Comparative Study on Effect of Powder Actuated Nail and Stud Welding on Steel Member

Manjae LEE
Sendai National College of Technology, Sendai, Japan

Go KOBAYASHI
HILTI Japan, Ltd., Yokohama, Japan

Yasuhisa TAGAWA
Yokohama National University, Yokohama, Japan

SUMMARY:
The aim of this study is to compare the influence of powder actuated nail (PAN) connection and stud welding connection on the tensile properties of a steel member, and to investigate the bonding mechanism of the PAN connection with microstructure observation. The effect of PAN connection and welding connection on the tensile properties of a steel member was investigated with tensile tests. In addition, the hardness of the steel member around the PAN and the stud welding were measured by Vickers hardness test. Also, the metal structure on the junction interface of the PAN and steel member was observed by an optical microscope and a scanning electron microscope. There was no difference of PAN connection and stud welding connection in yield and ultimate stress however PAN connection had an effect on the plastic deformation capacity of steel member as compared with stud welding connection.

Keywords: Powder Actuated Nail, Stud Welding, Shear Connector, Vickers Hardness, Structure Observation

1. INTRODUCTION

In composite beam system, steel beam is generally combined with concrete slab by using shear connector. The strength and stiffness of composite beam are definitely increased compared to pure steel beams, and further had the advantage of such restraint effect of lateral buckling and local buckling of the flange of wide flange steel beam.

In general, headed stud welding shear connector is most popular system as a shear connector in composite beam. Although headed stud welding has excellent mechanical properties and deformation capacities, it is very hard to control the metallurgical bonding quality of the stud welding in a construction site.

On the other hand, a mechanical shear connector fastened by a powder actuated nail (PAN) designed in European country has been formerly suggested in composite beam. Hardening of a PAN is especially treated to endure the impact at the moment of installation. Especially, constant construction quality and shortening work period are the most benefits of the PAN connection method. The authors have continued the research related to the PAN connection in the last few years.[1) - 8)]

In this study, two kinds of shear connector are suggested. One is a headed stud welding shear connector proposed as metallurgical connection method. The other is an L-shape shear connector joined by two PANs proposed as the mechanical connection method. This study is focused on comparing the mechanical behaviour of metallurgical connection method and mechanical connection method on the junction of a wide flange steel beam and a shear connector. The effect of the PAN connection method and welding connection method on the tensile properties of a steel member was investigated with tensile tests. In addition, the hardness of the steel member around the PAN and the stud welding were measured by Vickers hardness test. Also, the metal structure on the junction interface of the PAN and steel member was observed by an optical microscope and a scanning electron microscope.

The aim of this study is to compare the influence of the PAN connection method and the stud welding connection method on the tensile properties of a steel member, and to investigate the bonding mechanism of the PAN connection method with microstructure observation.

2. TENSILE TEST

2.1 Test Plan

2.1.1 Specimen

A Powder Actuated Nail (PAN) and L-shape shear connector chosen for this study are illustrated in Figure 1 and Figure 2. The PAN manufactured by HILTI Corp. and designated as “X-ENP-19-L15”. The PAN is 4.5mm in nominal diameters and 25mm in length. In addition to the knurled shaft, the PAN has a flat steel washer that assists in aligning the PAF in the installation tool. The PAN provided in JIS G 3506 SWRH 62B, High Carbon Steel Wire Rods, is used.

The shapes and the dimensions of MC specimen and WC specimen are shown in Figure 3. A headed stud welding connector of 16mm diameter are installed in WC specimen[9), 10)] and two L-shape shear connectors joined by four PANs are installed in MC specimen. List of tensile test specimens is shown in Table 1. There are two thicknesses of 12mm and 19mm in the specimens and the specimen of 150mm width has been designed to simplify a steel beam. The parallel portion of 150mm width in the specimen was prepared to assume the flange part of a wide flange steel beam. Three specimens are prepared with same condition and totally twelve specimens were tested. Also, the mechanical properties of a steel member used into specimens are presented in Table 2. Steel grade used in the specimen is the SN490B material of the Japan Industrial Standard (JIS), which is excellent in earthquake resistance and weld-ability. The swell around PANs observed in MC specimen but the cracks of steel member did not occur.

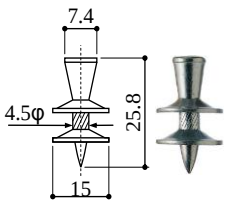

Figure 1 Powder Actuated Nail

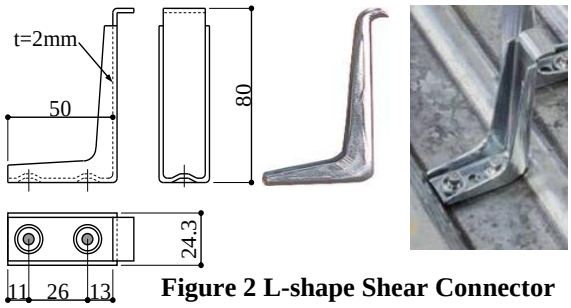

Figure 2 L-shape Shear Connector

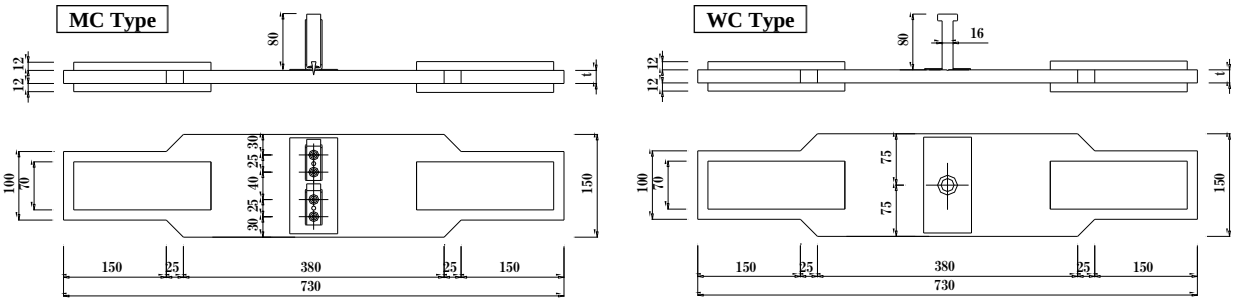

Figure 3 Shapes and dimensions of specimens

Table 1 List of Tensile Test Specimens

Specimen	Connector Type	Thickness of Steel Member	Number of Connector	Number of Damage	Width of Steel Member	Number of Specimen
MC-12	Mechanical Connector (MC)	12mm	2 Connectors	4 PANs	150	3
MC-19		12mm	2 Connectors	4 PANs	150	3
WC-12	Stud Welding Connector (WC)	19mm	1 Connector	1 Welding	150	3
WC-19		19mm	1 Connector	1 Welding	150	3

Table 2 Mechanical Properties of Steel Members

Steel	Thickness	Yield Stress(N/mm^2)	Ultimate Stress(N/mm^2)	Yield Ratio(%)	Strain at Yield Load(%)	Strain at Ultimate Load(%)
SN490B	12mm	359	543	66.2	0.214	-
		343	549	62.4	0.192	21.0
	19mm	374	572	65.4	0.217	20.5
		364	559	65.2	0.198	20.6

In former Push-out test[2), 3)] for composite beam system consisted of steel beam and concrete slab, ultimate shear strength of stud welding shear connector was 60～90kN and that of L-shape shear connector was almost 60kN. Additionally, two pieces of L-shape shear connectors are only able to be installed in 150mm width of steel member. Therefore, it was decided in this study that one piece of stud welding shear connector is installed in WC type specimen and two pieces of L-shape shear connector fastened by four PANs are installed in MC type specimen.

2.1.2 Measurement

The simplified specimens are tested to measure their yield strengths, ultimate strengths, maximum strain and elongation, etc. The specimens are subjected to an axial tensile load applied by a 2MN capacity universal testing machine. As shown in Figure 4, two LVDTs with 100mm gauge length were symmetrically placed to measure the displacement of the specimen. The tensile tests were performed until the specimen completely fractured under the axial tensile load. The stress value of MC type specimen was calculated from original cross-sectional area which was not considered the lacking of section with PANs. The elongation was calculated by 100mm gauge length in the middle of tensile axis direction. Also, fracture elongation was measured from 100mm gauge length.

As shown in Figure 5, four pieces of wire strain gauges were totally attached per one specimen in the reverse side of the damages. Two wire strain gauges were attached on the centre and edge of “A” cross-section, which PANs and stud welding are located on. More two wire strain gauges were additionally attached on “B” cross-section which is 100mm shifted from “A” cross-section. For example, wire strain gauge attached on the centre of “A” section is named with “AC”. The purpose of attaching wire strain gauge is to investigate the hardening of environs on the damages, and then compare the influence of PANs with that of stud welding on a steel member.

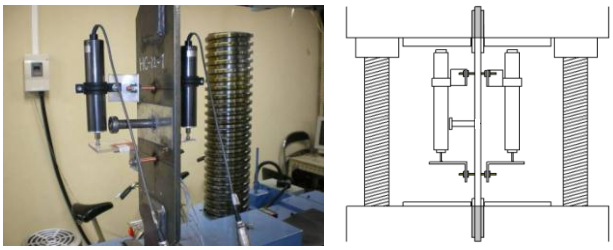

Figure 4 Set-up situation of specimen (WC Type)

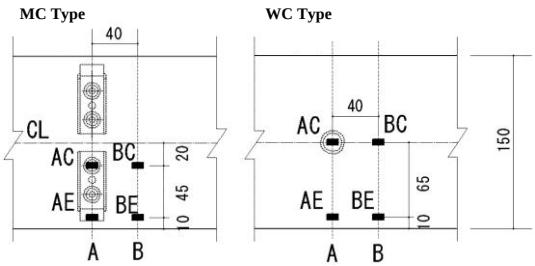

Figure 5 Arrangement of wire strain gauges

2.2 Test Result

2.2.1 Relationship of Stress and Strain

The test results, yield strengths, ultimate strengths, elongation and etc., of tensile test were listed in Table 3. Here, the stress values of MC specimen, which PANs are installed in, were calculated by dividing the strength by the net cross-sectional area (again, the section area of PANs was ignored). The non-dimensional value on the very right side of the table is calculated by dividing each value by the value of WC specimen individually. Also, typical stress-strain relationships of MC specimen and WC specimen were shown in Figure 6. The enlarged view near the yield point was shown in graph. The triangle marks on the graphs mean ultimate stress values.

Regardless of connection type, the yield point of 19mm specimen comparatively cleared in the stress-strain curves, while that of 12mm specimen did not clear. In particular, WC specimens sharply yielded as mild steel, while MC specimens gradually yielded. The reason why is that the sectional portion damaged by PANs in 12mm steel member was larger than that in 19mm steel member. As a result, it is considered that the influence of the damages of PANs in 12mm steel member was appeared in the yield point. There is almost no difference in the yield stress and ultimate stress between MC specimen and WC specimen. However, the strain on ultimate stress of MC specimen was definitely smaller than that of WC specimen.

The averaged strain values on ultimate load of 12mm and 19mm MC specimens in were 13.6% and 15.4%.The averaged strain values on ultimate load of 12mm and 19mm WC specimens were around 18.0% and 17.2%. For reference, the averaged strain value on ultimate load of steel material was 21%. The averaged strain value at fracture of 12mm and 19mm MC specimen was 23.0% and 27.7%.

Table 3 Tensile Test Results

	Yield Stress(σ_y) N/mm2		Ultimate Stress(σ_u) N/mm2		Strain at Ultimate Load(ε_u) %		Strain at Fracture(ε_f) %	
MC-12-1	373	1.02	503	1.03	13.5	0.75	23.6	0.51
-2	358	0.98	483	0.99	13.6	0.75	22.8	0.50
-3	359	0.99	499	1.02	13.9	0.77	22.6	0.49
Ave.	363	1.00	495	1.01	13.6	0.76	23.0	0.50
WC-12-1	366	1.01	494	1.01	17.8	0.99	46.5	1.01
-2	359	0.99	486	0.99	19.2	1.07	45.1	0.98
-3	367	1.01	490	1.00	17.0	0.94	46.4	1.01
Ave.	364	1.00	490	1.00	18.0	1.00	46.0	1.00
MC-19-1	381	1.01	544	1.00	15.2	0.84	28.5	0.62
-2	376	1.00	544	1.00	15.1	0.84	29.7	0.64
-3	373	0.99	540	0.99	15.8	0.88	24.8	0.54
Ave.	377	1.00	542	1.00	15.4	0.85	27.7	0.60
WC-12-1	374	0.99	543	1.00	17.9	1.04	44.0	0.97
-2	377	1.00	548	1.01	16.6	0.97	45.9	1.02
-3	377	1.00	544	1.00	17.0	0.99	45.6	1.02
Ave.	376	1.00	545	1.00	17.2	1.00	45.2	1.00

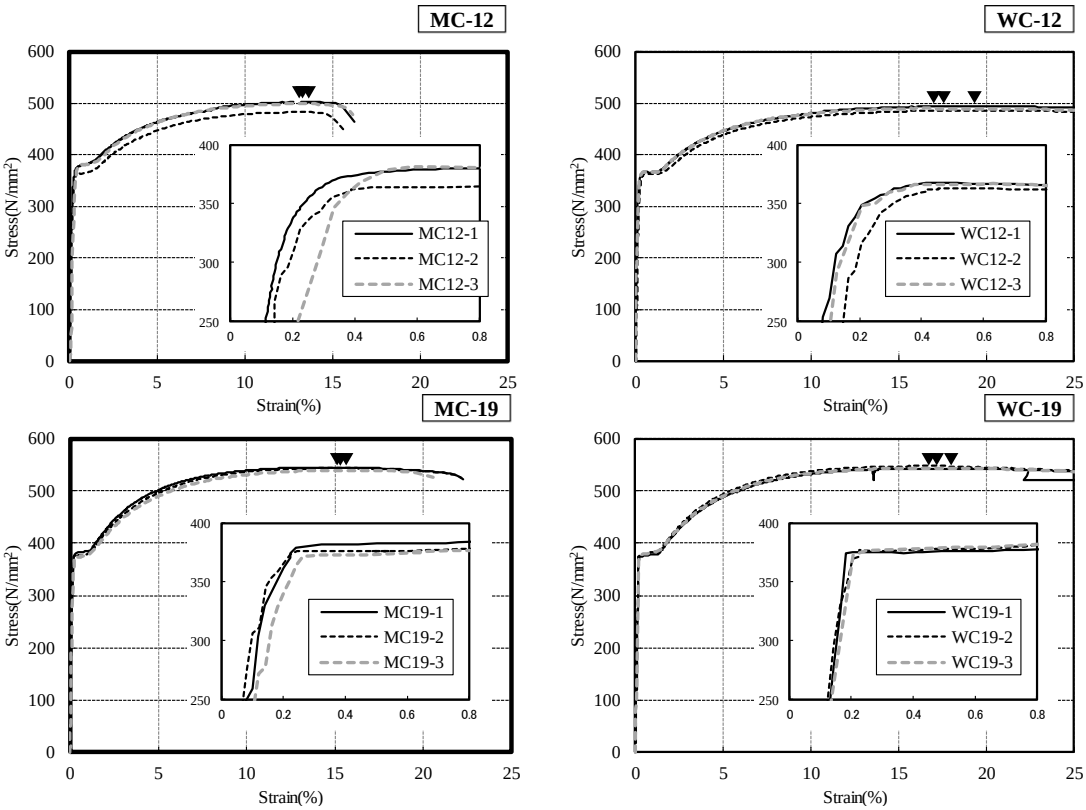

Figure 6 Relationships of stress and strain

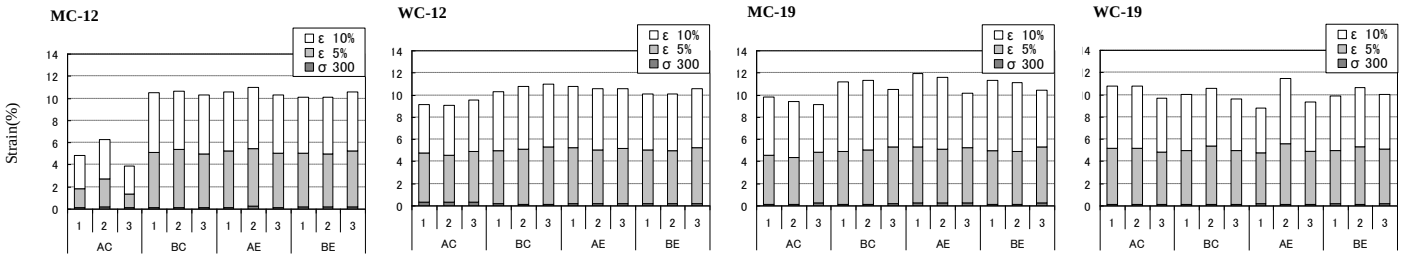

Figure 7 Distributions of strain values on specimens

The averaged strain value at fracture of 12mm and 19mm WC specimen was 46.0% and 45.2%. It was considered that the strain values at ultimate load of MC specimens are less than those of WC specimens. Therefore, the influence of PANs on the deformation capacity of steel member is clearly revealed in comparison with stud welding.

2.2.2 Strain Distribution

The distributions of strain values on specimens measured by wire strain gauges are shown in Figures 7. The strain values at 300N/mm^2 of stress value (σ300), 5% of strain value (ε5%) and 10% of strain value (ε10%) were represented in the figure. The X-axis shows measurement positions and the Y-axis shows strain values in the figure. For reference, the test result of MC specimen in ultimate stress could not be plotted because wire strain gauge before reaching the ultimate load was detached.

In the 12mm and 19mm thickness of MC specimen, the strain value of "AC" location close to a PAN was comparatively below than elsewhere after the yielding of the specimen. Especially, the strain value of AC location in 12mm thickness was particularly low. It is considered that the influence of a PAN which restrains steel material was greatly appeared because the wire strain gauge attached on "AC" of 12mm thickness specimen is closer to a PAN than that of 19mm thickness specimen.

In the 12mm thickness of WC specimen, the strain value of "AC" location was also a little lower than elsewhere however there was almost no difference of strain distribution in 19 mm thickness. In the case of 19mm WC specimen, it is considered that the influence of a PAN was not reached to the reverse position, which "AC" wire strain gauge was attached on.

The fracture situations of MC and WC specimen are shown in Photo 1. MC specimen fractured through every PAN in the right-angle of load direction. On the other hand, WC specimen fractured diagonally without passing through stud welding. The sufficient deformation capacity of WC specimen was shown in comparison with MC specimen.

MC-12 **WC-12** **MC-19** **WC-19**

Photo 1 Fracture situations of specimens

3. VICKERS HARDNESS TEST AND MICROSTRUCTURE OBSERVATION

3.1 Measurement and Observation Plans

The list of Vickers hardness test specimen is shown in Table 4. Vickers hardness test based on the JIS Z 2244 was carried out on cross section was cut with electrical discharge machine. The steel grade of SN490B and the thickness of 12 and 19mm are used in the specimen. Vickers hardness was measured with the interval of 0.5mm and the depth of 2mm, 6mm and 10 mm in each specimen respectively. Total measurement ranges of the MC1 and WC specimen are 30mm and that of MC2 specimen is 55mm.

The dimensions of specimens and the measurement ranges of Vickers hardness test are shown in Figure 8. Three types of specimen are prepared in the Vickers hardness test. One Powder Actuated Nail (PAN) with the steel deck of 1.6mm thickness is provided in MC1 specimen. Two PANs with a steel deck and the L-shape shear connector of 2mm thickness are provided in MC2 specimen. One stud shear connector of 16mm diameter is prepared in WC specimen. The length of a PAN only for fixing steel deck is 23mm and the length of a PAN for connecting L-shape shear connector is 25mm. The steel deck of 1.6mm thickness is only used in all specimens.

Microstructure observation was carried out by using the specimen after the measurement of Vickers hardness. Microstructure observation with optical microscope and scan electronic microscope were carried out only MC1 specimen and the position of the microstructure observation is the top, middle and bottom of a PAN in MC1 specimen.

Table 4 List of Vickers Hardness Test Specimen

Specimen	Damage	Thickness	Interval	Depth	Number of Measurement
MC1	PAN	12mm 19mm	0.5mm	2mm 6mm 10mm	330
MC2	L-shape Shear Connector + PAN				540
WC	Headed Stud Welding Shear Connector				330

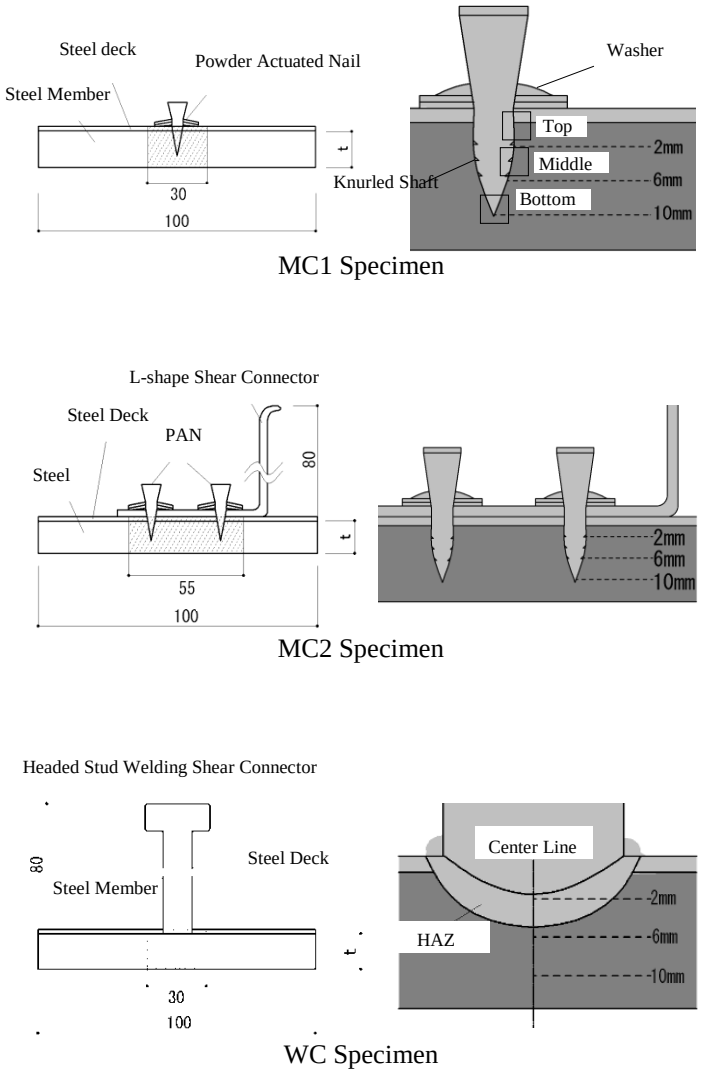

Figure 8 Measurement plan of Vickers hardness

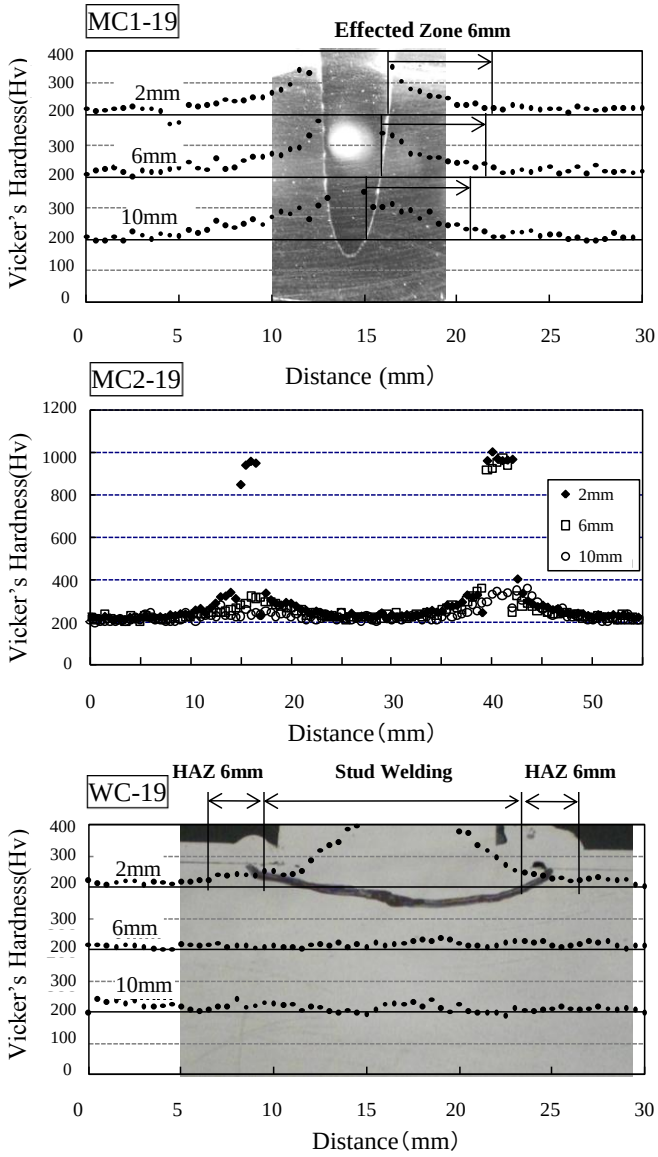

Figure 9 Measurement range of Vickers hardness

3.2 Measurement and Observation Results

3.2.1 Vickers hardness test

Vickers hardness test results are shown in Figures 9. The measurement result of 19mm specimen is represented because there were few differences in measurement results of 12mm and 19mm specimen.

In accordance with the distance from the surface of a PAN, Vickers hardness values converged in the range of 200 ~ 250Hv in all specimen. Therefore, this value is determined to be the hardness value of a base material. The change of hardness value was confirmed in the vicinity of a PAN in MC1 specimen. It is considered that this phenomenon is caused by occurrence of pre-strain in base material by means of installing a PAN. The distance converged in the hardness value of the base material is defined as the range affected by a PAN in this study. Therefore, the distance affected by a PAN was up to 6mm from the surface of a PAN.

The hardness values of only 2mm depth were very changed in WC specimen. The change of hardness values in 2mm depth is not the value of a base material but the value of a weld material. The range of welding bead in 2mm depth was about 14mm and heat-affected zone of stud welding was about 3mm away from the boundary of the weld bead and base metal. It is confirmed that there is no effect of welding on base material since there is no change in the hardness value of 6mm and 10 mm depth.

The hardness value of two PANs in MC2 specimen was 900 ~ 1000Hv and it was confirmed that the hardness value of the PAN was significantly greater than base material affected by a PAN.

it is considered that 25mm spacing of two PANs in a L-shape shear connector was appropriate since hardness value between two PANs in MC2 specimen converged in same hardness of base material,

The hardness of the base material is not affected by the presence or absence of L-shape shear connectors and the length of a PAN since there was no difference in the vicinity of the hardness distribution between MC1 and MC2 specimen.

3.2.2 Microstructure observation

The cross section of MC1 specimen observed by an optical microscope is shown in Photo 2. There was no change in the metal structure of a PAN however the flows of metal structure in the installation direction of PAN was observed. The phenomenon of pre-strain caused by installing PAN was demonstrated with the microstructure observation. It is considered that the PAN is strongly fixed in the base material with the residual stress by means of the pre-strain. In addition, the residual stress in the base material was confirmed as a change of hardness in the Vickers hardness test.

In the middle of the photo, melted zinc was ascertained at the knurl of the PAN. The galvanized surface of the PAN melted in the heat of friction caused by installation of the PAN and then the zinc remained at the knurl of the PAN.

Microstructure in the bottom of MC1 specimen observed with scanning electron microscope is shown in Photo 3. Clad phenomenon was ascertained at the interface of the PAN and the base metal and then melted zinc was not detected at all. Therefore, pressure welding occurred at the bottom of the PAN when the PAN is installed with high speed.

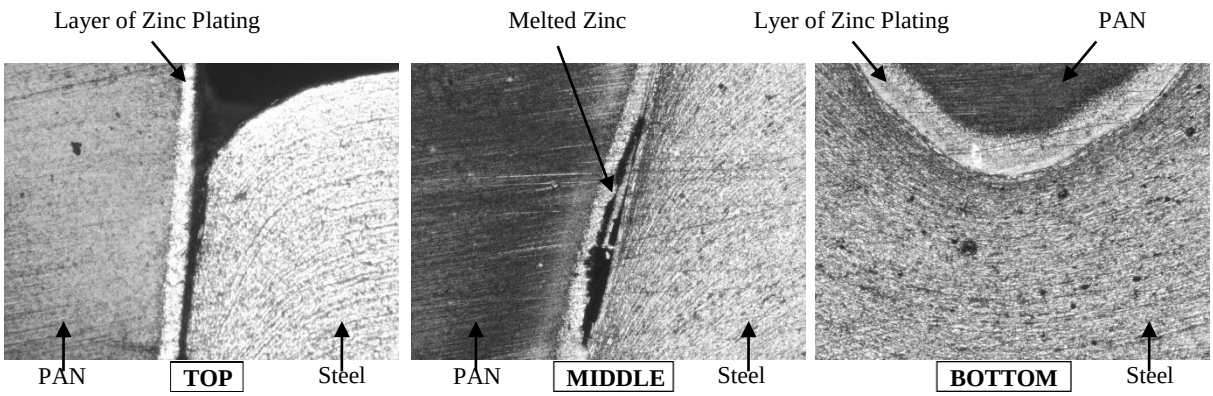

Photo 2 Metal structure with optical microscope

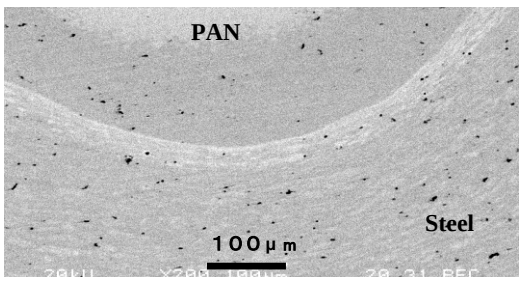

Photo 3 Observation with Scanning electron microscope

4 CONCLUDION

The knowledge acquired from the result of tensile test, Vickers hardness test and microstructure observation is as follows.

The tensile properties of the both connection methods, mechanical method with powder actuated nail and metallurgical method with stud welding, are almost same degree of yield stress and ultimate stress. However, the mechanical connection method has an effect on the plastic deformation capacity of steel member as compared with the stud welding connection method.

Although the fracture line of steel member with stud welding connection method avoided the stud welding part, the fracture line of steel member with mechanical connection method passed through every powder actuated nail.

The distance affected by a PAN was up to 6mm from the surface of a PAN and the hardness value of a PAN was 900 ~ 1000Hv. PAN is strongly fixed in steel member with the residual stress by means of the pre-strain and the phenomenon of pre-strain caused by installing PAN was demonstrated with the microstructure observation.

REFERENCES

1) HILTI Japan Ltd. (2008). Test Report on Mechanical Behavior of Shear Connector Fastened by Powder Actuated Nails. *Technical Report*

2) Kouhei NOGUCHI, Yasuhisa TAGAWA, Go KOBAYASHI, Akitoshi HIRANO (2007). Push-out Test of Shear Connector using Powder Actuated Nails. *Journal of Constructional Steel*. **Vol. 15**, 507-512

3) Manjae LEE, Go KOBAYASHI, Yasuhisa TAGAWA (2008). Study on Finite Element Analysis of Shear Connector using Powder Actuated Nails. *Journal of Constructional Steel*. **Vol. 16**, 353-358

4) Go KOBAYASHI, Manjae LEE, Kouhei NOGUCHI, Yasuhisa TAGAWA (2008). The Difference of Mechanical Performance by Number of Shear Connector Using Powder Actuated Nails. *Journal of Constructional Steel*. **Vol. 16**, 347-352

5) Manjae LEE, Go KOBAYASHI, Yasuhisa TAGAWA (2009). Shear Test and Pull-out Test of Powder Actuated Nails using in Shear Connector. *Journal of Constructional Steel*. **Vol. 17**, 599-606

6) Kouhei NOGUCHI, Manjae LEE, Go KOBAYASHI, Yasuhisa TAGAWA (2009).The Difference of Mechanical Performance by Number of Shear Connector Using Powder Actuated Nails. *Journal of Constructional Steel*. **Vol. 17**, 607-612

7) Manjae LEE, Kazuya MURAKAMI, Go KOBAYASHI, Yasuhisa TAGAWA (2010). Study on Connection Property of Powder Actuated Nails -Shear Test and Pull out Test of Steel Deck-. *Journal of Constructional Steel*. **Vol. 18**, 77-84

8) Hideharu Takahashi,Manjae Lee,Go Kobayashi,Yasuhisa Tagawa (2011). Comparison Study on Steel Member of Driving Pin and Welding –push out test of composite slab-. *Proceedings of AIJ Tohoku Chapter Architectural Research Meeting*. **Vol 74**, 33-36

9) Japan Society of Steel Construction (1996), Introduction of Standard Push-out Test Method for Headed Stud Shear Connectors

10) Japan Institute of Architecture (2010), Design Recommendations for Composite Constructions