台灣產杉木工字樑之應力分布

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【摘要】本研究係採用省產杉木造林木所組成之工字樑應用於樓板托樑系統之探討，樑翼材之尺寸為 38×89、38×140 及 38×180 mm，樑深為 300 mm，樑翼與樑腹構材之組合採用 16d 箱用釘，間距分別為 8、10、12 cm，並以環氧樹脂膠合劑于界面補強。工字樑試材長 3.6 m，以三分點載重進行靜曲試驗，跨距/樑深比為 11.7。試驗結果顯示，在最大靜曲破壞的 30%條件下，於載重跨距範圍內，以應變片測定所得樑斷面之應變分布呈線性關係；同時，在下樑翼構材所測得之拉伸應變值較上樑翼者高出 17.8%。在釘接與膠合之界面兩側的相鄰樑翼構材與樑腹構材，其應變值相差約-19.6%~+39.5%。以 38×89 mm 作為樑翼構材之工字樑彎曲剛性較佳。上下樑翼構材在表裏側的應變量平均差異分別為 12.3%及 21.9%。破壞時在剪斷跨距範圍樑翼所產生之剪斷應力，為樑腹構材斷面中央位置之最大剪斷應力之 36.3%，在樑翼與樑腹接合介面之剪斷應力則為最大值之 72.5%。利用 ANSYS 有限元素分析軟體，探討離支點 60 cm 處的工字樑斷面應力分布，以固體元素配合無缺點木材之彈性係數值模擬結果較實測者為低較為保守。

【關鍵詞】杉木、工字樑、彎曲性質、有限元素方法。

Stress Distribution of I-beam Fabricated with China-fir Lumber in Taiwan

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【Abstract】 China-fir is a fast-grown species and is used as materials for the assembly of I-beam for the application of flooring system. The sizes of flanges include 38X89, 38X140, and 38X180 mm and the depth of beam is 300 mm. The flanges and web were assembled with 16d box nails in nail spacing of 8 cm, 10 cm, and 12 cm, respectively, and with the application of epoxy adhesives. I-beam with 3.6 m in length was subjected to four-point loading for static flexural tests with a span/depth ratio of 11.7. The linear relationship of strain distribution on the cross section of I-beam can be found within the shear span based on the measurements of strain gages at the level of 30% of maximum load. It is indicated that there is 17.8% higher for tensile strain on lower flanges than that of compressive strain on upper flanges. The variation of −19.6% to +39.5% in strain measurements between flanges and adjacent web resulted due to the influence of the sizes of flanges on the stiffness of I-beam formed by nail joints and adhesives. Better improvement on the stiffness can be found in the case of I-beam fabricated with 2×4 flanges. The difference of strain measured at both sides of top and bottom flanges are 12.3% and 21.9%, respectively.

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The simulation on the stress distribution on the cross section of I-beam 60 cm from support within the shear span is performed. The maximum shearing stress occurred in the middle of web member is about 2.55 MPa. The shearing stress on the web near the interface is reduced to 72.5% of the maximum shearing stress. The shearing stresses on the flanges are only 36.3% of the maximum shearing stress. The flexural behavior of I-beam is modeled with a finite element method of the ANSYS software and solid 45 elements are employed. The more conservative results were obtained as the modulus of elasticity evaluated from small clear wood employed in the modeling.

【Key words】 China fir, I-beam, Flexural property, Finite element method.

I、INTRODUCTION

The development of composite I-beam products is recognized as the efficient usages of wood resources especially when the supply of large logs decreases. It is suggested that the structural performance and stability of I-beam can be assured by selecting higher grade of kiln-dried lumber as components for the fabrication of I-beam. China fir is one of the major plantation species in Taiwan and mostly used as purlin, post, beam, and other framing member in traditional building structures. And the boards also used as concrete form on the job sites and interior wall board due to its light weight, workability and appearance. However, the average harvest rotation for commercial China fir is 30 years. The logs or sawn lumber contains large portion of juvenile wood with knotty and low mechanical properties. The structural performance of I-beam becomes a major concern in the evaluation of the feasibility for making I-beam from China fir lumber. The long-term flexural properties of the composite I-beams and solid wood beams were investigated by Leichti and Tang (1989). It is indicated that although both types of beams showed the same mechanical properties and maximum loading capacity, solid wood beams were found having some early flexural failure due to natural defects such as knots, checks, and juvenile wood and having higher variability. To better understanding the stress and strain distribution across the China fir I-beams subjected to static bending loads, the strain gages were applied and finite element method was employed in the study.

II、MATERIALS AND METHOD

(Ⅰ)I-beam fabrication

China fir logs of 30 to 38 year old were sawn into the sizes of 38 × 89 mm, 38 × 140 mm, and 38 × 184 mm as flange materials and 39 × 224 mm as web member. I-beams were fabricated with 16d box nails with 8, 10, and 12 cm spacing, respectively, along the interface between flanges of each width designation and webs. The length of I-beams is 360 cm long and the depth is 30 cm. The epoxy resin adhesives (type: WA-902, Wood Glue Co.) were applied with the amount of 250 g/m^2 between flanges and web members during the fabrication of I-beams.

(Ⅱ)Flexural test

Static bending test was performed in four-point loading application based on ASTM D198-94 with a span/depth ratio of 11.7. Both the shear span and loading span are 117 cm and total span is 351 cm as shown on Fig. 1. The specimens were laterally supported at four points between vertical supports at both ends of beams. The strain gages (type: L-20-11, 120±0.3% ohm, Tokyo Sokki Kenkyujo Co. LTD.) with 20 mm long and ±20000 μ of strain ranges were attached to the I-beams at the position 60 cm from end support within the shear span. There are seven stain gages attached to the I-beams with 38 X 89 mm flanges in a way to obtain the general strain distribution across the beam section and 11 strain gages were applied to the I-beams with 38 × 140 mm or 38 × 184 mm flanges (Fig.2).

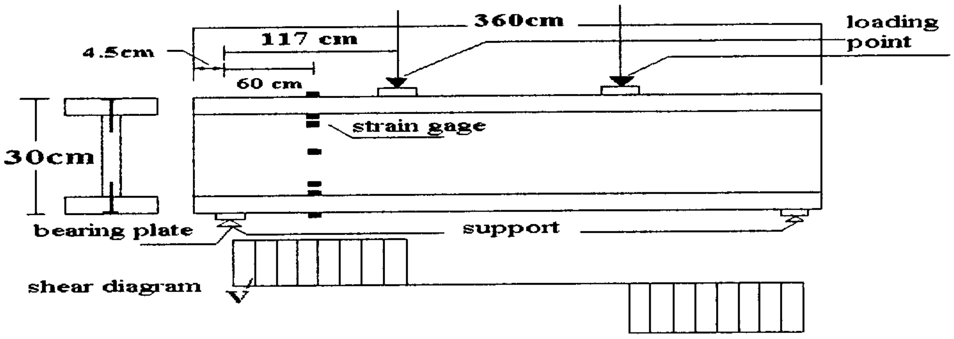
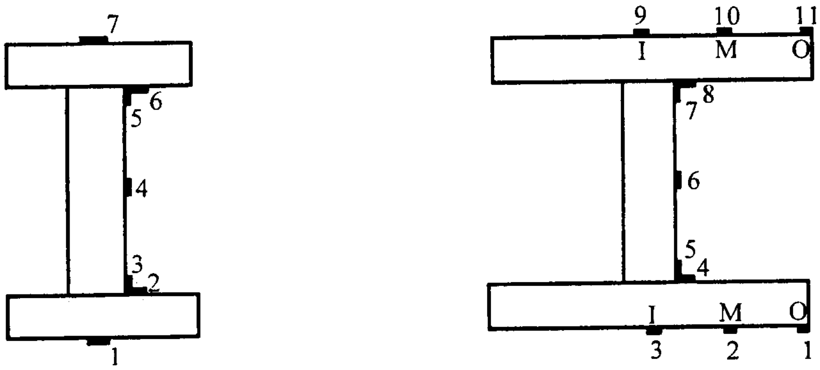


圖 1 工字樑之三分點載重靜曲試驗
Fig. 1 Static bending test for I-beam subjected to four-point loading.



(a) 38×89 mm (b) 38×140 and 38×180 mm

圖 2 應變片在杉木工字樑黏貼位置（a）38×89 mm 樑翼（b）38×140 及 38×180 mm 樑翼
Fig. 2 Arrangement of strain gages on the China fir I-beam with (a) 38×89 mm (b) 38×140 and 38×180 mm flanges.

The shearing properties of I-beams subjected to the flexural loads can be estimated based on the following equations. The ultimate shearing stresses on the web member will be:

$$\tau_{xy\cdot\max} = \frac{V}{2It}(bc^2 - bc_1^2 + tc_1^2)$$

$$\tau_{xy\cdot\min} = \frac{Vb}{2It}(c^2 - c_1^2)$$

where $\tau_{xy\cdot\max}$: maximum shearing stress at the center line of web (kgf/cm^2)

$\tau_{xy\cdot\min}$: minimum shearing stress on the web near the interface of web and flange (kgf/cm^2)

V: shear force (kgf), I : moment of intertia
t: thickness of web member (kgf)
b: width of flange (kgf)
c: half of I-beam depth (cm)
c_1: half of web depth (cm)

The shearing stress of flange at the juncture of web and flange (τ_{xy}) will be:

$$\tau_{xy} = \frac{V}{2I}(c^2 - c_1^2)$$

The maximum horizontal shearing stress in the middle of flanges will be:

$$\tau_{xz\cdot\max} = \frac{V}{2I}(c - \frac{t_f}{2})b$$

where t_f : flange depth.

(Ⅲ)Finite element simulation

The strain and stress distribution of I-beam subjected to flexural loads were simulated with finite element method by using 3-D structural solid linear hexahedron element (Solid 45). The ANSYS software was used for the simulation. Since the loading condition on the I-beam subjected to four-point testing configuration is symmetrical, it can be reduced into half section of the beam for the analysis with rigid boundary condition at the center of the I-beam. The size of the element on the cross section of web member is 19 × 37.3 mm, and the element on the flange member is divided into two layers. The length of each element is 38.1 mm. Therefore, the total number of elements for the beam with the flanges of 38 × 89, 38 × 140, and 38 ×184 mm are 4469, 5208, and 5925, respectively including the 552 elements for web member. One of the meshed I-beam is indicated on Fig. 3.

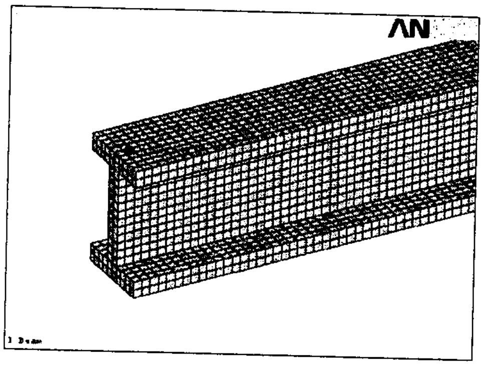


圖3 38×180×300 mm 杉木工字樑之有限元素分割

Fig. 3 Meshes of 38×180×300 mm China fir I-beam.

(Ⅳ)Elastic properties of small clear wood

The static bending properties of small clear China fir specimens were evaluated according to Chinese National Standard CNS 454. The moduli of elasticity and Poison's ratios on the longitudinal, radial, and tangential direction of wood, respectively, were also measured by using strain gages mounted on the proper face of clear wood blocks as shown on Fig. 4. The properties were estimated according to following equations:

$$Ei = \frac{\sigma}{-\varepsilon_2}$$

$$\nu = \frac{\Delta\varepsilon_1}{\Delta\varepsilon_2}$$

where E_i is modulus of elasticity along longitudinal(L), radial(R), and tangential(T) direction of wood measured from compressive loads, respectively. σ are relative stresses calculated between 20-25% of maximum load at failure or proportional limit, ε are strain measured at corresponding stresses. ε_1 is corresponding strain measured perpendicular to the loadings between 20-25% of maximum value. ε_2 is corresponding strain measured parallel to the loadings.

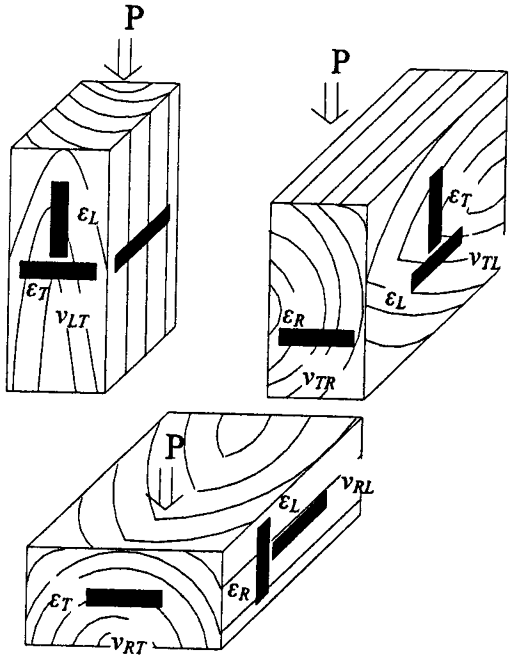


圖4 應變片在杉木試材三切面之黏貼位置

Fig. 4 Location of strain gages on the three faces of China fir lumber.

III、RESULTS AND DISCUSSION

(I) Elastic properties of small clear wood

The results evaluated based on small clear China fir specimens are indicated on Table 1. The average width of annual ring for China fir lumber is 0.68±0.08 cm, moisture content of specimens measured during the tests is 13.93±0.28%, and density is 0.41±0.01 g/cm^3. Wang *et al.* (1993) had investigated the variation of flexural properties of China fir lumber across the diameter of log, and the values measured from the specimens near the pith were similar to the tested results in this study. According to the investigation of Wang *et al.* (1992) for the physical sizes of 5 × 9 × 210 cm China fir lumber, the values of static modulus of rupture was 86.4% of small clear specimens in this study and 153% for the static modulus of elasticity (1990), which indicated that the size of the lumber may have major effects on the mechanical properties.

Wood can be taken as orthotropic materials and the orthotropic elastic theory is applied under certain assumption. Although the ratios of elastic parameters of wood differs according to the species, moisture content and loads, the degree of heterogeneity still can be determined from the difference of elastic parameters values measured from each direction. In this study, the strain measurements of China fir lumber from longitudinal, radial, and tangential direction were obtained through the strain gages. And the elastic parameters and Poison's ratios were calculated from the linear relations below 25% of compressive strength, i.e., 7.89 MPa, 1.55 MPa, and 0.74 MPa, respectively, as shown on Table 1. The ratio of moduli of elasticity for longitudinal, radial, and tangential directions is 34:3:1. It is suggested that the average ratio of 20:1.6:1 is common for wood materials by Bodig and Jayne (1982). Therefore, it is indicated that lower value of MOE in the tangential direction was found for China fir. The results also revealed extremely small values of ν_{RL} and ν_{TL}, which match the results from other reports. In general, the values of elastic parameters are close to that of spruce with slightly higher values of ν_{LT}, ν_{LR}, and ν_{RT}, and slightly lower values for ν_{TR}, ν_{RL}, and ν_{TL} as compared to those of averaged values of softwood. The variations of symmetry for compliance matrix calculated by Lee based on the measurements through ultrasonic evaluation were among 27 to 62% (Lee, 2000). He concluded that wood still features of anisotropic characteristics and is not true orthotropic materials. The variations of symmetry for elastic parameter of spruce wood were among 6 to 46% (Bodig *et al.* 1973), while around 40% of variation was found for China fir lumber in this study.

表 1 杉木無缺點小試材之機械性質
Table 1 Mechanical properties of small clear China fir specimens.

Modulus of rupture	52.9±7.1 MPa
Static modulus of elasticity in bending	5958±862 MPa
E_L (longitudinal) in compression	8044±853 MPa
E_R (radial) in compression	706.3±146 MPa
E_T (tangential) in compression	235.4±49 MPa
ν_{LT}	0.51±0.17
ν_{LR}	0.48±0.12
ν_{RL}	0.026±0.003
ν_{RT}	0.57±0.007
ν_{TL}	0.019±0.016
ν_{TR}	0.25±0.11
Shearing strength (with epoxy glue)	11.6±0.7 MPa
Lateral resistance (16d nail)	2.06±0.24 KN

(Ⅱ) Shearing stress

There is significant shear occurred within shear span of I-beam as subjected to the static bending loads. The distribution of shearing stress on the cross section of I-beam is usually considered a criterion for the selection of adequate sizes of web member and the reinforcement on the web (Leichti *et al.* 1990). In advance, the required nail spacings and load capacities of nail joints are always estimated through the shear flow at the interface between flange and web members. The resulted shear stresses across the I-beam section within the range of shear span are shown on Table 2. The maximum shearing stress ($\tau_{xy \cdot max}$) occurred in the middle of web member is about 2.55 MPa. Some I-beam specimens failed in horizontal shear mode during the flexural test may be due to the weak shear properties of China fir. The shearing stress on the web near the interface ($\tau_{xy \cdot min}$) is reduced to 72.5% of the maximum shearing stress. The shearing stresses on the flanges (τ_{xy}) are reduced tremendously, i.e., 0.926 MPa, due to wider dimension than web members, which is only 36.3% of the maximum shearing stress. The average shear flow between the web and flange juncture is 70.36 KN/m which is resisted by 16d box nails in the spacings of 8, 10, and 12 cm and epoxy adhesive.

表 2 杉木工字樑剪斷跨距範圍之斷面剪斷應力分布

Table 2 Shearing stress distribution at failure on the cross section of China fir I-beam within shear span.

Size of flange	38×89	38×140	38×180
$\tau_{xy \cdot max}$ in the middle of web (MPa)	2.57	2.74	2.33
$\tau_{xy \cdot min}$ on the web near the interface (MPa)	1.67	2.04	1.84
τ_{xy} on the flange near the interface (MPa)	0.714	0.556	0.388
$\tau_{xz \cdot max}$ (MPa)	0.837	1.022	0.919
flange shear flow at the interface (KN/m)	63.55	77.67	69.85

(Ⅲ) Strain and stress of I-beam

In general, the strain distribution across the section of homogenous bending member subjected to flexural loading within linear ranges shows the linear characteristics. The measurements from strain gages attached at the distance of 60 cm from the support within the ranges of shear span of China fir I-beam were sketched on the Fig. 5 to 7. It indicated that the average tensile strain at lower flanges of China fir I-beam as subjected to 30% of maximum flexural loads is 17.8% higher than that average compressive strain measured at top flange. From previous study, the compressive strength of China fir solid wood specimens is 94% of tensile strength (Chang and Yeh, 2001). Therefore, the bottom flange is subjected to higher stress due to the difference between compressive strength and tensile strength, which is typical characteristics of solid wood beams under flexural loading (Wang, 1993).

In the cases of I-beam fabricated with 38×140 mm flanges, the strain measurements from tensile side of flanges were smaller than that from compressive side. This may be contributed by the knots located within the loading span of the I-beam, causing larger deformation in the center portion of the beam and increasing compressive strain on upper flanges. If the linear distribution for tensile and compressive strain across the web section of I-beam still remains, and the location of neutral axis calculated based on the linear distribution was found 0.67 cm downward from the center line or symmetric axis of webs.

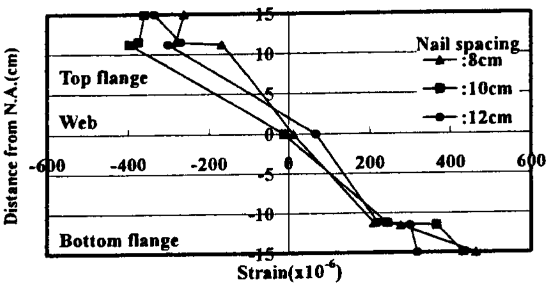


圖 5 38×89×300 mm 杉木工字樑在剪斷跨距範圍內于最大彎曲載重之 30%條件下斷面之應變分布

Fig. 5 Strain distribution on the cross section of 38×89×300 mm China fir I-beams within the shear span when subjected to 30% of maximum flexural loads.

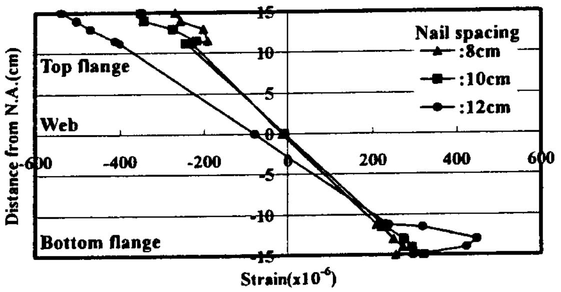


圖 6 38×140×300 mm 杉木工字樑在剪斷跨距範圍內于最大彎曲載重之 30%條件下斷面之應變分布

Fig. 6 Strain distribution on the cross section of 38×140×300 mm China fir I-beams within the shear span when subjected to 30% of maximum flexural loads.

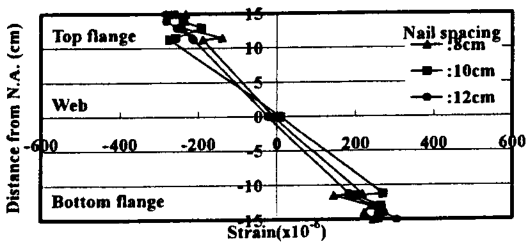


圖 7 38×180×300 mm 杉木工字樑在剪斷跨距範圍內于最大彎曲載重之 30%條件下斷面之應變分布

Fig.7 Strain distribution on the cross section of 38×180×300 China fir I-beams within the shear span when subjected to 30% of maximum flexural loads.

It is believed that the reinforcement of epoxy glue at the interface between flange and web materials have major effects on the overall flexural performance of the I-beam. The maximum loads at rupture of I-beam reinforced with epoxy glue showed 41% higher than those of I-beams fabricated only with nails (Chang and Yeh, 2001). The interface between the flange and web materials is a key position on the cross section of the I-beam due to the existence of various shearing resistance for a beam subjected to flexural loading. In general, the strain variation near the interface between the flange and web materials or relative difference of displacement among members of composite beams can be a indication for determining the stiffness of the beams.

The changes of strain between flange and web member under flexural loading were measured through adjacent strain gages near the interface or glue line, in which one gage is attached to the top or bottom flanges and another attached to the upper or lower edges of web. The resulted difference in strain may indicate the adequacy of bonding treatment or the suitability of flange sizes. There were 16.9%, -8.2%, and -9.9% in compressive strain were obtained between top flange and web member for the I-beam fabricated with the sixes of 38X89 mm, 38×140 mm, and 38×180 mm, respectively (Fig.8). And there were 39.5%, 14.1%, -19.6% in tensile strain were obtained in the tension side of the I-beam, respectively. It indicated that the reduction in the relative deformation between flange and web materials and the improvement in stiffness of I-beam depends on the width of flange members. The larger strain was incurred on the 38×89 mm flanges of I-beam than that of web component, which indicated that higher stress developed on the flanges and some slippage might occur between the interface of the flange and web. While the smaller strain was incurred on the 38×180 mm flange than that of web component, which indicated that lower stress developed on the flanges.

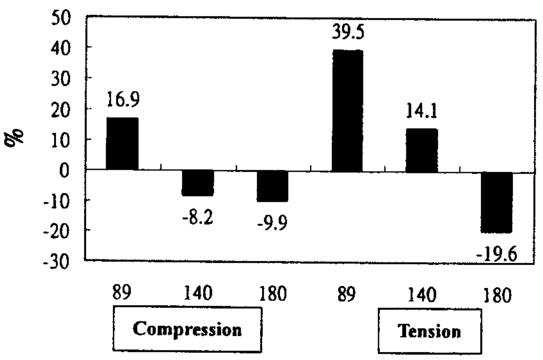


圖 8 在最大載重之 30%條件下工字樑離支點 60 cm 處的上下樑翼與樑腹構材介面處之應變差異

Fig.8 Strain changes at the interfaces of flanges and webs for both tension and compression sides of I-beams 60 cm from the supports and subjected to 30% of maximum loads.

In general, the strain on the flanges differs along the thickness direction or vertical axis as the I-beam subjected to flexural loading. The values on the outside of beam, i.e., top or bottom surface are higher than that measured inward positions, i.e., 38 mm thick in this study. There are 12.3% and 21.9% higher in compressive and tensile strain measured at top surface of top flanges and bottom surfaces of bottom flanges, respectively than those measured from the inner surfaces of flanges next to the web. According to the previous report, the maximum bending stress at the rupture for the I-beam fabricated with 38×89 mm flanges were 25.2 MPa, which were 84% and 29%, respectively, higher than that of fabricated with 38×180 and 38×140 mm flanges (Chang and Yeh, 2001). It might be adequate for fabricating I-beam of 300 mm depth with 38×140 mm member as flanges in terms of shearing performance at the interface. The compressive strain on the top surface of upper flanges varies across the width of flanges. The results indicated that the edges of flanges subjected to larger compressive strain during the bending deflection as compared to the center position across the width of flanges possibly due to the constraints through nail and glue application along the connection between webs and flanges (Fig. 9). The average strain measured at the center of 38×140 mm and 38×180 mm flange surface was 19.9% lower than that measured at the edges of top flanges.

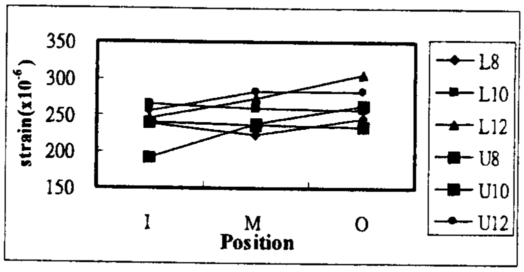


圖 9 以 8、10、12 cm 用釘間距組成之工字樑在最大載重 30%條件下離支點 60 cm 處其 38×180 mm 之上(U)下(L)樑翼材的內(I)中(M)外(O)位置的應變分布

Fig.9 Strain distribution across the width of 38×180 mm upper and lower flanges measured 60 cm from supports for the I-beams assembled with 8, 10, and 12 mm nail spacings, respectively, and subjected to 30% of maximum flexural loads.

Besides the effectiveness of glue application on the flexural performance of I-beam, the nail holding capacity between flanges and webs have major contribution to the shearing resistance of I-beam. Although each 16d box nail provided 2.06 KN in lateral resistance, the flanges tend to split along the center line where the nail holding the flange and web components together as the distance between nails become closer. Therefore, the nail spacing of 8, 10, and 12 cm did not have significant effect on the improvement of flexural performance China fir I-beam except the 38X89X300 mm I-beam nailed with 12 cm spacing, which resulted in larger strain on the top and bottom flanges. The stresses were obtained from the relationship between strain and the apparent modulus of elasticity of I-beam. The stress distribution on the cross section of China fir I-beams within the shear span as subjected to 30% of maximum flexural loads is shown on Fig. 10. The average stress on the bottom surface of bottom flanges was 16% higher than that on the top surface of top flanges.

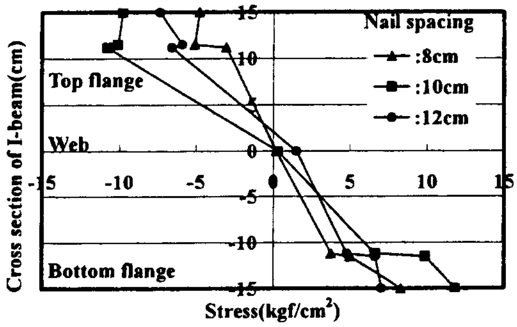


圖 10 38×89×300 mm 杉木工字樑在最大彎曲載重之 30%條件下離支點 60 cm 處之斷面應力分布

Fig. 10 Stress distribution on the cross section of 38×89×300 mm China fir I-beams within the shear span when subjected to 30% of maximum flexural loads.

(IV) Finite element modeling

The strain distribution of I-beam section 60 cm from supports under the four-point loading at 30% of maximum loads, i.e., 5591 N, 7365 N, and 3837 N, for 38×89, 38×140, and 38×180 mm, respectively, was modeled and the results were shown on Fig.11. The moduli of elasticity used in modeling were calculated from the relationship of loads and flexural displacements between 10% to 30 % of maximum load capacities for each I-beam assuming all the components of I-beam deflected integrally. The stress and strain distributed along the length of I-beam was shown on Fig. 11 and 12. In the case of using apparent modulus of elasticity based on the tested I-beam specimens in finite element modeling, the data measured from strain gages are always higher than the predicted strain values, i.e., 28%, 92%, and 105% higher for the 38×180×300 mm, 38×140×300 mm, and 38×89×300 mm I-beams, respectively. In the case of using static modulus of elasticity based on the small clear wood specimens in finite element modeling, the predicted strain values are always higher than the data measured from strain gages, i.e., 32%, 60%, and 57% higher for the 38×180×300 mm, 38×140×300 mm, and 38×89×300 mm I-beams, respectively. This is probably due to uncertainty of glue properties and lack of information on glue-wood interface, which need to be investigated further. In the case of using E_L, E_R, and ν_{LR} from strain gage measurements based on wood block specimens for finite element modeling, the data measured from I-beams are always higher than the predicted strain values, i.e., 47%, 47%, and 59% higher for the 38×180×300 mm, 38×140×300 mm, and 38×89×300 mm I-beams, respectively.

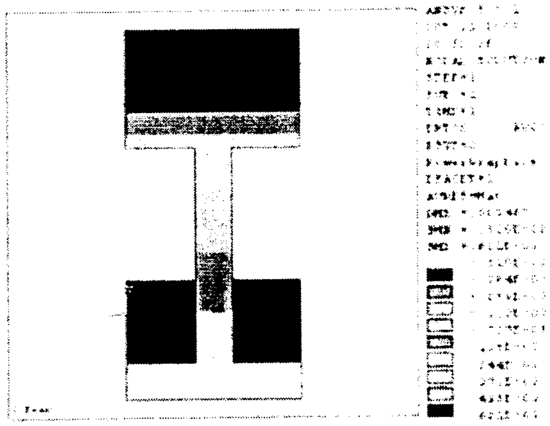


圖 11 38×180×300 mm 工字樑以有限元素分析離支點 60 cm 處之斷面應變分布

Fig.11 Estimated strain distribution across the 38×180×300 mm I-beam section 60 cm from support by using finite element method.

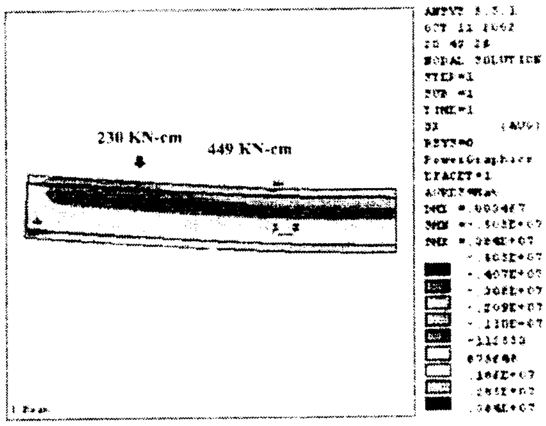


圖 12 38×180 mm 樑翼構材組成之杉木工字樑以 3-D 固體元素模擬所得之水平剪斷應力分布

Fig.12 Horizontal stress distribution on the China fir I-beam fabricated with 38×180 mm wide flanges as modeled with 3-D structural solid linear hexahedron elements.

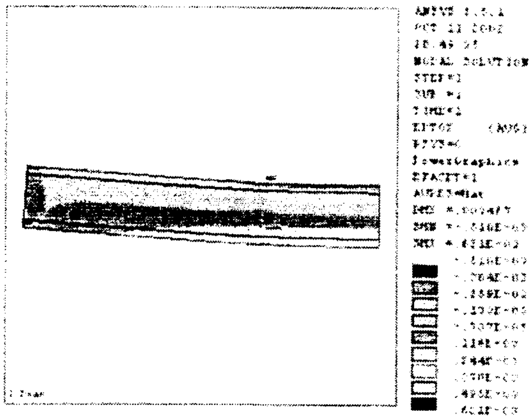


圖 13 38×180 mm 樑翼構材組成之杉木工字樑以 3-D 固體元素模擬所得之水平應變分布

Fig.13 Horizontal strain distribution on the China fir I-beam fabricated with 38×180 mm wide flanges as modeled with 3-D structural solid linear hexahedron elements.

IV、CONCLUSIONS

The linear relationship of strain distribution across the China fir I-beam section was found but with the neutral axis move downward from symmetrical axis. The tensile strain on the bottom surface of lower flanges was larger than compressive strain on the top surface of upper flanges. Based on the relative displacement between flanges and webs, it is suggested that 38×140×300 mm of China fir I-beam is more appropriate assembly configuration for flexural performance. The spacing of nailing may not be a major concern as the I-beam reinforced with epoxy glue for the fabrication.

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