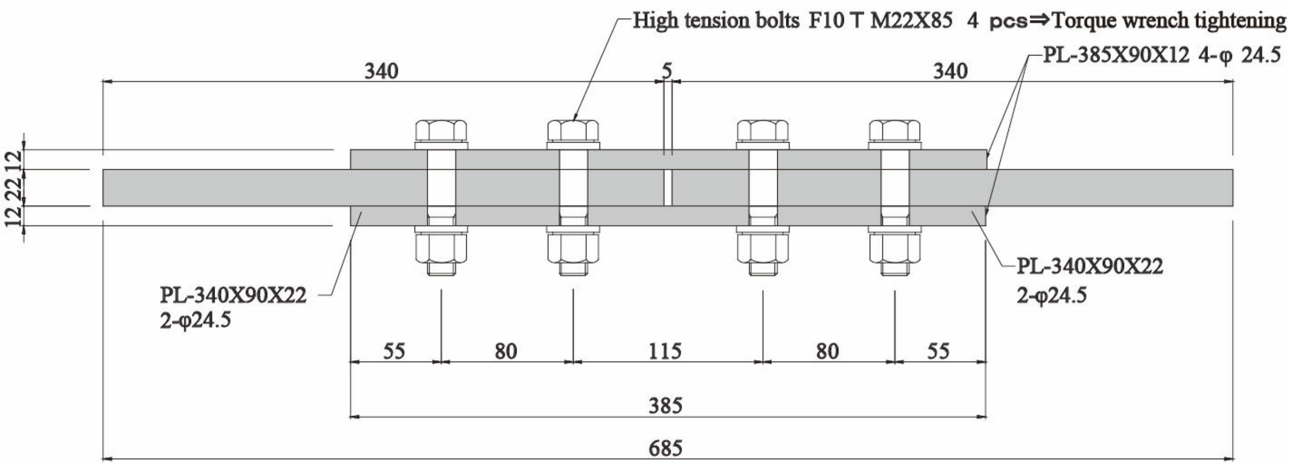


Fig.2. Detail view of test specimens

2.2 OVERVIEW OF THE BENDING EXPERIMENT OF THE BUILT-UP BEAM USING THE HIGH STRENGTH BOLTED JOINTS

The experiment aimed to understand the structural performance of the built-up beam, and results confirmed that the beam in which the H-beams are stacked and jointed functions as a united built-up beam.

The test specimens comprised a built-up beam containing two 1.6-m-long and wide H-beams of the following dimesnions 150 × 150 × 7 × 10, and the same cross-section. As a basic test of the members, experiments on a single H-section steel was also conducted.

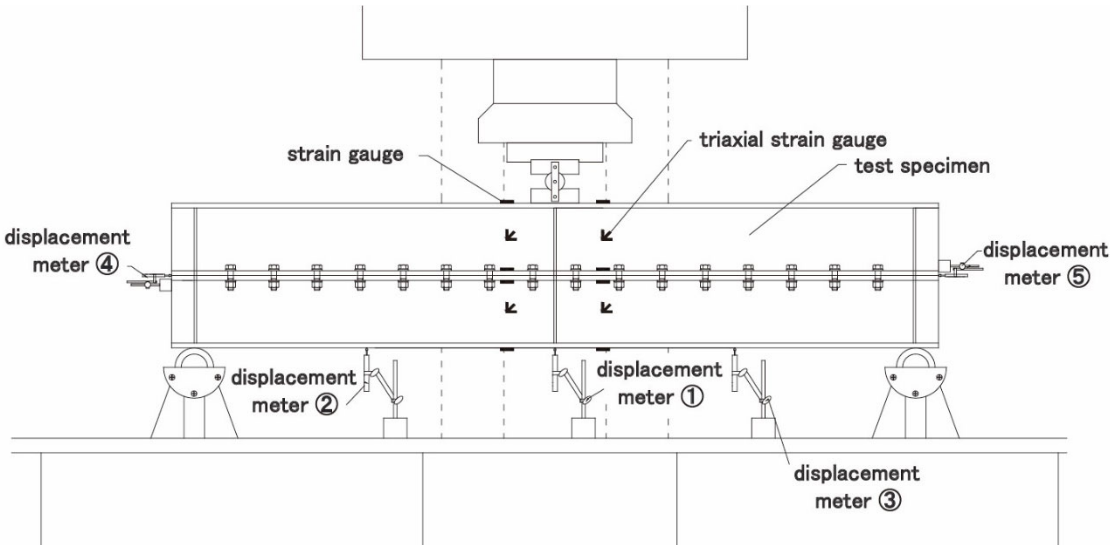


Fig.3. Situations of the bending experiment of the built-up beam using the high strength bolted joints

Figure 1 depicts a bending experiment of the built-up beam performed using high-strength bolted joints, and Fig. 2 shows details of the specimen. The processing method of the friction joint surface and the number of high-strength bolts were varied in the experiment. The number of bolts was set when the friction surface was shot-blasted against the yield strength of the beam. The bolt interval was set at 120 mm as is standard, in accordance with the high-strength bolts. Three experiments of 90 and 240 mm were conducted confirming the performance of a built-up beam. Furthermore, the experiment applied a load to mill scale and coating specimens with a friction surface with a bolt interval of 120 mm for comparison.

A 2,000 kN universal testing machine was used as the loading machine, and the loading method was central 3-point loading with a supporting point distance of L = 1.5 m. The experiment measured the strain of each part of the built-up beam, the maximum deflection at the center of the beam, the displacement between the upper and lower beams, and the slip strength. This experiment considers the structural performance of built-up beams by the difference in the friction surface.

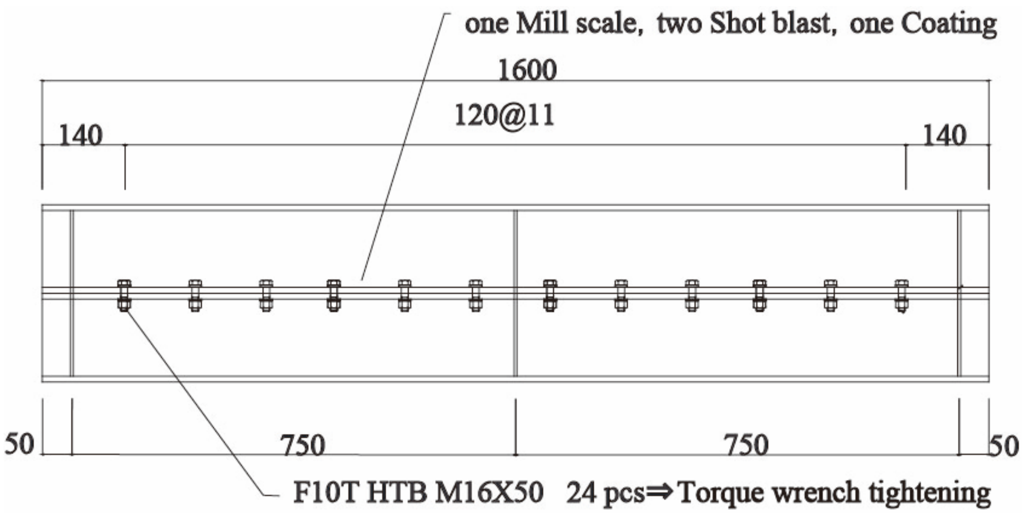


Fig.4. Detail view of test specimens

3. FRICTION JOINT TENSION EXPERIMENT

3.1 LOAD-DISPLACEMENT RELATIONSHIP

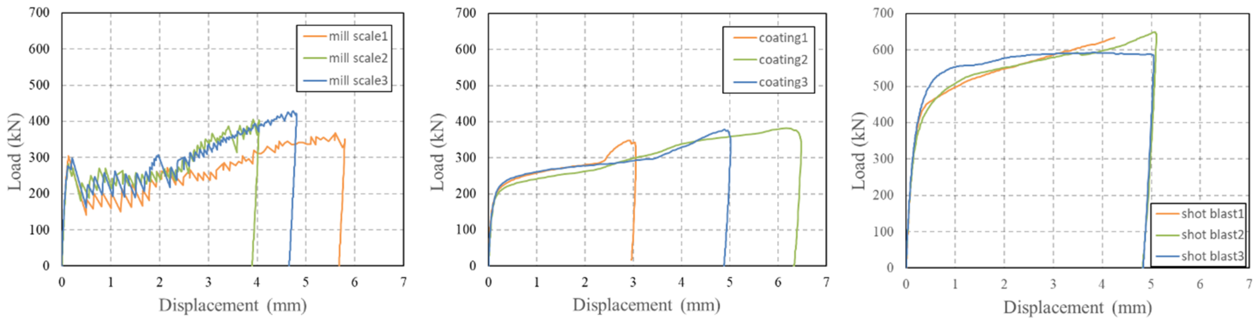
To determine the slip factor for a friction surface, it is standard to measure the relative displacement at the joint. In the friction joint tensile test, the absence of a clear main slip determines the slip strength based on the slip displacement obtained from the displacement meter. Therefore, measuring elongation by setting an appropriate measurement section used as a load-displacement relationship in addition to the relative displacement in necessary. In this regard, no standards are currently set. Thus, the sliding strength was defined as the strength corresponding to 0.2 mm relative displacement based on the results of many conventional experiments. The slip factor was determined based on the slip strength as defined in this definition.

Figure 5 shows the load-displacement relationships of the mill scale, coating and shot blasted specimens. For mill scale test specimens, mill scale-1 had a larger drop in load than mill scale-2 and -3 when the main slip occurred. It was then confirmed that only mill scale-1 had a significantly small load. Furthermore, the load sharply increased at a displacement of about 2 mm regarding mill scale-3.

In the coating test specimens, a sharp increase in the load was observed in coating-1 and -3 owing to the change caused by frictional force to bearing pressure. Coating-2 did not show a sharp rise within the range of the graph. However, different rising in load were observed for the test pieces because of differences in the displacement of the bolts in the holes. The maximum load value confirmed that the load is slightly up and down.

For the shot blasted specimens, shot blast-3 at a displacement of 0.5 mm was higher than that of the other specimens. The load value became substantially constant as the load was applied. Furthermore, shot blast-2 showed a point where the load suddenly dropped near a displacement of 3.5 mm. Considering the slip factor, the value of shot blast-2 was lower than that of the other two specimens.

Finally, only shot blast-3 was different in the shape of the slip position graph. Thus, the yield of the base metal partially exclusively occurred near the slip strength of shot blast-3.



(a) mill scale (b) coating (c) shot blast

Fig.5. Load-Displacement Relationship

3.2 EXAMINATION OF SLIP FACTOR

The slip factor is obtained using the following equation.

$$F = m \cdot \mu \cdot N \quad \text{.......} \quad (1)$$

where F is the inter-material frictional force (kN), m is the number of friction surfaces, μ is the slip factor, and N is the design bolt tension (kN). The substituted value was m = 2, from two-sided friction welding and standard tension was N = 205 kN × 2 = 410 using two bolts F10T and M22. Different slip factors could be obtained depending on the processing conditions of the friction surface.

Table 1 shows the results of the friction joint tension experiment. As a whole comparison , the slip strength was larger in the order of shot blast> mill scale> coating, and the same results were obtained for the proportional slip factor.

As can be seen from Fig. 5, the coating and shot blasted specimens plotted a smooth curve and gradually began to slip, with no apparent main slip. However, based on Fig. 5, the load rapidly decreased only in the mill scale test specimen, and a clear main slip was observed. After the main slip occurred, the load was repeatedly increased and decreased, possibly because the displacement continued to occur because of the regular peeling of the mill scale.

When a slip occurred, a loud slipping sound was heard. Over time, the quality of the sound changed and it became quieter.

Regarding the slip factor, μ = 0.45 or more is expected to be obtained by the processing shot blast. Table 1 shows that the average value of the shot blast slip factor was 0.447, which was 0.45 or less. In this experiment, the sliding strength was evaluated at a displacement of 0.2 mm. However, the value obtained by the measurement method in the experiment includes the elongation of the base metal, and the load at which the actual slip occurred was about 420 kN according to Fig.8 Therefore, it is considered that a slip factor of 0.5 or more could be obtained.

Further, to obtain a slip factor higher than the present result, the friction surface roughness of the shot blast must be increased. In this experiment, the friction surface roughness was designed to satisfy the maximum height roughness of 50 μm or more, but the actual value of the specimen was not measured. It has been found that a slip factor of 0.45 or more could be obtained when the maximum height roughness is 50 μm or more.

Table 1. Slip factor of friction surface processing

material		slip load capacity(kN)	slip factor	slip factor Ave
black scale	①	303.68	0.370	0.359
	②	282.90	0.345	
	③	297.42	0.363	
coating	①	209.79	0.256	0.255
	②	202.25	0.246	
	③	214.68	0.262	
shot blast	①	368.59	0.450	0.443
	②	346.57	0.423	
	③	373.90	0.443	

4. BENDING EXPERIMENT OF THE BUILT-UP BEAM USING HIGH-STRENGTH BOLTED JOINTS

4.1 LOAD-DISPLACEMENT RELATIONSHIP (LATERAL DISPLACEMENT)

Figure 6 shows the average value of displacement meters ④ and ⑤, and Fig. 7 shows the values of displacement meter ①.

Figure 6, confirms that the displacement of the mill scale and coating is large, and that slip remarkably occurred compared with the shot blast. However, regardless of the difference in slip, the difference in maximum load was small, as shown in Fig. 7, and the effect on the strength was small. Furthermore, the difference between the maximum load of shot blast specimens 120 and 90 mm was small, and the effect of the difference in bolts was small. In this experiment, the increase in proof strength after the slip strength was higher than expected, and it is considered that exceeding the yield point of steel material had a great effect. Therefore, a similar experiment was performed on a bolt pitch on a 240 mm specimen with a reduced number of bolts to confirm the slip behavior.

Figure 6 shows the difference in lateral displacement due to the reduction in the number of bolts, and Fig. 7 shows the difference in maximum deflection. Figure 6 showed that the slip of the shot blast at 240 mm is as large as the mill scale and coating. Figure 7 showed that the maximum load for the shot blast at 120 mm was larger than that for the shot blast at 240 mm. Therefore, the effect of the friction joint created using the high-strength bolts was large and the small number of bolts caused the slip.

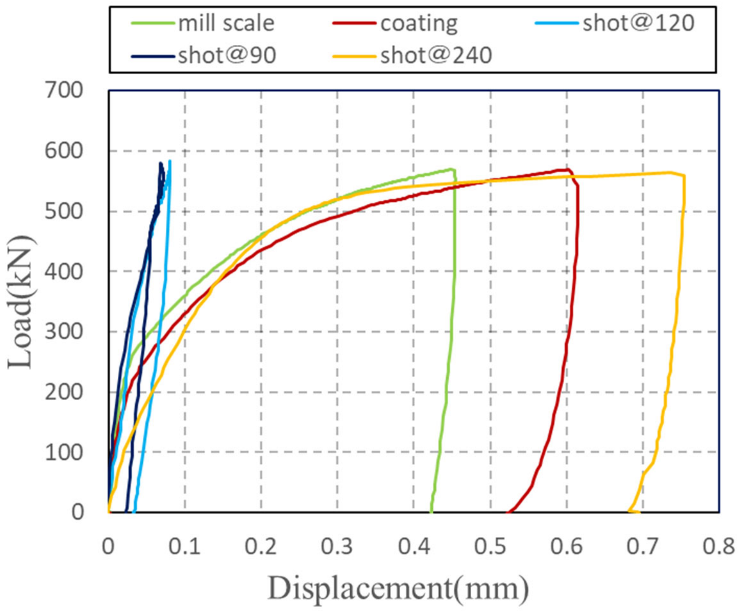
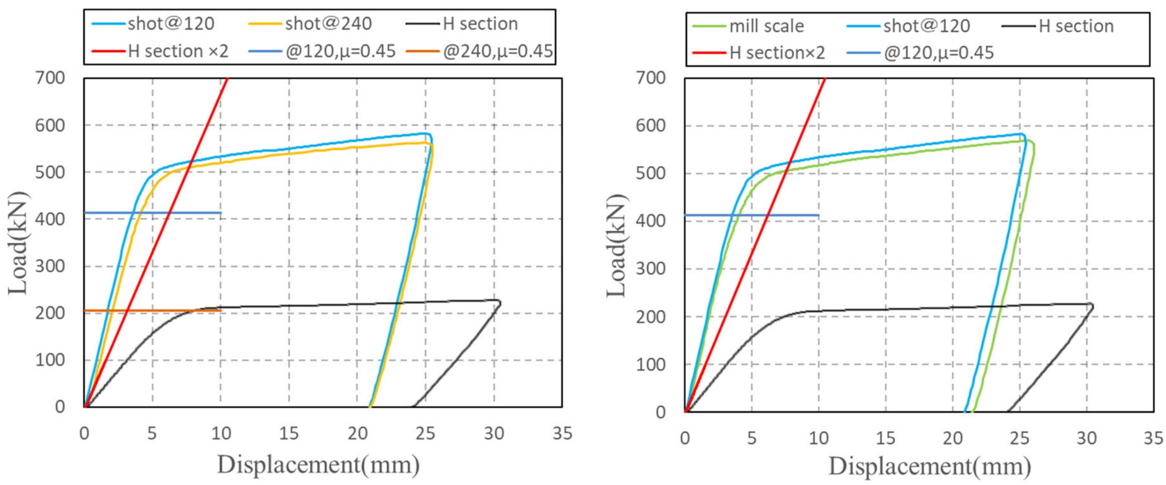


Fig.6. Load-Lateral displacement Relationship of built-up beams

4.2 RIGIDITY EXAMINATION

Figures 9 and 10 show the rigidity of two non-united H-beams based on the rigidity of a single H-beam.



(a) Shot blast at 120 mm and 240 mm (b) Shot blast at 120 mm and Mill scale

Fig.7. Load-Displacement Relationships of built-up beams

As the rigidity of the built-up beam specimen was higher than that of two non-unified H-section pieces of steel, the rigidity was improved by unifying them. Figure 7 shows that the difference in the inclination of the test specimen was small, and the influence of the slip on the rigidity was small. However, the rigidity of shot blast at the 120 mm specimen with a small slip was higher than that of the mill scale, and it is considered that the smaller slip improved the rigidity. Furthermore, the rigidity of the shot blast at 120 and 90 mm was similar.

In Fig. 7, the inclination of the shot blast at 240 mm was smaller than the shot blast at 120 mm, as in the mill scale. Thus, few bolts caused the slip and reduced rigidity.

4.3 EXAMINATION OF SLIP STRENGTH

Figure 7, and Table 4 show the calculated values of slip strength. The calculated value is obtained from the following equation.

$$P = 2Q = \frac{4IR_1}{S_1\rho_1} \qquad \text{......} (2)$$

where P is the slip strength (kN), Q is the shear force (kN), I is the moment of second order (mm^4), $R1$ is the bolt tension (kN), $S1$ is the statistical moment of area (mm^3), and $\rho 1$ is the bolt pitch (mm).

Table 4 shows that the slip strength of the shot blast at 120 and 90 mm was higher than the yield strength. Therefore, it is considered that the built-up beams caused lateral displacement before the yield of the steel material. For mill scale, coating, and the shot blast at 240 mm, the yield strength was higher than the slip strength. It is considered that the maximum strength was lower than the shot blast at 120 mm because the steel material yielded first. Because the difference between the maximum strength was small in Fig. 7, the effect of the high-strength bolts is, however, considered to be greater than the effect of the slip.

Table 2. Dimensions and Rigidity of Test Specimens

	H	B	tw	tf	A	I	E	G	Aw	ks	L	Kb	Ks
	(mm)	(mm)	(mm)	(mm)	(mm^2)	(mm^4)	(N/mm^2)	(N/mm^2)	(mm^2)		(mm)	(N/mm)	(N/mm)
H-section	150	150	6.76	9.76	3810	15671079	205000	78846	882	1.2	1500	45690	154546
two H-sections	150	150	6.76	9.76	3810	31342157	205000	78846	1764	1.2	1500	91380	309093
built-up beam	150	150	6.76	9.76	3810	74205161	205000	78846	1764	1.2	1500	216349	309093

Note: H = beam depth, B = beam wepth, tw = web thickness, tf = flange thickness, A = sectional area, I = geometrical moment of interia, E = Young's modulus, G = modulus of rigidity, Aw = sectional area of web, ks = shape factor, L = span, Kb = flexural rigidity, Ks = shear rigidity.

Table 3. Calculation results of Test Specimens

	σyf	σyw	Z	Zpf	Zpw	My	Qy	Py	Mp	Qp	Pp
	(N/mm^2)	(N/mm^2)	(mm^3)	(mm^3)	(mm^3)	(kN·m)	(kN)	(kN)	(kN·m)	(kN)	(kN)
H-section	297	312	208948	205311	28772	62.1	83	165	70.0	93	187
two H-sections	297	312	417895	410623	57545	124.1	165	331	139.9	187	373
built-up beam	297	312	494701	439200	132307	146.9	196	392	171.7	229	458

Note: σyf = flange yield strength, σyw = web yield strength, Z = section modulus, Zpf = flange plastic section modulus, Zpw = web plastic section modulus, My = yield moment, Qy = yield shear force, Py = yield load, Mp = plastic moment, Qp = plastic shear force, Pp= plastic load.

Table 4. Slip factor and strength of Test Specimens (built-up beams)

friction surface processing	one H-section value										
	H (mm)	*B* (mm)	*tw* (mm)	*tf* (mm)	*A* (mm^2)	*I* (mm^4)	*S1* (mm^3)	*T* (kN)	*@* (mm)	μ	*P(0.3)* (kN)
shot blast	150	150	6.76	9.76	3810	74205161	285753	106	120	0.450	413
										0.443	406
mill scale	150	150	6.76	9.76	3810	74205161	285753	106	120	0.300	275
										0.359	329
coating	150	150	6.76	9.76	3810	74205161	285753	106	120	0.225	206
shot blast	150	150	6.76	9.76	3810	74205161	285753	106	90	0.450	551
										0.443	542
	150	150	6.76	9.76	3810	74205161	285753	106	240	0.450	206
										0.443	203

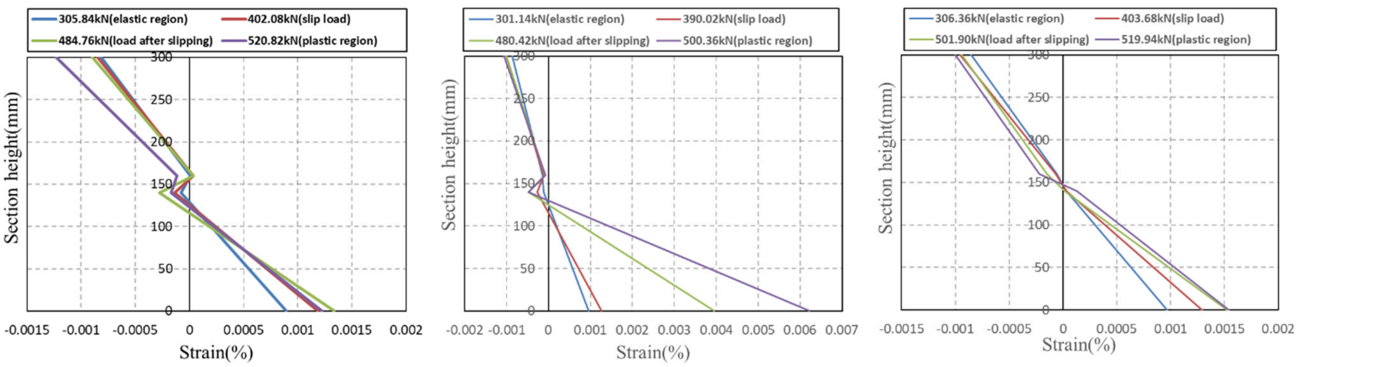
Note: *H* = beam depth, *B* = beam wepth, *tw* = web thickness, *tf* = flange thickness, *A* = sectional area, *I* = geometrical moment of interia, *S1* = geometrical moment of area, *T* = design bolt tension, @ = bolt pitch, μ = shape factor, *P* = slip strength.

Figure 7 shows that all of the specimens with mill scale, the shot blast at 120 and 240 mm have higher maximum strength than slip strength (calculated value). Accordingly, the high-strength bolt increased the load even after the slip occurred. Furthermore, Fig. 9 shows that the difference between the maximum strength and the sliding strength of the mill scale test specimen is large. Therefore, it can be confirmed that the strength of the built-up beam was increased using the high-strength bolts.

4.4 CROSS-SECTION-STRAIN RELATIONSHIP

The results for the mill scale and coating specimens were similar. Additionally, the results for the shot blast at 120 and 90 mm were similar. Therefore, Fig. 8 focuses on the mill scale and shot blast at 120 and 240 mm.

Figure 8 shows that as the load increased in the black scale specimen, the graph became discontinuous near the sectional height at 150 mm of the friction joint, but changed continuously in the shot blast specimen. This result indicated that the degree of jointing for the members differed depending on the friction surface processing. In the mill scale test specimen with a small slip factor, slip occurred owing to a decrease in the frictional force between the H-shaped steels, and the unification of the two H-sections was released. Therefore, it is considered that the strain occurred in the central portion. The strain increased as the specimen yielded and became plasticized, and the unification of the two H-sections was released. The unification of the shot blast at 120 mm, however, was maintained even after the yield of the test specimens, and no strain occurred in the central part. Thus, shot blasting of the friction joint surface increases the slip factor and unites the built-up beams Furthermore, the shot blast at 240 mm had the same tendency.



(a) Shot blast at 240 mm (b) Mill scale (c) Shot blast at 120 mm

Fig.8. Sectional height-Strain Relationships

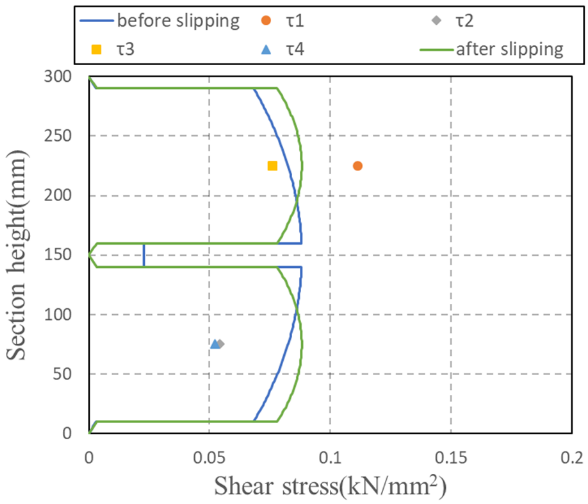
Regarding the bolt pitch, the shot blasts at both 120 and 90 mm maintained their joints after yielding, and showed a graph shape close to a straight line. Because the shot blast at 240 mm could not obtain a linear graph, it is probable that sufficient frictional force was obtained with the shot blast at 120 mm.

4.5 SECTION HEIGHT -SHEAR STRESS RELATIONSHIP

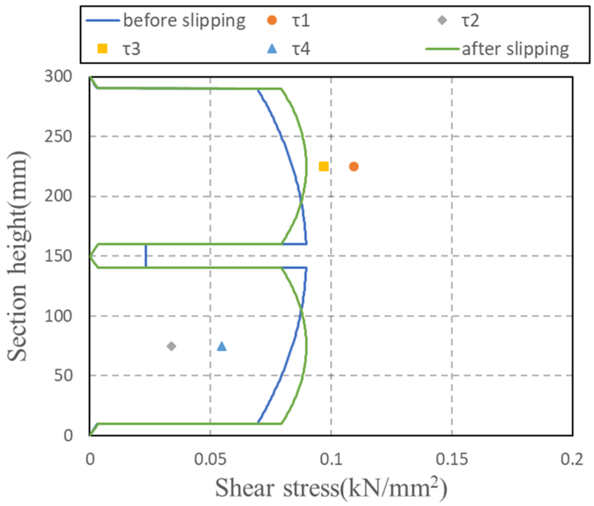
Figure 9 shows the shear stress distribution on the cross-section before and after slipping when the H-section steel is united. Figure 9 shows the shear stress distribution of the mill scale and the shot blast at 120 mm. The plots in figure 9 show the values of the shear stress and the bending stress corresponding to the positions of the gauges.

Fig. 9 shows that the shear stress exerts a large force on the entire web and the value at the flange is small. Thus, the web bore the shear stress. Additionally, in the cross-sections from 10 to 90 mm and 200 to 290 mm, the value of the graph after the slip was larger than that before the slip, but the value before the slip near the cross-section of 150 mm was larger.

In Fig. 9, the values of the plots for the upper H-section steel were larger than those for the lower scale for both the mill scale and shot blast at 120 mm. Furthermore, because some plots were far from the values in the distribution, no agreement was found between the plots and the distribution.
Based on the above, the upper stage H-section steel tended to exert large shear stress. In contrast, the effect of the shear force seems small for the lower H-section steel because the plot was smaller than the value of the distribution.



(a) Mill scale



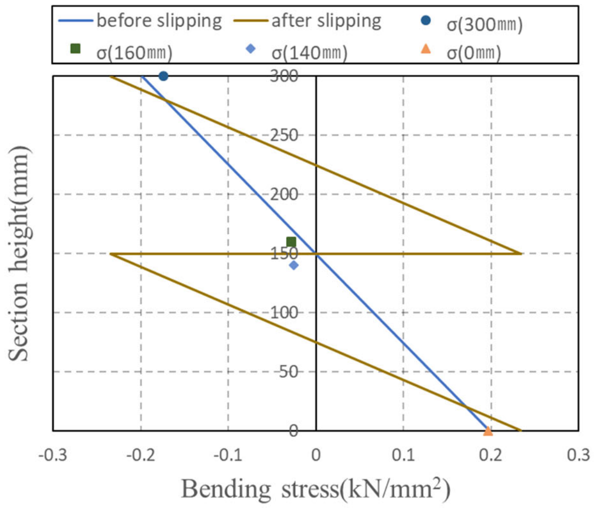
(b) Shot blast at 120 mm

Fig.9. Sectional height-Shear stress Relationships

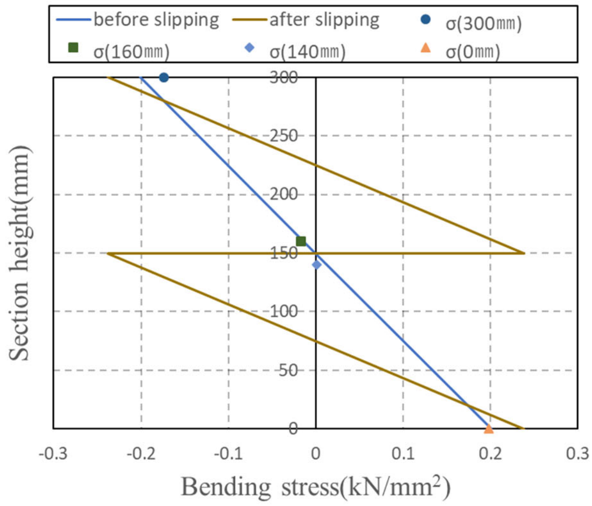
4.6 SECTION HEIGHT -BENDING STRESS RELATIONSHIP

Fig. 10 shows the bending stress distribution on the cross-section before and after slipping. The plots in figure 10 show the values of the shear stress and the bending stress corresponding to the positions of the gauges.

Figure 10 show straight-line graphs before the slip, and that the upper and lower H-section steels are separately subjected to bending stress after slipping. Furthermore, the value of the bending stress degree was larger after slipping.



(a) Mill scale



(b) Shot blast at 120 mm

Fig.10. Sectional height-Bending stress Relationships

Because the plots for the mill scale and shot blast at 120 mm were close to the distribution before slipping, the effect of the unification of the built-up beams was confirmed. However, in the mill scale with a small slip factor, the value of the plot near the center was shifted from the distribution by the influence of the lateral displacement due to the processing of the friction surface.

5.CONCLUSIONS

Herein. the structural performance of the built-up beam was studied based on a friction joint tension experiment and a bending experiment of the built-up beam using high-strength bolted joints. The following findings were obtained.

- A load drop occurred on the mill scale test specimen, and a clear main slip was confirmed. However, the load drop did not occur on the coating and shot blast test specimens, and no clear main slip occurred.

- In all specimens, it was confirmed that the rigidity increased after the occurrence of the slip, and the resistance mechanism changed from frictional force to bearing pressure.

- It was found that the smaller the slip between steel materials, the higher both the maximum load and rigidity. However, the shot blast test specimen had a smaller sliding strength than the steel yield strength, and the difference in the maximum load was small.

- Because the rigidity of all the built-up beam specimens was higher than twice the rigidity of the H-section steel, the rigidity was considered to have improved by uniting them with high-strength bolts.

- The reduction in the number of high-strength bolts caused the slip and reduced the maximum load and rigidity. However, the difference was small similar to the case of the difference in the friction surface processing method.

6. REFERENCES

[1] Architectural Institute of Japan (2012) “Recommendation for Design of Connections in Steel Structures”.

