AN EXPERIMENTAL STUDY ON SHEAR CHARACTERISTICS OF PERFOBOND STRIP AND ITS RATIONAL STRENGTH EQUATIONS

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Abstract
This paper deals with the rational shearing strength equation and the slip behavior for shear connectors called the Perfobond Strip (Concrete Dowel: hereinafter, abbreviated to PBL) that is used at the continuous composite girder of railroad bridges. This PBL is the shear connector proposed by Leonhardt in Germany, and its composite effect between steel and concrete is very high due to the shearing resistance of the concrete in perforations of the steel plate. Also, the PBL shear connectors Strip is recognized having high fatigue strength. Strength evaluation equations for the design of PBL shear connectors are proposed by various investigators in the world. Existing research has clarified that the shearing strength of PBL shear connectors is very dependent on the perforation diameter and the compression strength of concrete in case of no reinforcement bars. In actual structure, however, the reinforcing bars were arranged to the neighborhood of shear connectors in most of the case. Thus, in this investigation, the authors chose the strip thickness, the distance of strips, the presence of reinforcing bars and the perforation diameter as experimental parameters. Also, from the result of a multi linear regression analysis based on data published in the world including our data, two kinds of new rational strength equations for PBL shear connectors were derived. One is a strength equation without reinforcing bars and the other is a strength equation with reinforcing bars. It became clear that these evaluation equations express data of push-out test well. The strength equations for design are also proposed, respectively.
1. Introduction

At present, the construction of continuous composite girders is being examined from the consideration of noise and vibration in the train transit-time on steel railway bridges. Much research on shear connectors of steel beam and concrete slab has been carried out until now for the multi-main girder bridge [1], [2], [3]. And, the research on 2 main I cross section girder bridges, in which the floor system span is wide, is carried out for the continuous composite railway girder in order to promote further rationalization [4], [5].

As shear connector structure in this bridge type, it is also anticipated that the necessity of arranging many horseshoe-shaped shear connectors occurs and that its arrangement becomes physically difficult, since the horizontal shearing force that has to be transmitted from the girder to the concrete slab by 2 main girders increases, when the horseshoe-shaped shear connectors in railway bridge are applied with heretofore similarly. On the other hand, one has to worry about the fatigue strength of the flange plane of steel beams at the intermediate support division of continuous girder bridges, when stud shear connectors were applied. Therefore, the development of a shear connector structure that is resistant to tensile force of bridge axial direction is required.

Then, the application of PBL shear connectors developed by Leonhardt et al [6] of Germany, which also have high durability, to the continuous composite girder is examined with the transmission force of the equivalent horizontal shearing force with horseshoe-shaped shear connectors and stud shear connectors in railway bridges. There are results which have already adopted the PBL shear connectors at intermediate support parts such as Hokuriku Shinkansen "the Hokuriku way overbrige" in Japan.

In until now research, these PBL shear connectors were designed so that the concrete in the perforations was fractured by shearing stress as precondition. In the reason, the following are considered as factors influencing the ultimate strength: perforation diameter and compression strength of the concrete [6], [7], [8]. Afterwards, experimental researchs were carried out in Japan [9], [10], [11]. However, there seems to be no research yet, which clarifies the behavior of the reinforcing bars, the plate thickness of PBL shear connectors, existence of the reinforcing bars running through the perforations of PBL and the number of sheets of PBL shear connectors placed on the flange plane.

Thus, in this study, test specimens of 8 types with those factors were manufactured, and static push-out shearing tests were carried out. Especially, a comparison examination was carried out for the slippage constant and failure mode.

And, collection, arrangement and statistic analysis in respect of the test data (including this experiment result) for previous shear capacity were made, in order to lead to strength evaluation equations of necessary shear load-carrying capacity in the design of the PBL shear connectors. The purpose of this investigation is to arrange knowledge on the PBL shear connectors.
2. Failure conditions

In order to understand the conditions of concrete cracks after completing the tests, a concrete block part of the specimen was cut, and the final failure condition was visually observed.

2.1 Influence of strip thickness

Here, specimens without penetration reinforcing bars re-bars will be observed. First, concrete in perforations of the thin 8mm-strip specimen was pulverized in the steel plate of PBL. However, concrete of the thicker strip specimens sheared on both sides of the strip.

As differences in failure phenomena by strip thickness are shown in Figure 1, the small thickness causes the area of compression to be minimized and the force to be concentrated. This concentration of force is thought to have generated splitting tension.

On the other hand, when the strip thickness is large, the area of compression is large, and the force is thought to dispersively work on the concrete. This dispersed force is thought to finally reach the maximum shear strength of concrete on extended lines of both sides of the strip, and subsequently cause it to shear (see Photos 1 and 2). Failures in specimens with penetration reinforcing bars re-bars will be shown later 2.2. Furthermore,
3-axial compressive stress areas shown in Figures 1 and 2 were assumed to be those in which concrete does not completely generate tension (areas in the figures are assumptions).

2.2 Influence by the existence of the penetration reinforcing bars

It was clarified that final failure conditions of specimens without penetration reinforcing bars would vary depending on the strip thickness as mentioned above. 8 and 16mm specimens with penetration reinforcing bars both failed because the concrete in the perforations pulverized from compression. Factors for these specimens with penetration reinforcing bars to indicate similar tendencies in final failure conditions are thought to be the penetration reinforcing bars restraining each compressive area of Figure 1 (a) shown in Figure 2, which contributed to the improvement of shear strength at the same time (see Photos 3 and 4). Here, it was also confirmed that the specimen with penetration reinforcing bars had local deformations on the inner sides of the perforations in contact with the reinforcing bars.

3. Study on strength evaluation equations

The authors of this research have decided to collect and organize previous experiment data on PBL shear connectors including experiment values of maximum shear strengths.
to obtain new rational strength evaluation equations for specimens with and without penetration reinforcing bars.

3.1 Previous strength evaluation equations
The influential factors on shear strengths of PBL shear connectors are thought to be many, and do not seem to be unified. A relationship of influencing factors used by the equations (d²f_{cu}; where, d: perforation diameter; f_{cu}: concrete cylinder compressive strength) and experimental shear strength value per perforation in PBL (Q_{max}) is shown in Figures 3, 4. Here, the equation proposed by Leonhardt, et al., is without consideration of penetration reinforcing bars in perforations of PBL, and as made clear by Figure 4, it can be seen that all test data were not successfully taken into account. Also, H. Andrä [7] himself proposed equation by expanding equation of Leonhardt. Also in 1994 in Japan, Ogata et al., [9] proposed equation for PBL shear connectors to be applied to bridge piers. According to the strength equations proposed previously, concrete shear failure was assumed to precede; therefore, influential factors on ultimate shear strengths were thought to be perforation diameters in PBL (d) and concrete cylinder compressive strength (f_{cu}). Furthermore, equation (1) shown in Figures 3 and 4 include coefficients to convert cube strengths into cylinder strengths in order to have the same condition as the concrete strength used in this experiment. Later, Kraus et al., [12] proposed equation which limited the perforation diameter and strip thickness (t) of PBL (d=70mm, t=10mm), adding its thickness t to the influencing factors. Experiments were conducted, changing the number of perforations in PBL, their diameters, reinforcing bars arrangement, etc., by Taira et al., [10] in 1997, Hosaka, Hiragi, Koeda, et al., [5] and Tomimaga, Nishiumi et al., [13] in 1998. Ebina et al., [11] conducted experiments on a shear connector structure to be applied to lower floor slabs of a PC bridge with corrugated web, and Uehira et al., [15] also similarly proposed equation. In addition, there are experiment reports on rigid connection structures to be applied to RC piers and steel girders in a few references [15], [16], [17]. Thus in this research, efforts were made to collect as much test data as possible, and in the experiment values shown above, only experiment results that had all definite data were selected to taken into account. And strength equation relations previously proposed on shear strength were used in an attempt to reorganize test data collected and organized for this research.

3.2 Proposal of strength evaluation equations
Using previous research results, the results of the experiments conducted this time, and selecting d, t, f_{cu}, f_{st}, etc., as influential factors on experiment values of shear strengths for PBL (Q_{max per perforation}), an attempt was made to propose a strength evaluation equation through a statistical analysis method shown in Reference [18].

(1) Organization based on the influence factor d²f_{cu}
Failure conditions of the results of this experiment shown in Section 2.2 were thought to differ depending on the existence of penetration reinforcing bars. Thus, the experiment
data without penetration reinforcing bars were plotted in Figure 3, and those with reinforcing bars placed were plotted in Figure 4. These figures also have evaluation equation accompanying the equations (1) proposed by Leonhardt. The correlation coefficients shown in the figures 3 and 4 are indices showing a variation in experiment values for this arranging sorting method, and data of this experiment shows a positive correlation. As a result, although experiment data without penetration reinforcing bars had a significantly high coefficient 0.935 as shown in Figure 3, it was confirmed that this coefficient varied slightly in all areas of the experiment data. This is thought to be caused by the lack of consideration for the progression of failure condition progress influenced by the strip thickness shown in Figure 1 of Section 2.1. On the other hand, data from experiments with penetration reinforcing bars shown in Figure 4 had a coefficient of 0.810, which confirmed a wide variation for this arranging method. However, the influence of penetration reinforcing bars was not considered in equation (1). Thus, it was concluded that strength evaluation equations for PBL shear connectors should be proposed in 2 types of strength equations by having or not having penetration reinforcing bars to consider failure conditions.

(2) Rational strength evaluation equation without penetration reinforcing bars

![Figure 3. Influence factor d²f₂ (without reinforcing bars)](image)

![Figure 4. Influence factor d²f₂ (with reinforcing bars)](image)
Failure conditions without penetration reinforcing bars were seen as bearing splitting failures besides shear failures in the experiment results of the 8mm-thick specimen. Therefore, failure conditions without penetration reinforcing bars are thought to be caused by the coupling of shear and bearing progresses. The difference between these progresses in respect of the thickness variation is thought to be influenced by the dimension effects of the perforations in PBL, i.e., the ratio between strip thickness (t) and perforation diameter (d) in PBL, although shear failure occurs at the ultimate. Thus, a multiple regression analysis was conducted to add the influence of thickness-diameter ratio (t/d) to the equation (1) proposed by Leonhardt et al., using all test data (without penetration reinforcing bars) collected and organized for this investigation. As a result, the equation (2) was obtained as a rational evaluation equation on ultimate shear strength per perforation in PBL.

\[ Q_u = 3.38d^2 \left( \frac{t}{d} \right)^{1/2} f_{cu}^2 \cdot 39.0 \]  

(2)

Where,

- \( Q_u \): Ultimate shear strength(N)
- \( t \): Strip thickness(mm)
- \( d \): Perforation diameter(mm)
- \( f_{cu} \): Concrete cylinder compressive strength(N/mm²)
Also, considering experiment values, the range of application for equation (2) is assumed to be:
\[ 22.0 < d \left( \frac{t}{d} \right)^{1/2} f_{cu} < 194.0 \]
The result reorganized by the influencing factors of evaluation equation (2) is shown in Figure 5. As a result, the correlation with the experiment values further increased compared to the expression method proposed by Leonhardt et al., and the correlation coefficient became 0.971. Here in equation (2), the thickness-diameter ratio \((t/d)\) increased with the increase in the strip thickness, and a dominance of shear failure can be reproduced; the thickness-diameter ratio \((t/d)\) decreased with the decrease in the strip thickness, and a tendency of bearing splitting failure dominating prior to shear failure can also be reproduced. Also, as a shear strength equation to be used for design \((Q_d)\), equation (3) shifted twice as low as the standard deviation is shown in a form including the lowest limit value of scattering experiment values.
\[
Q_d = 3.58 d^{2/3} \sqrt{d} f_{cu} \cdot 121.0 \quad (3)
\]
Here, 
\(Q_d\): Design shear strength \((N)\)

(3) Rational strength evaluation equation with penetration reinforcing bars

With penetration reinforcing bars, it is confirmed from Figures 3-6 of Section 2.1 and Section 2.2 that penetration reinforcing bars contribute to shear strength. Thus, a multiple regression analysis similarly mentioned above was conducted by adding the penetration reinforcing bars diameter \((D_{st})\) and its tensile strength \((f_{st})\) as influence factors. As a result, the relation shown in Figure 6 was finally obtained. Here, the experiment value \(D_{st}\) shown in the figure was the diameter of a penetration reinforcing bars inserted into a perforation of PBL, and for the case, that not all perforations had reinforcing bars, a reinforcing bar diameter converted into diameter per perforation in PBL was used. As a result, equation (4) was obtained as an evaluation equation for ultimate shear strength per perforation in PBL.
\[
Q_u = 1.45 \left[ (t^2 - D_{st}^2) f_{cu} + D_{st}^2 f_{st} \right] 26.1 \quad (4)
\]
Where,
\(D_{st}\): Penetrating re-bar diameter \((mm)\)
\(f_{st}\): Penetrating re-bar tensile strength

Also, considering the experiment values, the range of application is of equation (4) assumed to be:
\[ 51.0 < \left( t^2 - D_{st}^2 \right) f_{cu} + D_{st}^2 f_{st} < 488.0 \]
The first item bracketed \(\left\{ \right\}\) in equation (4) is the shear strength for the actual area of concrete between perforations in PBL and penetration reinforcing bars (the value which subtracted the reinforcing bar cross section area subtracted from the perforation area in PBL), and the second item is the factor equivalent to the tensile strength of the penetration reinforcing bars. Superimposing these factors lead to obtaining an arranging method with a high correlation and even a correlation coefficient of 0.979, which resulted in supporting the explanation of failure conditions shown in Figure 2. Also, as a shear strength equation for PBL to be used for design, equation (5) shifted twice as low
as the standard deviation is shown in a form including the lowest limit value of scattering experiment values.

\[ Q_d = 1.45 \left( d^2 - D_c^2 \right) f_{tc} + D_c^2 f_{tc} \left( 106.1 \right) \]  \hspace{1cm} (5)

From the results above, it can be judged that a rational evaluation equation with a high correlation was obtained on ultimate shear strengths for PBL shear connectors with and without penetrating re-bars.

4. Conclusion

In this paper, special attention was paid to important factors of Perfobond Strips such as strip thickness, existence of penetration reinforcing bars and the number of strips, to describe results of basic push-out tests. Also, based on existing previous results including the our present results, a rational strength evaluation equation for PBL was proposed. Main results obtained in this experiment are summarized below.

(1) This experiment made it possible to propose a rational shear strength evaluation equation \((Q_u)\) on PBL without penetration reinforcing bars. This evaluation equation was derived considering the influence of dimension effect (thickness/diameter ratio) to methods of expression obtained in the previous research. In addition, a shear strength evaluation equation for design \((Q_d)\) was proposed.

(2) It became possible to propose a rational shear strength evaluation equation \((Q_u)\) on PBL shear connectors with penetration reinforcing bars. This evaluation equation was derived, based on relation expressions obtained in previous research, from adding shear strength in the actual area of concrete between perforations in PBL and penetration reinforcing bars (a value which subtracted the reinforcing bar area from the perforation area) and the tensile strength of penetration reinforcing bars. Also, a shear strength evaluation equation for design \((Q_d)\) was proposed.

Considering the application of wide span floor slabs to 2 continuous composite I-sectional main girder systems on railway bridges, and based on this research, it is intended to conduct further fatigue experiments on the PBL shear connectors subject to uplift action from a floor slab.

5. References


