# EVALUATION OF TIMBER-CONCRETE SLAB CONNECTED WITH NOTCHED CONNECTION MADE OF KOREAN LARCH STRUCTURAL PLYWOOD

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**ABSTRACT:** In this study, a novel notched connection has been developed made of Korean Larch structural plywood for timber-concrete composite (TCC) slabs to improve their bending performance in non-residential buildings. The use of TCC for non-residential buildings has become increasingly popular as horizontal members such as beams and slabs in such structures have been designed to have longer spans to create more space. Because the TCC system can provide greater stiffness to horizontal members, TCC slabs or beams have advantages for application in non-residential building members. The notched connection design in this study divided a sheet of structural plywood into several units and fastened them with timber flanges using nails. Insulations were inserted between connections to create an even concrete layer, and concrete was cast. The bending performance of TCC specimens was then evaluated through tests, with the results compared to the performance of other slabs estimated with the gamma method. The study found that the new notched connection significantly improved the effective bending stiffness of TCC slabs, which could lead to the wider adoption of TCC in non-residential building design.

**KEYWORDS:** Timber-concrete composite, TPC slab, Notch connection, Plywood segment, Double shear test, Full-scale bending test

## 1 INTRODUCTION

According to statistical data from The Ministry of Land, Infrastructure, and Transport in South Korea, most buildings have been constructed in recent years for commercial, industrial, or public purposes called non-residential buildings. In general, Horizontal members (beam and slab) in non-residential buildings are designed to have long spans to make more space. Timber-concrete composite (TCC) is a suitable material to apply to non-residential buildings since its effective bending stiffness ($EI_{eff}$) is high because of concrete topping. $EI_{eff}$ of TCC is decided by not only material properties; but the performance of the shear connection between timber and concrete. The composite efficiency is decided with connection efficiency derived from the stiffness of the shear connection. Numerous types of shear connections have been investigated by past research [1]. Among these, a notched connection which is made by grooving in timber showed higher stiffness than metal connections [2]. However, the notched connection is difficult to process. Also, the loss of cross-section in timber can reduce bending capacity, so the increase of stiffness by lengthening or grooving deeper can be limited [3]. Therefore, the performance of TCC with traditional notched connections can be improved by increasing the amount of timber or concrete, but it is thought to be inefficient from the engineering point of view. In this study, a notched connection made of Korean Larch structural plywood was designed. A sheet of structural plywood was divided into several units and they are fastened with timber flanges using nails. After insulations are inserted between connections to make the concrete layer level even, concrete is cast. With this processing, TCC specimens were prepared to evaluate the bending performance. Test results were compared with the performance of other slabs which is estimated with the γ-method.

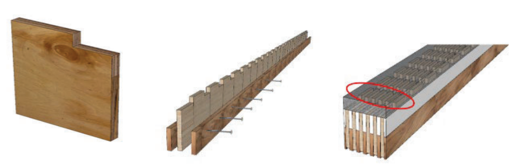

*Figure 1: Notched connection made of plywood segments*

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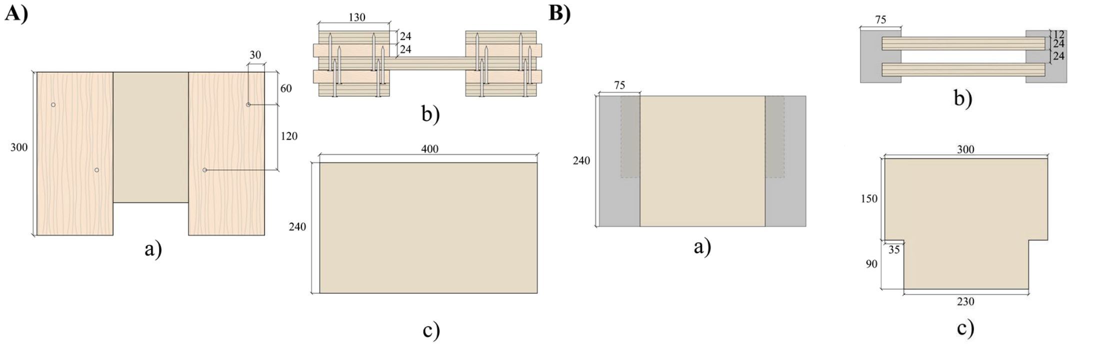


***Figure 2:*** *Test specimen to evaluate the slip modulus value of A) nails, B) notches – a) front view, b) top view, c) plywood dimension*

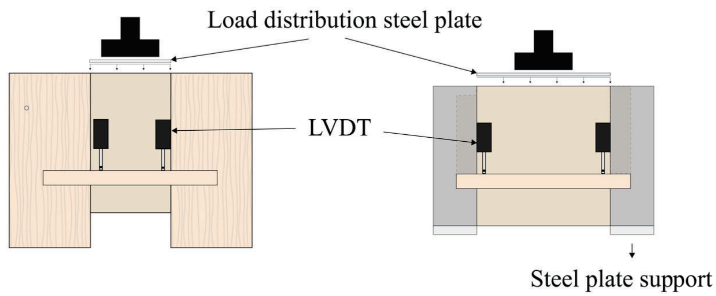


***Figure 3:*** *Double shear test set up*

## 2 Materials and Method

### 2.1 CONSTITUENT ELEMENTS

TPC slab has three main components: Finger-jointed lumber, normal concrete and plywood segments.
Considering the properties of wood in South Korea, it is possible to achieve a depth of up to 140 mm. In a longitudinal direction, 6,210 mm length was obtained by finger-joint (24 mm × 140 mm × 6,210 mm - width × depth × length). The thickness of the concrete layer was set at 75 mm to satisfy the minimum cover thickness of the reinforcing bars if reinforcement is required by arranging reinforcing bars in the concrete layer, depending on the requirements. The mechanical properties of elements are specified in Table 1,2,3 and it was used to estimate the structural performance of TPC composite slab with the γ-method.

***Table 1:*** *Mechanical properties of concrete*

| Elements | $F_c$ (MPa) | E (MPa) |
|---|---|---|
| Ready-mixed concrete | 27 | 26,701 |

***Table 2:*** *Mechanical properties of finger-jointed lumber*

| Elements | $F_t$ (MPa) | E (MPa) |
|---|---|---|
| Korean Larch lumber | 13.5 | 10,000 |

### 2.2 DESCRIPTION OF THE COMPOSITE SYSTEM

Since wood fastened with plywood segments by nails (Figure 1). The spacing, edge and end distance of nails followed Nail-laminated timber design & construction guide and Eurocode 5 [4], [5]. In the compressive zone, ready-mixed concrete was topped on the timber-plywood panel and it was connected mechanically by notches, and the plywood segments were aligned in a line with 240 mm spacing.

### 2.3 DOUBLE SHEAR TEST

The slip modulus value is one of the main parameters in the γ-method estimation. It can be derived from by push-out test, and the test procedure has followed EN 26891 in most research [6]. To derive the slip modulus value, the double shear test was conducted as shown in Figure 3. The two types of test specimens were prepared to evaluate the slip modulus value of notches in the concrete layer and nails in the timber layer. Using LVDT, the relative slip of plywood segments between concrete and timber was measured. The slip modulus value can be derived from the load-slip curve. It can be used to calculate the connection efficiency factor (γ), and $EI_{eff}$. In the load-slip curve, the slip modulus values of the serviceability limit state ($K_{SLS}$) and the ultimate limit state ($K_{ULS}$) can be classified with the load level. $K_{SLS}$ refers to the secant modulus of the load-slip curve between two specific points, namely 10% and 40% of $F_{max}$ and $K_{ULS}$. $K_{SLS}$ is utilized in determining the connection efficiency factor and $EI_{eff}$ at the


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serviceability limit state, while $K_{ULS}$ is used to predict the load-carrying capacity of TCC

$$K_{SLS} = \frac{0.4F_{max} - 0.1F_{max}}{0.4v_{max} - 0.1v_{max}} \tag{1}$$

$$K_{ULS} = \frac{0.8F_{max} - 0.1F_{max}}{0.8v_{max} - 0.1v_{max}} \tag{2}$$

Where, $K_{SLS}$ = the slip modulus value in the serviceability limit state, $K_{ULT}$ = the slip modulus value in the ultimate limit state, $F_{max}$ = The maximum load observed in the load-slip curve during double shear tests, $v_{max}$ = The slip value corresponding to the point of maximum load.

## 2.4 FULL-SCALE BENDING TEST

The bending performance, including moment resistance ($M$) and $EI_{eff}$ of TPC slabs, were measured through experiments with 10 specimens. The dimensions of the slab components are illustrated in the figure below, with a length of 6,210 mm and a span of 6,000 mm. In the longitudinal direction, the plywood segments are aligned. Figure 4C illustrates that plywood segments (b) function as shear connectors between layers. The plywood segments located at the midpoint of the span were aligned to ensure equal spacing of connections. the dimension of plywood was specified. Using a universal test machine, the load was applied to one-third of the TPC slab at a rate of 10 mm/min. Moment resistance was determined by the load at which failure occurred, while $EI_{eff}$ was calculated by measuring the deformation at the centre of the span using a wire displacement sensor. The loading rate was 10 mm/min.

$$M = \frac{P_{max}a}{2} \tag{3}$$

Where, $M$ = moment resistance, $P$ = maximum load, $a$ = the distance from support to the loading point.

$$EI_{eff} = \frac{a}{24}\frac{\Delta P}{\Delta v}(3l^2 - 4a^2) \tag{4}$$

Where, $EI_{eff}$ = experimental effective bending stiffness, $a$ = the distance from support to the loading point, $\Delta P$ = load increment, $\Delta v$ = vertical deformation increment, $l$ = length of the specimen.

## 2.5 GAMMA METHOD PREDICTION

The design of TPC was validated by comparing the bending performance of the TPC slab, as measured experimentally, with the predicted bending performance calculated using the equations specified in Eurocode 5. The slip modulus value used in the prediction equation was obtained from the value measured during a double shear test. It should be noted that the physical properties of plywood were not reflected in the equations since the plywood segments were not connected with each other.

$$EI_{eff,est} = E_1I_1 + \gamma_1E_1A_1a_1^2 + E_3I_3 + \gamma_3E_3A_3a_3^2 \tag{5}$$

Where, $EI_{eff,est}$ = estimated $EI_{eff}$ of a specimen, $E_i$ = elastic modulus, $I_i$ = the moment of inertia, $\gamma_i$ = connection efficiency factor, $A_i$ = the cross-section of elements, $a_i$ = the distance from neutral axis to centroid of elements, $i$ = the number of elements (1- concrete, 3-timber)

$$M_{i,est} = \frac{f_i}{\gamma_iE_ia_i + 0.5E_ih_i} \times EI_{eff,est} \tag{6}$$

Where, $M_{i,est}$ = estimated moment resistance of elements, $E_i$ = elastic modulus, $h_i$ = the depth of elements,

The moment resistance of the TPC slab was determined based on the minimum moment resistance of its constituent elements, namely the compressive strength of concrete and the tensile strength of finger-jointed lumber.

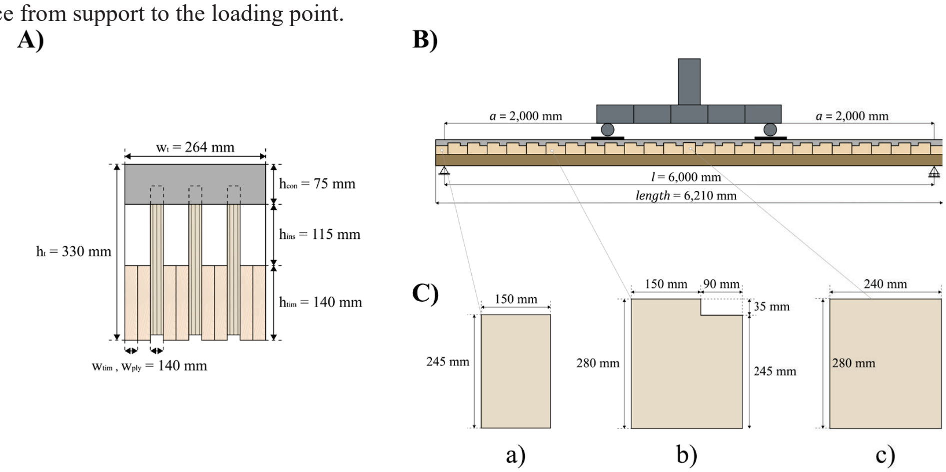


***Figure 4:*** *A) the cross section of TPC slab specimen, B) 4-point bending test set up, C) detail of plywood segments*

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## 3 RESULT & DISCUSSION

### 3.1 RESULT

#### 3.1.1 DOUBLE SHEAR TEST

The slip modulus values for the nails and notches were determined experimentally by double shear tests, and these data were subsequently used to predict the bending performance of TPC slabs which have similar geometry to specimens in full-scale bending tests.

#### 3.1.2 FULL-SCALE BENDING TEST

Based on the full-scale bending test, the primary failure mode of the TPC slab was identified as the tensile failure of the finger-jointed lumber. Additionally, some shear cracks were observed in the concrete layer; however, they were not considered critical to the load-carrying capacity of the TPC slab. A 2-parameter Weibull distribution was estimated using 10 datasets (Full data fitting), from which the 5% lower percentile value of the TPC slab's load-carrying capacity was calculated. The $EI_{eff}$ was determined as the mean value of 10 datasets. (Figure 5).

***Table 3:*** *Double shear test results*

| Connection | $K_{0.4}$ (kN/mm) | $K_{0.8}$ (kN/mm) | $v_{max}$ (mm) | $F_{est}$ * (kN) |
|---|---|---|---|---|
| Notch in concrete | 35.93 | 22.03 | 1.53 | 66.21 |
| Nail in timber | 15.28 | 3.66 | 8.09 | 20.00 |

*Measured by preliminary test to determine the loading rate.

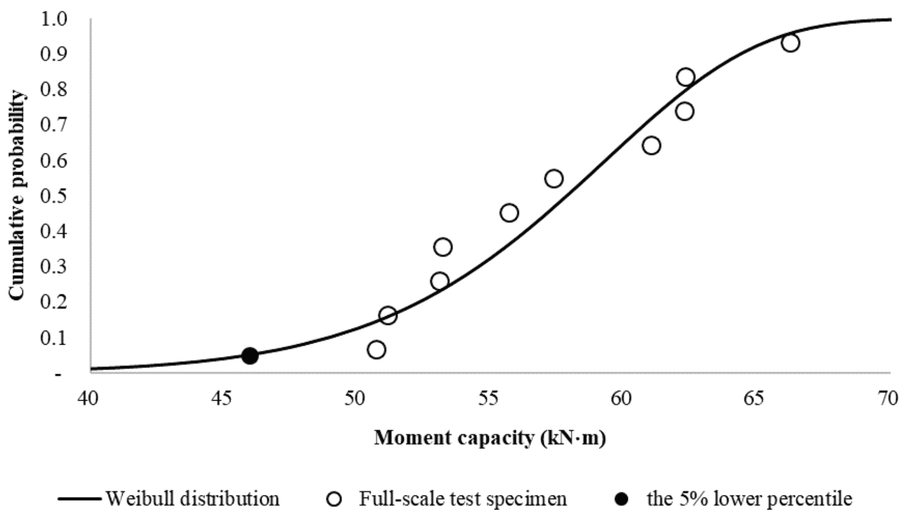


***Figure 5:*** *Distribution of full-scale test specimen*

### 3.2 DISCUSSION

#### 3.2.1 COMPARISON OF EXPERIMENTAL VALUE WITH PREDICTION

To assess the feasibility of the connection system, the bending performance of the TPC slabs measured experimental test was compared with the predicted values using the γ-method. The comparison showed that a conservative design of the TPC slab using the system is possible (Table 4). It was considered that plywood segments just serve as connections, but the observed error in comparison was attributed to the partial compression of the upper part caused by the rotation of the plywood during the experiment. This will be investigated in future research to enhance design efficiency.

***Table 4:*** *Comparison measurement with estimation*

| Test specimen | $M$ (kN·m) | $EI_{eff}$ (kN·m$^2$) |
|---|---|---|
| Full-scale test | 45.935 | 16,514 |
| γ-method prediction | 27.458 | 10,231 |

#### 3.2.2 COMPARISON OF TPC SLAB WITH OTHER TCC SLABS

In order to evaluate the structural benefits of the TPC slab, a comparison was made with the structural performance of the TCC slab using other joints as proposed in the existing literature. However, it should be noted that objective comparison of different TCC slabs is challenging as they differ in not only the slip modulus of the joint used, but also the slab dimensions, physical


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properties of the components, and longitudinal and width directions of the joint arrangement. To address this challenge, the bending performance of TCC slabs was calculated according to the following criteria. Firstly, assuming that the slab introduced in each paper was designed and optimized, the mechanical properties of elements and joint arrangement of the slab specimen were maintained. Secondly, the structural performance of each slab was compared using MOE and MOR values. The MOR and MOE values were calculated assuming a rectangular cross-section of the slab made up of a single material. As shown in Table 5, the load-bearing capacity of the TPC slab was lower than other TCC slabs. The reason why the MOR value is lower in this particular TCC slab is due to the arrangement of plywood segments instead of using timber laminae that resist tensile force. As a result, the tensile layer in the cross-section of the slab was lost to the same extent as the area where the plywood was placed, leading to a decrease in the load-bearing capacity. On the other hand, the $EI_{eff}$ stiffness was found to be superior to that of other slabs. Through γ-method prediction, it is expected that the design of spans ranging from 8 m to 11 m can be possible with 1.2 m width, achieving the project's objective to apply the slab with long spans to buildings for using as non-residential purposes.

## 4 CONCLUSIONS

While the application of TCC systems has advantages in response to the increasing demand for non-residential construction in the market, various shear connections that connect timber and concrete have been developed, considering their performance and workability. This paper presents the development of a notch connection using structural plywood made of Korean larch species and an evaluation of the structural performance of the TCC slab. Also, the investigation was carried out to measure the actual bending performance and predict it using the gamma method on specimens of the same geometry. It was observed that the actual measured value exceeded the predicted value, confirming the possibility of the connection design through the gamma method. A comparison of the developed slab with other shear connections revealed that the effective bending stiffness of the former was superior to that of other TCC slabs. Considering that the structural capacity of building member with long span is determined by deflection, it is believed that this will confer structural advantages. However, future research is needed to evaluate the structural behavior of TPC slabs, including the improvement of load-bearing capacity and the efficiency of the prediction model.

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***Table 5: Bending performance comparison between each TCC slabs***

| Connection | Geometry | | | Bending performance | | | | Reference |
|---|---|---|---|---|---|---|---|---|
| | Width (m) | Height (m) | Span (m) | $M$ (kN·m) | $EI_{eff}$ (kN·m$^2$) | MOR (kN/m$^2$) | MOE ($10^3$ kN/m$^2$) | |
| Inclined screw | 0.4 | 0.3 | 5.1 | 105.9 | 5,440 | 24272.5 | 11353.9 | [7] |
| Notch | 0.6 | 0.2 | 6.0 | 112.2 | 5,642 | 25613.8 | 11442.5 | [8] |
| Notch with inclined screw | 0.6 | 0.2 | 6.0 | 118.4 | 5,686 | 24422.1 | 9842.3 | [8] |
| Nail and notch in plywood segments | 0.3 | 0.3 | 6.0 | 45.9 | 16,514 | 9586.5 | 20887.5 | In this study |

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