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Load-Displacement Characteristics and Interactive Load Capacity Model for Metal Plate Connections in Wood (I)*1
- Load-displacement characteristics -

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木材-金屬플레이트 接合部의 荷重-變位 特性 및 組合荷重性能에 대한 模型 分析 (I)*1
- 荷重-變位 特性 -

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要 約

高度의 엔지니어링 構造物로 경제성이 높은 輕骨 木造 트러스에 사용될 수 있는 소나무 (*Pinus densiflora*) 材에 적용한 20게이지 아연도금鋼 플레이트 接合部의 荷重-變位 特性을 평가하기 위하여 Foschi 모형을 사용하여 모형 母數를 산출하고 실험치와 계산치를 비교·분석하였다.

接合部의 荷重-變位 曲線은 비선형 특성을 나타내었다. 접합부의 하중성능 및 剛性은 플레이트 및 목리에 평행한 형태에서 최대치를 나타내었고, 플레이트에 직각이고 木理에 평행한 형태로부터 플레이트에 평행이고 목리에 직각인 형태순으로 감소하다 플레이트 및 목리에 직각인 형태에서 최소치를 나타내었다. 3-母數 비선형 모형으로 예측된 스테인레스 鋼 및 아연도금 鋼 플레이트 접합부의 하중-변위 특성에 대한 계산치는 실험치와 잘 일치하였다.

Keywords: Nonlinear, model parameter, metal plate connection, load-displacement characteristics

1. INTRODUCTION

Light-frame wood trusses have a merit of a mass produced structural component for housing which can be easily adapted to Korean building practice with a minimum on-site labor. Light-frame wood trusses are highly engineered and most material- and performance-efficient wood structural system manufactured under controlled condition in factory.

It is important to design joints of trusses carefully, because structural members transfer their loads to other members through joints which are the weakest structural elements in wood structures. When loads are applied in wood structures such as trusses, corresponding displacement appears in the structures. This displacement shows more complex aspects in joints.

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Various kind of analysis methods for the connections have been developed to model the loadd-isplacement characteristics of the structural systems. Load-displacement relationship of the connections showed the nonlinear character, so this nonlinearity should be taken into account if the designer want to estimate allowable or ultimate loads based on joint behavior.

Using a finite element elasto-plastic analysis, Foschi[3] developed a nonlinear character model of the load-displacement relationship for nailed joints. Foschi[4] also developed a finite element model, which treated the problem without recording to equivalent spring or fititious members for the three parameter nonlinear performance of truss plate joints.

In order to apply Foschi's model, parameter values should be fitted to experimentally determined load-displacement curves. MaCarthy and Wolfe[7] determined Foschi's nonlinear model parameters to characterize the lateral resistance of truss plated joints. The parameters obtained could be used to model the nonlinear performance of truss plate joints in full scale roof system models. Lau[6] reported that the applicability and usefulness of existing computerbased techniques could be expanded if better joint models could be incorporated into SAT [4], or if PPSA II [9] could be advanced to describe the be havior of joints. Gebremedhin, Jorgensen and Woelfel[5] developed models that would predict the load-displacement relationships and stiffness values for the joint.

The objective of this study was to evaluate load-displacement characteristics of the connections under load by deriving parameters of Foschi's model for 20 gage galvanized steel plates in Korean red pine lumber. Parameters of nonlinear model are be useful to estimate full-scale truss performance by eliminating time- and cost consuming full-scale truss tests.

2. MATERIALS & METHODS

2.1 Materials

2.1.1 Material preparation

Lumber for this study was selected from 38×89mm(nominal 2×4inch) lumber of Korean red pine (*Pinus densiflora*) that met No. 2 or better grade specifications[12]. Lumber was four side surfaced and was conditioned to 12 percent moisture content.

The modulus of elasticity of lumber used ranged from 69 to 123×10^3kgf/cm^2, with an average of 90×103kgf/cm^2. Specific gravity based on oven-dry volume of lumber ranged from 0.45 to 0.59 with an average of 0.52.

Metal plate connectors applied for lumber joints were 20 gage (nominal thickness: 0.89 mm) galvanized steel plates manufactured by Truswal Systems Corporation, U.S.A. These plate connectors were used for joint tests of four standard configurations, two nonstandard configurations. Galvanized steel plates had tooth density of 3.1 teeth per cm^2, tooth length of 6.9 mm. In all cases of test joints, there were 40 teeth per target plate wood interface. Connectors for joints loaded parallel to plate principal axis were 81.0mm wide by 134.0mm long. Connectors for joints loaded perpendicular to plate principal axis were 75.0mm wide by 81.0mm long. For two nonstandard configuration joints, connectors were prepared by removing teeth to have 40 teeth per target plate wood interface.

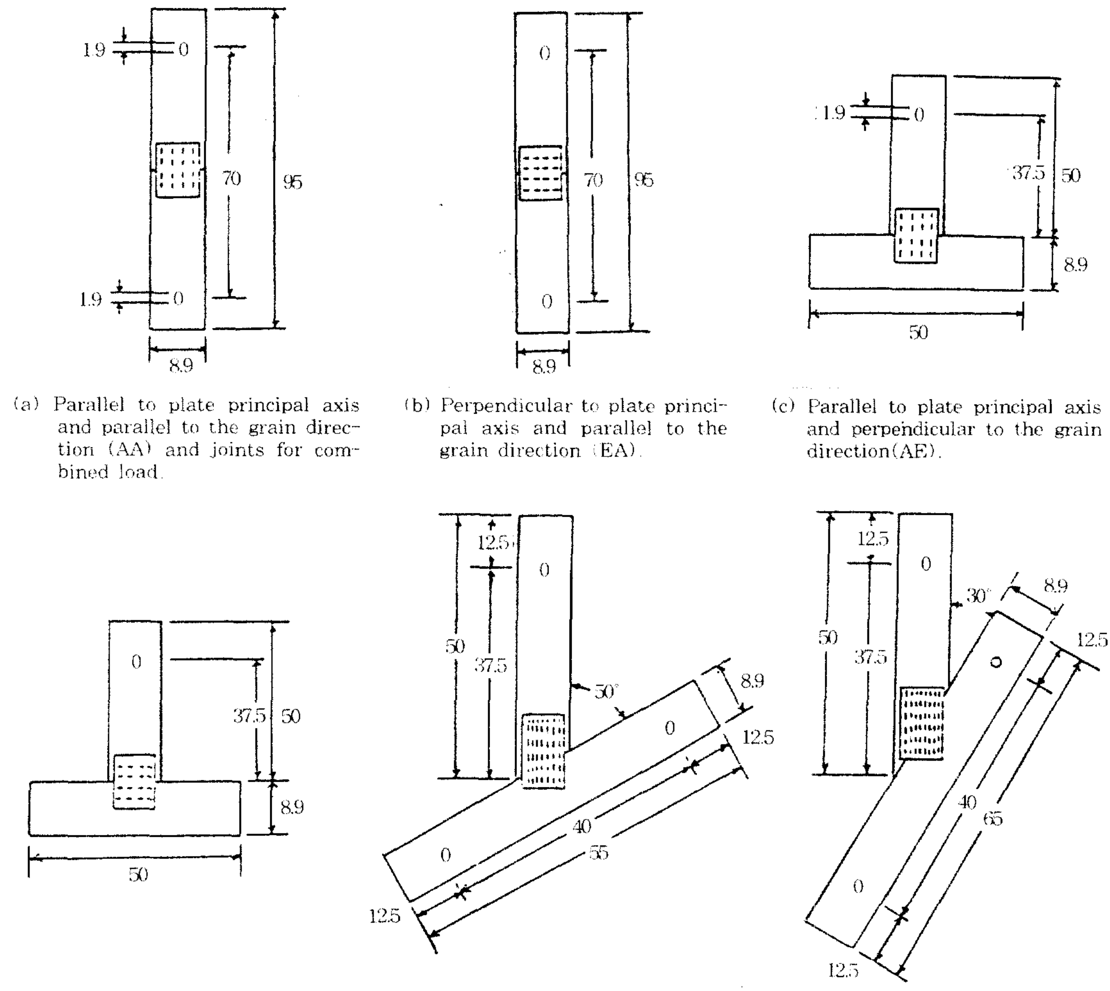
2.1.2 Joint fabrication

Five test joints for each four standard joint configuration were fabricated(Fig. 1). Two types of nonstandard joint configurations were fabricated to have 30 and 60 degrees between the grain direction of target plate side lumber and plate principal axis.

Testing machines were used to give uniform pressure of the metal plate connectors on the joint during fabricating connections. After fabrication, the connections were stored in a conditioning room of 12 percent MC for more than 14 days before testing in order to minimize possible variation due to time effects.

2.2 Test procedure of standard - and non-standard- joint configurations

For joint tests, load was applied at a constant strain rate of 1.0mm/min using a universal testing machine of 15,000 kgf capacity. The



(a) Parallel to plate principal axis and parallel to the grain direction (AA) and joints for combined load.

(b) Perpendicular to plate principal axis and parallel to the grain direction (EA).

(c) Parallel to plate principal axis and perpendicular to the grain direction(AE).

(d) Perpendicular to plate principal axis and perpendicular to the grain direction(AE).

(e) With 30 degrees between plate principal axis and the grain direction(A30G).

(f) With 60 degrees between plate principal axis and the grain direction (A60G).

Fig. 1. Standard-and nonstandard-joint configuration of metal plate connectors.

data from load cell and LVDTs (Linear Variable Differential Transducers) was acquisited by computer. Moisture content of each block of joint specimen was measured by a resistance type moisture meter after joint testing.

The sheet steel plates were tested according to ASTM E 489[1] to determine tensile properties of the plate. MOE for sheet plate of galvanized steel averaged $1,780 \times 10^3$ kgf/cm^2 with coefficient of variance of 4.3 percent.

Four standard configuration joints were tested according to CSA S347 M1980 standard[2]. Two nonstandard configuration joints were tested to evaluate joint performance at intermediate angle between the grain direction of target plate side lumber and plate principal axis. Four LVDTs were installed at each side of the joint specimen and at each metal plate to measure the joint displacement.

2.3 Modeling of the load-displacement relationships for joint tension performance

Three parameter nonlinear model described by Foschi[4] was used to determine the load-displacement behavior of the connections. He proposed the following model to describe the load-displacement behavior of the connections:

$$P = (M_0 + M_1 |\Delta|)\left[1 - \exp\left(\frac{-K|\Delta|}{M_0}\right)\right] \quad \cdots\cdots (1)$$

where,

P : the load on the joint, kg.
$|\Delta|$: the joint displacement, cm.
K : the initial stiffness, that is, the initial slope of the curve.
M_1 : the stiffness at large displacement.
M_0 : the intercept of the asympdote with slope M_1 (Fig. 2).

Three parameters, K, M_1, M_0, in this model were determined by least-square method for each of the four standard joint configurations.

3. RESULTS & DISCUSSION

3.1 Joint failure modes

Two kind of failure modes were possible in standard joint configurations: tooth with drawal and wood failure. Tooth withdrawal was evident in all AA and EA joints. Both tooth withdrawal and wood failure appeared in all AE, EE, A30G, and A60G joints, and this failure mode was considered to be due to weaker wood bearing strength for AE, EE, A30G, and A60G joints than that for AA and EA joints.

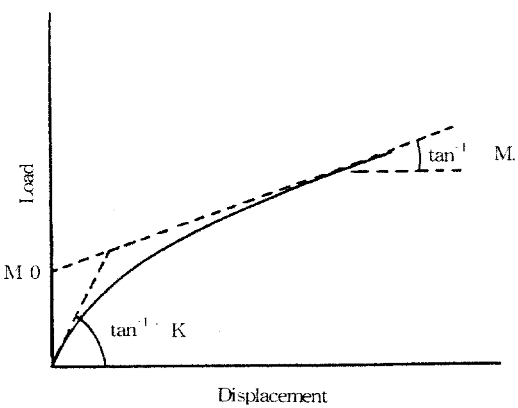


Fig 2. Foschi's three parameter nonlinear model for metal plate load-displacement curve.

3.2 Load-displacement curves and stiffness values of each joint configurations

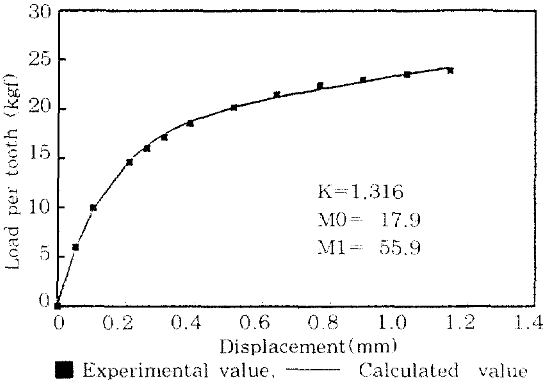
The load-displacement curves of standard and nonstandard- joint configurations showed a nonlinear characteristics. The lower one third section by load of the curve could be described as nearly linear. The slope of the load-displacement curve decreased nonlinearly according to approaching the maximum load of the connections after this one third section. This facts showed the semi-rigid properties of the connections experimentally.

For the standard joint configurations tested in tension, the average ultimate load per tooth varied from 23.8 to 13.7 kgf(Fig. 3 and Table 1). Basic design load per tooth, determined by the load at the critical value of 0.38mm displacement[11], ranged from 18.5 to 13.6 kgf. For the connections of nonstandard joint configurations loaded with the angle of 30 and 60 degrees in tension, the average ultimate load per tooth were 19.5 and 17.3 kgf, respectively, and basic design load per tooth were 18.3 and 17.2 kgf, respectively.

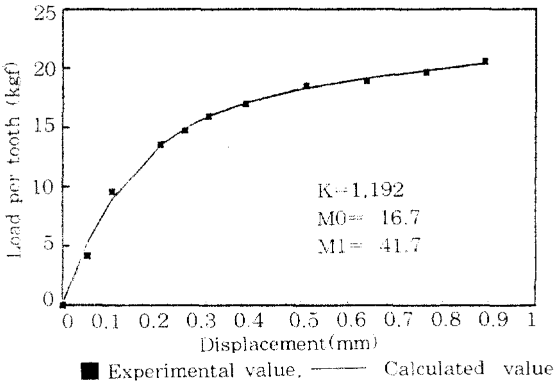
The stiffness for the joints was determined by dividing basic design load by the critical displacement[5,11] as shown in Table 2. The stiffness for the connections varied from 39,078 to 28,789 kgf/cm, and showed 1.4 times of difference according to joint configurations.

The load capacity and the stiffness for standard joint configurations showed the largest value at joint configuration AA, decreased from joint configuration EA to AE, and showed the smallest at joint configuration EE. These values for standard- and nonstandard- joint configurations showed the largest value at the joint configuration AA, and decreased according to increase of intermediate angle between the grain and loading direction.

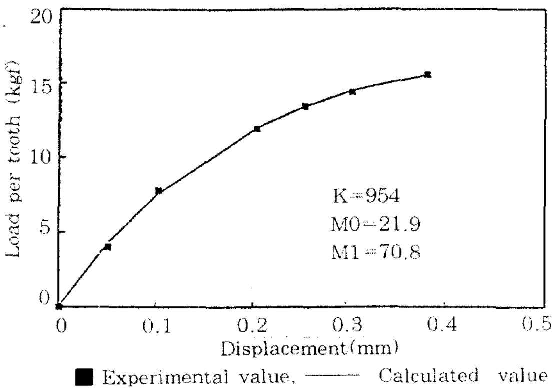
The trend that structural performance of the connections perpendicular to the grain was smaller than that of the connections parallel to the grain, agreed well with the literatures



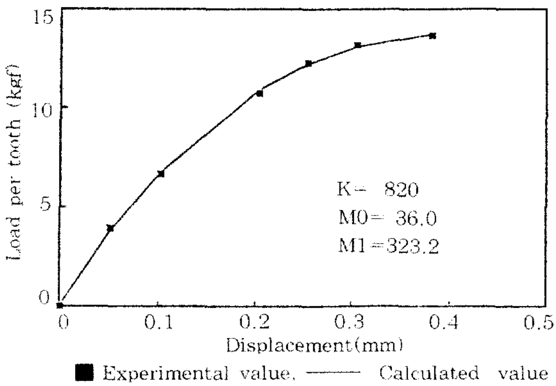
(a) Parallel to plate principal axis and parallel to the grain direction (AA).



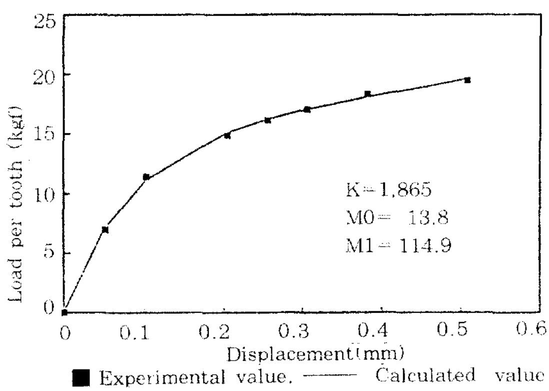
(b) Parallel to platd principal axis and perpendicular to the grain direction (EA)



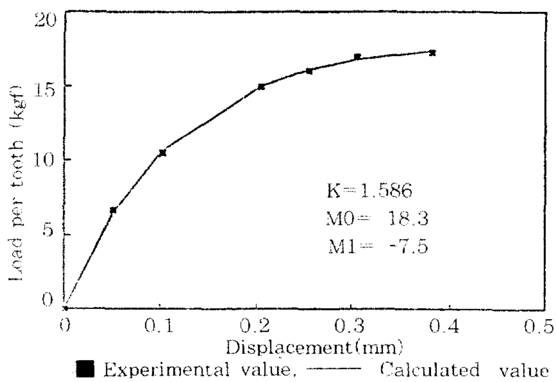
(c) Perpendicular to plate principal axis and pardllel to the grain direction (AE).



(d) Perpendicular to plate principal axis and pardllel to the grain direction (EE).



(e) With 30 degrees between plate principal axis and the grain direction (A30G)



(f) With 60 degrees between plate principal axis and the grain direction (A60G).

Fig 3. Experimental and predicted load-displacement curves for each standard-and nonstandard-joint configuration of galvanized steel plate connentors.

[4,7,11]. The trend that structural performance of the connections perpendicular to the plate was smaller than that of the connections parallel to the plate, was similar to the results by

Table 1. Ultimate load and design load for standard- and nonstandard-joint configurations.

Joint configuration	At ultimate load						At basic design load			
	Ultimate load		Load per tooth		Displacement		Load		Load per tooth	
	Average (kgf)	CV (%)	Average (mm)	CV (%)	Average (mm)	CV (%)	Average (mm)	CV (%)	Average (mm)	CV (%)
AA	1,908	9.7	23.8	9.7	1.14	25.2	1,485	6.2	18.5	6.2
EA	1,645	8.9	20.5	8.9	0.89	31.3	1,361	7.4	17.0	7.4
AA	1,286	7.2	16.0	7.2	0.40	6.8	1,286	5.5	16.0	5.5
EE	1,098	10.7	13.7	10.7	0.41	10.9	1,094	4.9	13.6	4.9
A30G	1,563	11.2	19.5	11.2	0.51	21.7	1,467	6.8	18.3	6.8
A60G	1,386	9.6	17.5	9.6	0.43	9.1	1,380	4.5	17.2	4.5

Table 2. Stiffness values for the connection.

Joint configuration	Stiffness by critical displacement	
	Average (kgf/cm)	CV (%)
AA	39,078	6.2
EA	35,815	7.4
AE	33,842	5.5
EE	28,789	4.9
A30G	38,605	6.8
A60G	36,315	4.5

Triche[10], but this trend was somewhat different from the results[7] that load capacity of the connections perpendicular to the plate was somewhat larger than that of the connections parallel to the plate. These showed that there were two types of trend in structural performance by each joint configurations. The different trends by connection types were considered due to the combined effect of the plate characteristics : that is, tooth width, tooth length, and plate stiffness. These load capacity and stiffness by each joint configurations can be applied to accomplish advanced design of the connections by using database of the connections and by interpolating for intermediate angled joint elements easily found in light frame wood trusses.

3.3 Model parameters of the load-displacement curves for standard joint configurations

The three parameter nonlinear model[4] was fitted quite well to the experimental load and displacement data for the connections. Table 3 showed the model parameters curve-fitted by the least square method. The intercept of the asymptote with slope M_1, M_0, was evaluated in the order of their magnitude from the joint configuration EE, the largest, to AE, EA, and AA, the smallest. The stiffness at large displacement, M_1, was in the order of their magnitude from the joint configuration AA, the largest, to EA, AE, and EE, the smallest. The initial stiffness, K, was evaluated in the order of their magnitude from the joint configuration AA, the largest, to EA, AE, and EE, the smallest, and was evaluated in the same order of stiffness. The parameters were compared to other data obtained by McCarthy and Wolfe[7], Triche[10] and Foschi[4]. The parameters for the connections were most close to the results by McCarthy and Wolfe[7] except negative M_1 for joint con-figurations AE and EE, but the trend in this study was somewhat different from their results[7] that the parameters of the connections perpendicular to the plate showed bigger value than those parallel to the plate. The negative M_1 in this study was occured because the parameters were derived from the entire curve, extending from zero to the ultimate load, letting M_1 become negative[5]. The different trend of characteristics by type of the connection were considered due to the combined effect of the plate characteristics: that is, tooth width, tooth length, and plate stiffness.

4. CONCLUSION

This study was accomplished to evaluate load-displacement characteristics for metal plate connections in Korean red pine lumber. Failure modes were tooth withdrawal for all specimens in standard joint configurations AA and EA.

Table 3. Nonlinear model parameters for each standard jiont configurations compared with results of other studies.

Parameter*	Joint cobfiguration	Current study*2	McCarthy*3	Triche*4	Foschi*5
K (kgf.cm)	AA	1,316	1,910	5,370	562
	EA	1,192	1,969	4,940	1,246
	AE	904	632	637	528
	EE	820	607	607	847
M_0 (kgf)	AA	17.9	18.3	26.7	22.5
	EA	16.7	20.7	21.1	8.4
	AE	21.9	11.5	27.9	6.9
	EE	36.0	22.5	8.8	7.8
M_1 (kgf/cm)	AA	55.9	91	467	0
	EA	41.7	75	430	0
	AE	-70.8	38	0	0
	EE	-323.2	50	378	0

*1 Evaluated by the load-displacement data based on load per tooth.
*2 20 gage galvanized plates and Korean red pine(2″×4″) lumber.
*3 20 gage galvanized plates and Southern pine(2″×4″) lumber.
*4 20 gage galvanized plates and Hem-fir lumber.
*5 20 gage galvamized plates and spruce(2″×6″) lumber.

Combined tooth withdrawal and wood failure were evident in the joint configuration AE, EE, A30G, and A60G. The load-displacement curves for standard- and nonstandard- joint configurations showed nonlinear characteristics. The lower one third section by load of the curve could be described as nearly linear. Slope of the load-displacement curve decreased nonlinearly according to approaching the maximum load of the connection.

The load capacity and the stiffness for standard joint configurations showed the largest value at joint configuration AA, decreased from joint configurations EA and AE, and showed the smallest at joint configuration EE. These values for standard- and nonstandard-joint configurations showed the largest value at the joints loaded parallel to the plate and the grain, and decreased according to the increase of intermediate angle between the grain and loading direction. Load-displacement relationships estimated by Fosch's nonlinear model for the connections was fitted quite well to the experimental values.

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