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# IMPROVING THE BENDING STIFFNESS OF DLT BEAMS: EXPERIMENTAL ANALYSIS AND ANALYTICAL MODEL VERIFICATION

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***Abstract***

The search for environmentally friendly building materials has led to the development of dowel laminated timber (DLT), a product in which sawn timber boards are laminated using hardwood dowels. The dowels in DLT reduce the need for metal fasteners and synthetic adhesives. However, the application of DLT beams is challenged by the relatively low bending stiffness resulting from the low composite action. In this research, we evaluated the effectiveness of the dowel composite connection depending on different dowel angle positions to improve the bending stiffness and further enhance the environmental benefits of DLT beams. Double shear tests were performed on three-layer connections assembled with beech wood dowels. Three-layer beams were then fabricated and tested under four-point bending load. The efficiency of the composite action and the resulting flexural behaviour were evaluated. The results show that the angular position of the dowels can improve the bending stiffness by up to 50 %. The simplified design method, also known as the $\gamma$-method, was used to estimate the efficiency of composite beams. A comparison of the experimental and theoretical results helps to verify the feasibility of the EC5 model for composite beams for use with DLT beams.

*Keywords: dowel laminated timber, bending stiffness, experimental analysis, analytical model*

## 1. Introduction

Timber constructions have proven to be a viable construction option in recent decades. To meet the increasing demand for timber constructions, there is a growing interest in laminated timber elements with larger dimensions or higher load-bearing capacity. Glulam and cross-laminated timber (CLT), both glue-laminated products, are widely used due to their strength, stiffness and reliability. However, non-glue-laminated timber is also gaining increasing attention in both the academic and industrial sectors. This type of timber, which does not require adhesives, has a lower environmental impact and produces fewer pollutants [1]. Its easy disassembly and the possibility of reuse increase its ecological efficiency, especially in terms of carbon sequestration and energy savings. While there is limited experience in producing non-glued wood, the manufacturing process requires only basic techniques and equipment, making it accessible to small manufacturers. Despite its potential in circular economy, there is little data on the structural behaviour of unglued wood. In particular, the structural properties of beams made from unglued wood have not yet been sufficiently researched and their bending properties need further investigation. Various factors can influence the effectiveness of dowel composite connection: different dowel angle positions and number of dowels [2], different lamination techniques or different materials [3].

Despite the increasing importance of DLT in modern construction, Eurocode 5 lacks specific provisions for its unique properties. EC5 primarily addresses more established engineered wood products such as glulam and CLT, which are widely used in modern timber construction. As DLT is relatively new compared to these products, its specific design properties and performance in various structural applications have not been included in the Eurocode standards. The only given solution is the design approach of the "γ-method", which can be used to assess the load-bearing capacity of composite beams. The accuracy of this analytical model for assessing the composite behaviour of DLT beams needs to be validated by comparing experimental data with theoretical predictions. To address these concerns, full-scale bending tests were conducted in this study and the results were compared with analytical assessments.

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Two types of connections were analysed: Dowels inserted at an angle of 45° to the plane of the layers and at an angle of 90°. The slip modulus was determined on five specimens of each connection type by a double shear test according to EN 26891 [5]. The modulus of elasticity was determined by four-point bending test according to EN 408 [6] on five simply supported specimens. Two series of three-layer beams measuring 80 x 57 x 1000 mm were then tested in the four-point bending test, with load and deflection being monitored. The experimentally determined stiffness values were compared with the analytical values.

## 2. Analytical calculation

Using the "$\gamma$ - method" from Eurocode 5 [4], the effective bending stiffness of a simply supported composite beam consisting of three layers can be approximated as follows:

$$(EI)_{eff} = \sum_{i=1}^{3} (E_i \cdot I_i + \gamma_i \cdot E_i \cdot A_i \cdot e_i^2) \tag{1}$$

$$\gamma_i = \frac{1}{1 + \frac{\pi^2 \cdot E_i \cdot A_i \cdot s_i}{k_s \cdot L^2}} \tag{2}$$

$$k_s = (\rho^{1.5} \cdot \frac{d}{23}) \tag{3}$$

where $I_i$, $A_i$ and $E_i$ represent the second moment of inertia, the area and the elasticity modulus of the wood layers, $s_i$ is the spacing between the dowels, $L$ is the span of the beam, $k_s$ is the slip modulus and $e_i$ is the distance between the center of each layer and the neutral axis of the beam, Figure 1. In eq. (3), $\rho$ is the wood density and $d$ is the diameter of a dowel.

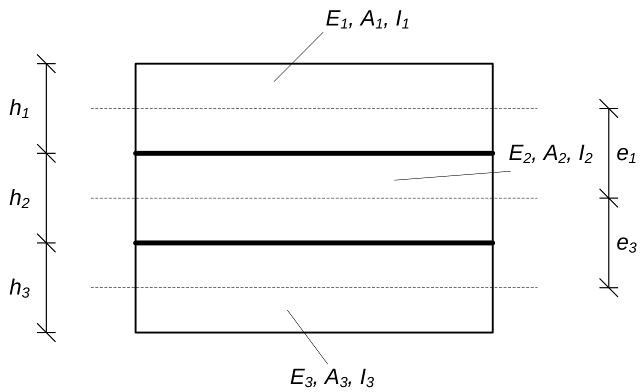


Figure 1. Cross-section of a three-layer beam with dowel connection

In previous equations, $\gamma = 1$ represents a fully bonded system (composite connection), while $\gamma = 0$ represents no shear transition between the layers.

The normal stress in the composite cross-section of the individual wood layers at mid-span can be calculated as follows:

$$\sigma_i = \frac{0{,}5 \cdot E_i \cdot h_i + \gamma_i \cdot E_i \cdot e_i}{(EI)_{eff}} \cdot M_d, \tag{4}$$

and deflection can be calculated as:

$$w_{max} = \frac{F \cdot a}{48(EI)_{eff}} (3 \cdot L^2 - 4 \cdot a^2), \tag{5}$$

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where $F$ is the applied force in the four-point bending test, $w_{max}$ is the deflection at mid-span, $M_d$ is the maximum bending moment, $L$ is the span and $a$ is the distance between the load grip and a support.

## 3. Experimental study

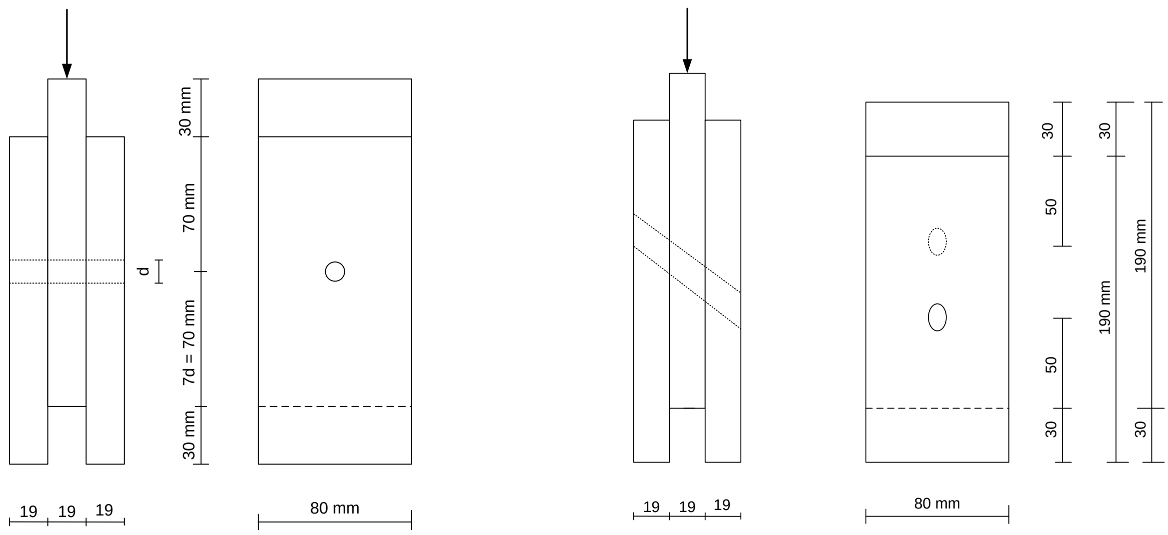
Fir wood with a moisture content of 12 % and a density of 452 kg/m$^3$ was used for the construction of the multi-layered element. Each layer was 19 mm thick. Commercially available fluted beech dowels with a diameter of 10 mm and a length of 100 mm were used for the assembly. The dowels were inserted at 90° and 45° angles to determine whether transferring the applied stress from shear only to a combination of shear and tension could result in higher shear strength.

The slip modulus was determined on five specimens according to EN 26891 [5], Figure 2. During all experiments, the load was applied by a servo-hydraulic actuator with a capacity of 50 kN. For each series, a preliminary test was first conducted to determine the estimated load. The load was then applied up to 40 % of the estimated force and held for 30 s. The load was then reduced to 10 % of the estimated force and held for an additional 30 s. Thereafter, the load was increased to the ultimate load or a slip of 15 mm. The slip modulus is calculated as follows:

$$k_s = \frac{0{,}4F_{est}}{v_{i,mod}}, \tag{6}$$

$$v_{i,mod} = \frac{4}{3}(v_{04} - v_{01}), \tag{7}$$

where $F_{est}$ is the estimated maximum load, $v_{i,mod}$ is the modified initial slip, $v_{01}$ and $v_{04}$ are the slip values at $0.1F_{est}$ and $0.4F_{est}$ respectively.




a b

Figure 2. Specimens for slip modulus testing: a) dowel connection at 90°, b) dowel connection at 45°

The elasticity modulus was determined by four-point bending according to EN 408 [6] on five simply supported monolithic specimens with dimensions 80 x 57 x 1000 mm (labelled M), Figure 3. The load was applied at a displacement-controlled rate of 8 mm/min. Two linear variable differential transformers (LVDT) HBM WA 50 mm were used to measure the vertical displacements. They were positioned at mid-span on the neutral axis of the specimen, one on each side of the specimen, Figure 4. The test was performed until failure of the specimen to determine the flexural strength.

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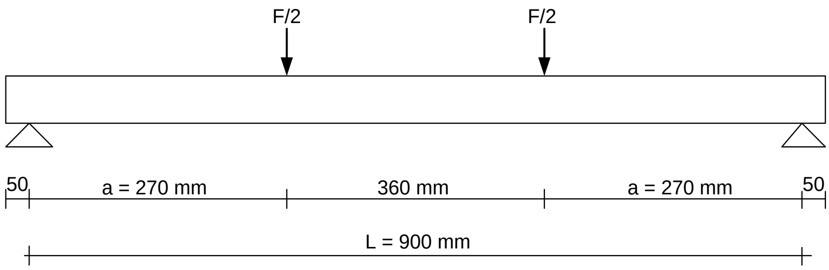


Figure 3. Test set-up for elasticity modulus testing

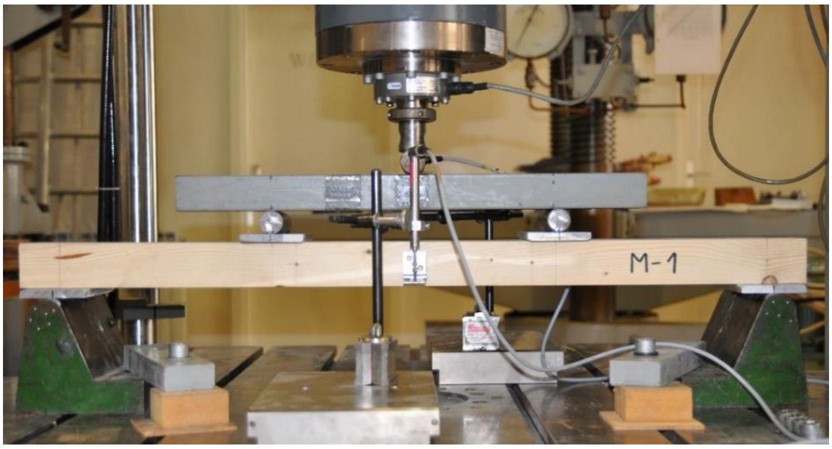


Figure 4. Modulus of elasticity test set-up

The global elasticity modulus was calculated as follows:

$$E_{m,g} = \frac{3aL^2 - 4a^3}{2bh\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)}, \tag{8}$$

where $F_2 - F_1$ is a load increments in newtons on the regression line with a correlation coefficient of 0.99 or better, $w_2 - w_1$ is the deformation increment corresponding to $F_2 - F_1$ in millimeters, and $G$ is the shear modulus, which can be assumed to be infinite.

Two series of three-layer beams were assembled: with dowels inserted at an angle of 45° to the plane of the layers, labelled DLT-45 (Figure 5) and at an angle of 90°, labelled DLT-90. Each series consisted of six specimens, with each layer measuring 80 x 19 x 1000 mm. The final dimensions of the three-layer beam were $b$ x $h$ x $L$ = 80 x 57 x 1000 mm. The holes were drilled at a distance of 50 mm. Due to the geometry, the 90° beams were assembled with 20 dowels and the 45° beams with 18 dowels. The dowels were soaked in sunflower oil for 10 minutes before insertion to ensure a better connection. The dowels were hammered in while the lamellas were under the clamp. The test setup was the same as for the elasticity modulus test, Figure 3 and Figure 4.

Figure 5. Laminated beam with dowels inserted at 45° (DLT-45)

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## 4. Results and discussion

The slip modulus was determined on five specimens of each connection type by a double shear test according to EN 26891 [5]. The load-slip curves of the test specimens are shown in Figure 6 and

Figure 7. The shear capacity and shear stiffness results are listed in Table 1. The plastic behaviour results from the embedding of the wooden dowels in the lamellas during loading. The failure mechanism of the dowel connection was associated with the compression and fracture of the dowels at the two shear surfaces. The shear capacity $F_s$ was defined as the maximum load observed during the test. In general, the shear strength of a 45° series is 8 % lower than that of a 90° series. The slip modulus of a 45° series was 48 % lower than that of a 90° series. For comparison, the slip modulus calculated according to eq. (3) is $k_s = 4178\ \text{N/mm}$, which significantly overestimates the experimentally determined values.

Table 1. Slip test results

| **Specimen** | $F_s$ **(kN)** | $k_s$ **(N/mm)** |
|---|---|---|
| 45-1 | 3.6 | 1024 |
| 45-2 | 3.5 | 825 |
| 45-3 | 3.6 | 930 |
| 45-4 | 3.1 | 737 |
| 45-5 | 3.2 | 994 |
| **Average 45** | **3.4** | **902±120** |
| 90-1 | 4.4 | 1705 |
| 90-2 | 4.0 | 1497 |
| 90-3 | 3.5 | 1993 |
| 90-4 | 2.8 | 1429 |
| 90-5 | 3.8 | 2093 |
| **Average 90** | **3.7** | **1741±291** |

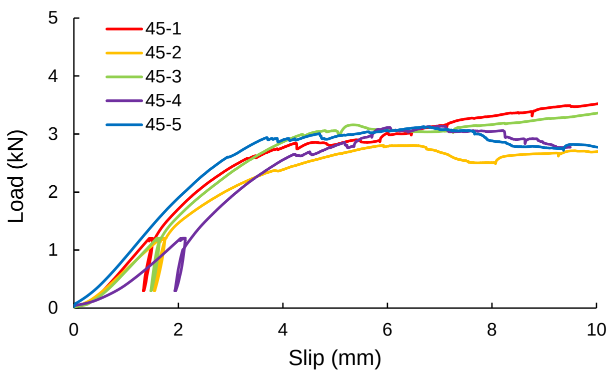


Figure 6. Load-slip curves of 45° series

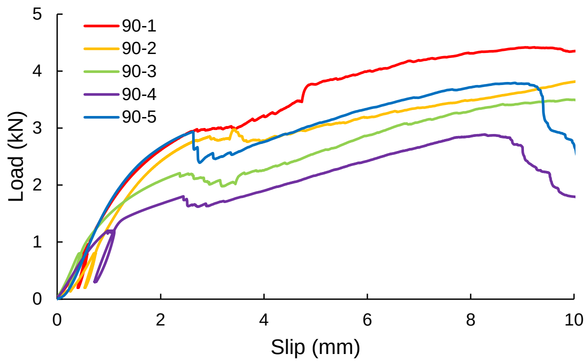

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Figure 7. Load-slip curves of 90° series

The elasticity modulus and bending strength are calculated on monolithic specimens based on EN 408 [6]. The results are summarized in Table 2. The variations in the results are relatively small.

Table 2. Physical and mechanical properties of the timber

| **Specimen** | **Elasticity modulus (MPa)** | **Flexural strength (MPa)** | **Density ($kg/m^3$)** | **Moisture content (%)** |
|---|---|---|---|---|
| M-1 | 11064 | 52.4 | 437.2 | 12.0 |
| M-2 | 12768 | 63.9 | 455.2 | 12.5 |
| M-3 | 12130 | 49.2 | 466.6 | 12.6 |
| M-4 | 12152 | 54.6 | 451.3 | 12.0 |
| M-5 | 12667 | 60.8 | 444.9 | 11.5 |
| **Average** | **12156±605** | **56.2±5.4** | **452.2±9.9** | **12.1±0.4** |

Two series of three-layer beams were tested in the four-point bending test, with load and deflection being monitored. Five specimens were tested for each connection type. The typical failure mode was bending (Figure 8), meaning that the dowels resisted well to shear loading in the mid-plane of the composite beam. Figure 9 and Figure 10 show the experimentally determined load-displacement curves for each specimen. A certain non-linearity can be seen just before the peak load. Table 3 summarises the results of the maximum load, flexural strength and initial stiffness for all tested specimens. It is noticeable that the 45° series shows better flexural behaviour than the 90° series, which is consistent with the results of previous studies [7]. When comparing the two test series, it is noticeable that the 45° series has 35% higher values for load-bearing capacity and 49% higher values for stiffness than the 90° series.

Figure 9 and Figure 10 also show the result of an analytical calculation. The accuracy of the calculation depends on the experimentally determined values of the slip modulus, the modulus of elasticity and the flexural strength. It can be seen that the analytical model for the 45° series predicts the behaviour of the composite beam quite well, while the analytical model for the 90° series overestimates the load-bearing capacity by 46 % and the stiffness by 40 %. This could be due to the fact that the load bearing capacity is most strongly influenced by the value of the slip modulus. In the 90° series, the dowel is subjected to pure shear during the shear test, whereas in the 45° series the dowel is subjected to shear and tension simultaneously. The stress state specified for the 45° specimen corresponds better to the dowel conditions that occur in the four-point bending test. This difference between the experimental and analytical results would be even more pronounced if the calculated value of the slip modulus according to the eq. (3) given by EC5 was used instead of the experimental results of the slip modulus.

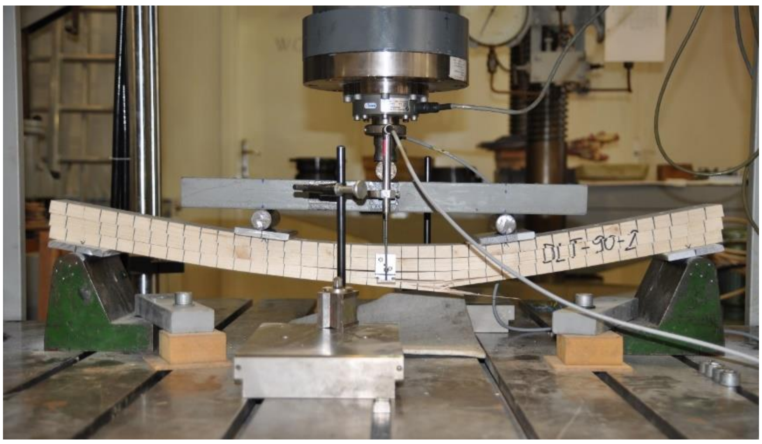

Figure 8. Failure mode

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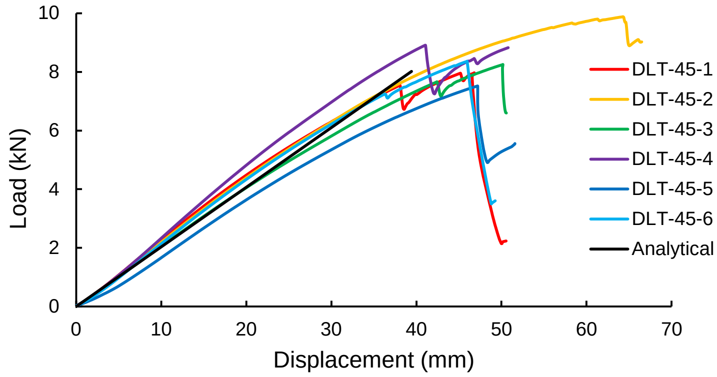


Figure 9. Load – displacement curve of 45° connection DLT beam

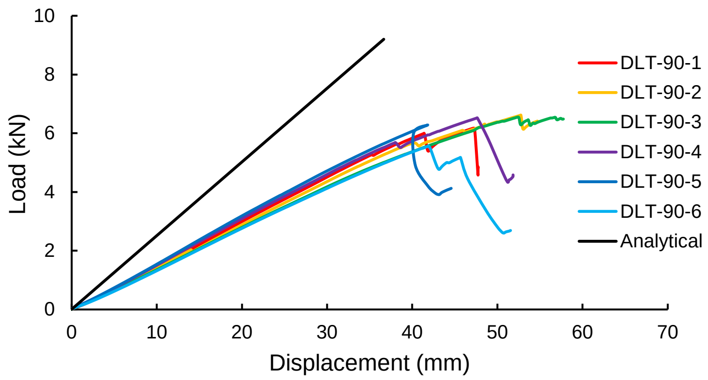


Figure 10. Load-displacement curve of 90° connection DLT beam

Table 3. Maximum load, flexural strength and initial stiffness for all tested specimens

| **Specimen** | **Maximum load (kN)** | **Flexural strength (MPa)** | **Stiffness (N/mm)** | |
|---|---|---|---|---|
| | | | Experimental | Analytical |
| DLT-45-1 | 7.97 | 8.28 | 235.1 | **203.3** |
| DLT-45-2 | 9.88 | 10.26 | 228.2 | |
| DLT-45-3 | 8.25 | 8.57 | 205.1 | |
| DLT-45-4 | 8.90 | 9.25 | 255.4 | |
| DLT-45-5 | 7.52 | 7.81 | 197.7 | |
| DLT-45-6 | 8.36 | 8.69 | 228.7 | |
| **Average 45** | **8.48 ± 0.75** | **8.81 ± 0.78** | **225.0 ± 19.1** | |
| DLT-90-1 | 6.17 | 6.41 | 154.9 | **251.0** |
| DLT-90-2 | 6.62 | 6.87 | 144.3 | |
| DLT-90-3 | 6.55 | 6.81 | 143.4 | |
| DLT-90-4 | 6.53 | 6.78 | 159.0 | |
| DLT-90-5 | 6.28 | 6.53 | 163.6 | |
| DLT-90-6 | 5.56 | 5.78 | 142.6 | |
| **Average 90** | **6.29 ± 0.36** | **6.53 ± 0.37** | **151.3 ± 8.27** | |

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## 5. Conclusion

In this study, the effectiveness of the dowel composite connection is evaluated depending on different dowel angle positions to improve bending stiffness. The dowels were inserted at 90° and 45° angles to determine whether transferring the applied stress from pure shear to a combination of shear and tension could result in higher shear strength. The results obtained on five specimen series of 1 m long beams show that the 45° angle position of the dowels can improve the bending stiffness by up to 50 % and the load bearing capacity by 35 %.

The lack of specific regulations for DLT design in Eurocode 5 reflects the general challenge of standardizing emerging construction technologies. Whilst EC5 is comprehensive for more established products such as CLT and glulam, it has yet to catch up with the unique design considerations of DLT. Currently, the only given solution for DLT is the design approach of the "γ-method", which can be used to assess the load-bearing capacity of composite beams. A key factor in this calculation is the slip modulus, which is determined here on five specimens per series in accordance with EN 26891. The results show that the analytical model greatly overestimates the load-bearing capacity and stiffness of the beams in case of the 90° series. This difference between experimental and analytical results would be even more pronounced if the calculated value of the slip modulus according to EC5 was used instead of the experimental value. Future experimental tests need to be conducted to update EC5, overcome the provisions gap and provide clearer guidance for DLT design.

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