Katsuo Nakata
Science University of Tokyo,
Faculty of Science & Engineering
2641 Yamazaki, Noda-city,
Chiba, Japan

Timber Construction in Japan New possibility of Joint system and Actual Projects

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Abstract

To estimate the cracking stress around drift-pin perpendicular to the gram is very important to calculate the safety of timber structure. In order to introduce the new connector Bertsche Verpress Dubel. BVD – to Japan, this stresses should be manifested. One trial to utilize analytical solution of infinite plane stress is shown. By getting two solutions of symmetrical and anti-symmetrical lording problem, the stresses of non-symmetrical lording can be analyzed. Using the result of this calculation, the retaining cracking force of drift-pin is defined. Using this connector, big space structures of glue-laminated timbers are realized in Japan. The recent works using this connectors by author are also introduced.

Additionally, new possibilities of new connecting system are presented. One is the possibility to prevent the ductile fracture around drift-pins by adopting carbon-fiber reinforcement. Another is the possibility to adopt high-strength square pin, using epoxy-resin grouting.

1. Introduction

After revision of Japanese Building Standard Law at 1987, the restrictions on timber structures in city area are deregulated. This causes “timber building boom” rapidly and many structures are planned by using glu-laminated heavy timbers.
Also, two basic experimental studies are shown. One is possibility of reinforcement around drift-pins using carbon fiber sheet. The tensile strength perpendicular to grain will be reinforced and the ductility of joint will be improved.

When calculations are carried out, the most important problem is design and estimate the connecting capacity. It is well-known that the most simple and popular joint is metal-pin connect joint. But, we cannot expect high performance and rigidity to this joint because of the looseness around drift-pins and normal stresses perpendicular to grain which causes brittle fracture. In case of BVD, the gap between hanger and timber is grouted by high-strength mortar in order to keep the rigidity of joints. Another problem is how to analyze the stress and deformation accurately and utilize the result to calculation.

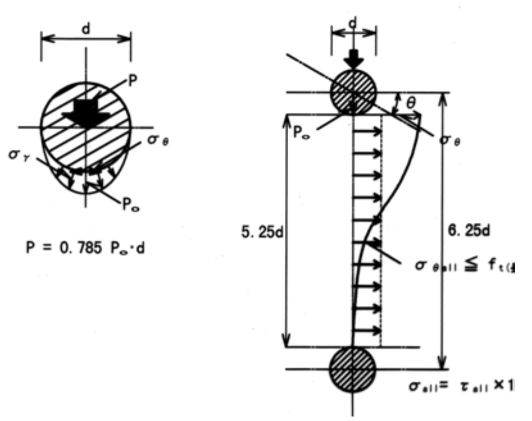
In order to analyze the behavior of timber around drift-pin, analytical solution of holes in the infinite plane is used. In this paper, the outlines of analyses are shown.

The possibility of traditional style square-pin system is discussed. By adopting high strength screw bolt (tensile strength 7000kg/cm^2) and square drift-pin, the capacity of transferring tensile force can be improved, and by grouting epoxy resin into small space between pin and timber, the initial rigidity of loading-deformation relation will be also improved.

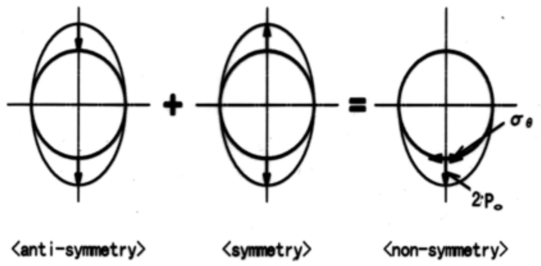
Finally, actual projects using BVD are shown. All buildings are designed and calculated by author and K.Nakata & Associates. (structure)

2. Stress Analysis around Drift –Pins in Infinite Plane

The stress and strain around holes in infinite plane can be obtained by Fourier analysis using Airy's stress function of polar coordinate. In order to make the problem simple, the analysis are done based on the assumption that the plane is assumed to be homogeneous nevertheless the Young's modulus of timber is not same for the direction of fabrics. As the cracking fracture is caused by the circumference tensile stress σ_θ on $\theta=\pi/2$ line, the safety criteria is set as to make the mean value of σ_θ to next hole smaller than allowable tensile stress perpendicular to grain.



(Fig.1)



(Fig.2)

When analyzing non-symmetrical load distribution, shown above it is useful to analyze two load conditions, symmetric and anti-symmetric loading problems. Assuming that the distance to next hole is long enough to redact, the divergence term of radius argument ρ in stress function can be eliminated. The symmetrisity regarding θ is also taken into consideration.

2.1 Stress Function given in the form of Polar Coordinate

The compatibility equation using Anty's stress function is shown as follows,

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}\right)\left(\frac{\partial^2 F}{\partial r^2}+\frac{1}{r}\frac{\partial F}{\partial r}+\frac{1}{r^2}\frac{\partial^2 F}{\partial \theta^2}\right)=0 \tag{2.1}$$

The general solution of above differential equation is given as a form of

$$\begin{aligned}F=&A+B\rho^2+C\rho^2\log\rho+D\log\rho+H\theta+K\rho^2\theta+L\rho\theta\cos\theta+M\rho\theta\cos\theta\\&+(a_1\rho+b_1\rho^{-1}+c_1\rho^3+d_1\rho\log\rho)\cos\theta\\&+(\overline{a_1}\rho+\overline{b_1}\rho^{-1}+\overline{c_1}\rho^3+\overline{d_1}\rho\log\rho)\sin\theta\\&+\sum_{n=2,3,...}(a_n\rho^n+b_n\rho^{-n}+c_n\rho^{n+2}+d_n\rho^{-n+2})\cos n\theta\\&+\sum_{n=2,3,...}(\overline{a_n}\rho^n+\overline{b_n}\rho^{-n}+\overline{c_n}\rho^{n+2}+\overline{d_n}\rho^{-n+2})\sin n\theta\end{aligned}$$

$$\rho=\frac{r}{a} \tag{2.2}$$

The strain-displacement relations and stress –strain relations are as follows

$$\varepsilon_r = \frac{\partial u}{\partial r} \qquad \varepsilon_\theta = \frac{u}{r} + \frac{1}{r}\frac{\partial v}{\partial \theta} \qquad \gamma_{r\theta} = \frac{1}{r}\frac{\partial u}{\partial \theta} + \frac{\partial v}{\partial r} - \frac{v}{r} \tag{2.3}$$

$$\varepsilon_r = \frac{1}{E}(\sigma_r - \nu\sigma_\theta)\ ,\quad \varepsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu\sigma_r)\ ,\quad \gamma_{r\theta} = \frac{1}{G}\tau_{r\theta} \tag{2.4}$$

2.2 Infinite Plane Stress Problem with Circular Hole Symmetrical Edge Loading

The symmetrical in-plane load along hole edge is given in the form of Fourier series,

$$\sigma_r |_{r=r_0} = p_0 |\sin\theta| = p_0 f(\theta)$$

$$f(\theta) = \frac{2}{\pi} - \frac{4}{\pi}\sum_{n=2,4,6,\ldots}^{\infty} \frac{1}{(n+1)(n-1)}\cos n\theta \tag{2.5}$$

Introducing the condition of symmetry to stress function and eliminate the divergence terms regardingρ, the unknown constants in stress function are D, H, bn and dn, respectively. Introducing the boundary conditions along hole edge, these unknown constants are determined.

$$\begin{aligned}\sigma_r &= \frac{2P_0}{\pi}\rho^{-2} + \sum\left\{-n(n+1)b_n\rho^{-n-2} - (n^2+n-2)d_n\rho^{-n}\right\}\frac{2P_0}{\pi}\cos n\theta \\ &= \frac{2P_0}{\pi}\left[\rho^{-2} + \sum_n \frac{\rho^{-2}}{(n+1)(n-1)}\left\{n\rho^{-2} - (n+2)\right\}\cos n\theta\right]\end{aligned} \tag{2.6}$$

$$\begin{aligned}\sigma_\theta &= -\frac{2P_0}{\pi}\rho - 2 + \sum\left\{n(n+1)b_n\rho^{-n-2} + (-n+2)(-n+1)d_n\rho^{-n}\right\}\frac{2P_0}{\pi}\cos n\theta \\ &= -\frac{2P_0}{\pi}\left[\rho^{-2} + \sum_n \frac{\rho^{-n}}{(n+1)(n-1)}\left\{n\rho^{-2} - (n+2)\right\}\cos n\theta\right]\end{aligned} \tag{2.7}$$

$$\begin{aligned}\tau_{r\theta} &= \sum_n\left\{-(n+1)b_n\rho^{-n-2} + (-n+1)d_n\rho^{-n}\right\}n\sin n\theta \\ &= \frac{2P_0}{\pi}\sum_n \frac{n\rho^{-n}}{(n+1)(n-1)}(\rho^{-2} - 1)\sin n\theta\end{aligned} \tag{2.8}$$

2.3 Infinite Plane Stress Problem with Circular Hole Anti-Symmetrical Edge Loading

In the same manner as 2.2, anti-symmetrical condition of Airy's stress function will be applied. The conditions along hole edge are as follows,

$$\sigma_r\big|_{\rho=1} = P_0 \sin\theta \, , \ \tau_{r\theta}=0 \qquad (2.9)$$

And using that for u=v=0 for $\rho=\infty$, consequently all stresses are given as follows.

$$\sigma_{r\theta}= \frac{1-\nu}{2}(\rho^{-1}+\rho^{-3})\sin\theta P_0 \qquad (2.10)$$

$$\sigma_{\theta}= -\frac{1-\nu}{2}(\rho^{-1}+\rho^{-3})\sin\theta P_0 \qquad (2.11)$$

$$\tau_{r\theta}= \frac{1-\nu}{2}(\rho^{-1}+\rho^{-3})\cos\theta P_0 \qquad (2.12)$$

2.4 Stress around Hole by Drift-Pin

Assuming that the material is elastic, the stresses around hole caused by non-symmetrical edge force will be obtained as the sum of these two loading conditions. If the distribution of load along hole-edge is shown as a function of sinθ, the total resultant force P acting to timber by drift-pin is :

$$P= 2\int_0^{\frac{\pi}{2}} p_0 r\sin^2\theta d\theta = 2p_0 r\left[\frac{\theta}{2}-\frac{\sin 2\theta}{4}\right]_0^{\frac{\pi}{2}} = \frac{\pi}{4} p_0 2r = \frac{\pi}{4} p_0 d$$

d :diameter of drift-pin (2.13)

Cracking force is also obtained by integrating $\sigma_\theta\big|_{\theta=\frac{\pi}{2}}$ from ρ=1 to ∞.

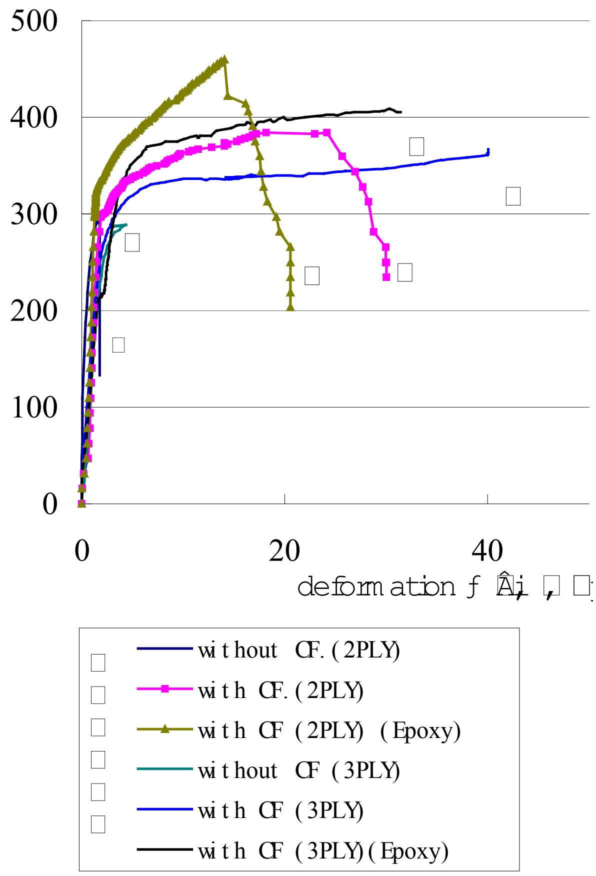
3. Experimental Study on Joint Performance

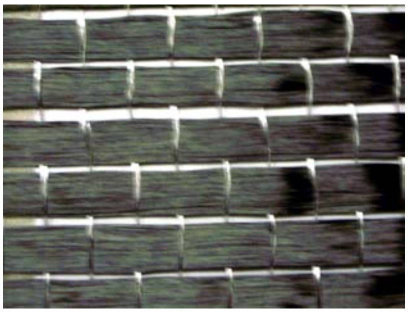
3.1 A possibility to improve the deformation capacity of pin connector

In order to evaluate the transmitting capacity of pin connector, many tests are carried out. Regarding the pin joint system, we can assume some different fracture patterns according to the dimensions of details. One of the most important factors is bending strength of drift-pins. Normally, the bearing capacity of connector using drift-pins is determined by the strength of pins. But in some cases, we have experienced brittle cracking fracture caused by tensile stress perpendicular to grain.
For the purpose to prevent this brittle fracture, a possibility to utilize carbon fiber by laminating carbon fiber sheet between laminas perpendicular to axis.
The dimension of specimen, carbon fiber sheet are shown as belows. The compressive stress of timber around hole - deformation relation are shown in Fig 3.
It is clear that the reinforcement is efficient to improve the deformation capacity of joint but is not effective to improve the strength itself.

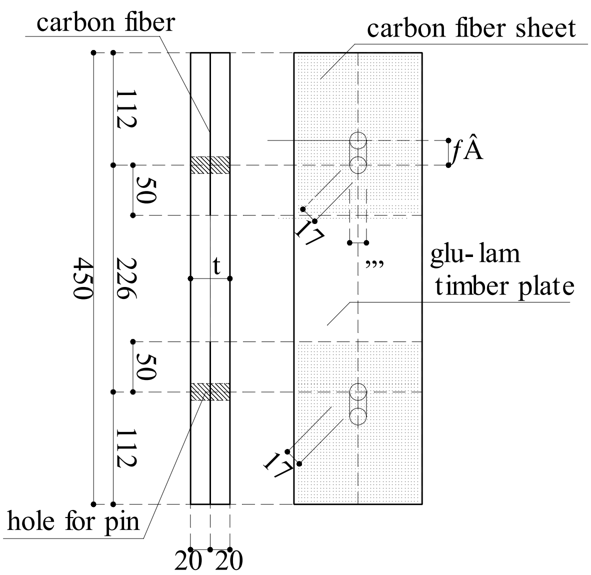
(Fig. 3)

load-deformation relation





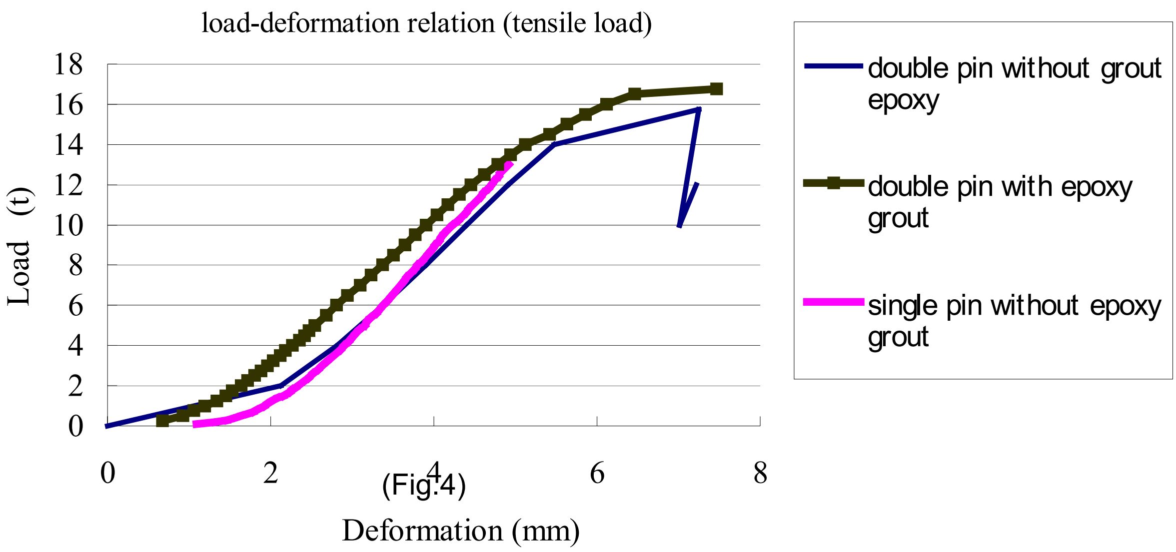
Carbon fiber sheet



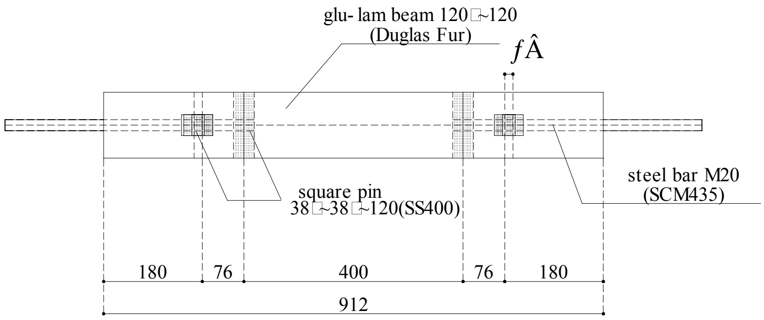
specimen (2 ply)

3.2 Improvement of square pin joint system

The basic idea of square pin joint is not special and new and it has been used widely as simple connector so-called “Hiki – bolt” in Japan. The common shape of this pin is usually round and the quality of pin is not high grade steel.
In this study, we adopted square pin to avoid big tensile stress around hole perpendicular to grain and high strength steel bar to transmit the timber force to connector.
Adding to it, in order to obtain the rigidity of joint, small space between timber and pin is filled by epoxy resin. By this grouting, the slip deformation of P□δ relation are improved.
The ultimate strength is determined by shear strength fracture of surface along fiber of wood. (see photo) This test was carried out to examine the possibility to make the joint much stronger. Additional tests should be done to get more detailed data of this system.



(Fig.4)



specimen

Fracture of joint

4. Realization Of Glu-Lam Space Structures

Using BVD hangers, glu-lam timber structure for various purposes are designed and constructed. The most exquisite characters of this connector are:

1) High load carrying performance, of which allowable long-term loading capacity is 26t at the maximum.
2) High rigidity of joint. No creeps are observed after completion of building.
3) Beautiful out looking
4) Easiness of erection. Almost of all parts are pre-installed at factory.

Followings are the actual projects completed during this 5 years. All building are designed and supervised by K.Nakata & Associates.

Photo 1

Photo 2

Photo 1,2,3:
Iono Golf Club (architect: Yuji Noga)
First project using BVD Hanger. Special approval by MOC needed. Roof is 5000m^2 and maximum span is 35m. Main beam is 222×1080 Southern Yellow Pine.
In total, 1000m^3 of SYP heavy timber is used Moment connection test are carried out and the results are utilized for approval.
Results of analysis around pin joints are introduced to estimate the allowable force of BVD joints.

Photo 3

Photo 4

Photo 5

Photo 4,5:
Himi Fureai Sports Center (design: Ishimoto Sekkei)
Roof area is $5000m^2$.The roof 50m×100m covers 2 gymnasiums and entrance hall.
$1500m^3$ of SYP are used.Max. beam size is 272×1920 in section. 22m of curved beams are fabricated in USA and carried by ship.

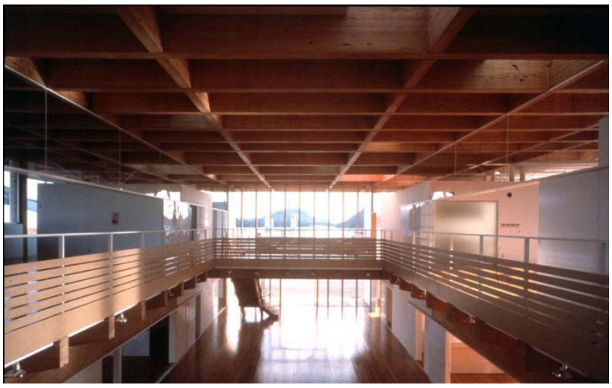


Photo 6

Photo 7

Photo 6,7:
Suzuki – mokuzai Head Office
(architect: Nagisa Kidosaki)
The roof is two – way grid girder system. Crosswise beams are jointed rigidly to transmit the bending moment respectively. Vertical loads are supported by pin post located at both wall line of building and horizontal force are carried by tensile steel bars to RC core at four corners.

Photo 8,9,10:
Kibikogen Elementary School (archtect:Masao Koizumi & Kazuhiro Kozima)
Teaching rooms are scheduled to use middle size glu–Lam beams of SYP and gymnasium are build using big size heavy timber of SYP. From the view point of fire protection, only roof structures are allowed to use timbers. Max span of roof is 28.0m and 222×1200 beams are used.

Photo 8

Photo 9

Photo 10

Photo 11

Photo 12

Photo 11,12:
Okutsu Hot spa and Multi purpose hall (architect: Hirofumi Sugimoto)
Various purpose building are constructed. Photo 11 is hot spa hall and photo 12 is multipurpose hall. Botanic garden is also constructed. All buildings are designed and calculated by using CAD & CAM system. Attractive interia is realized.

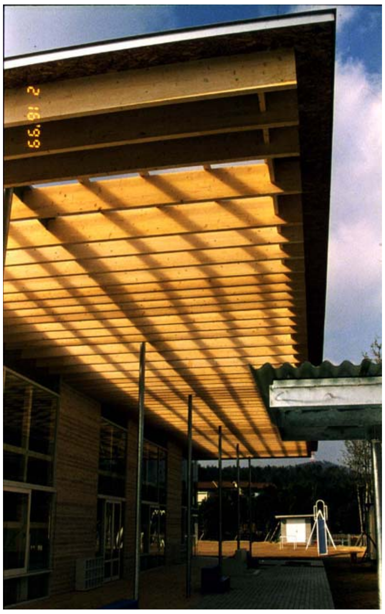


Photo 14

Photo 13

Photo 15

Photo 13:
Yume minato Exhibition Hall (architect: Hirofumi Sugimoto)
Gate rahem frame by L–shape rigid moment connection using BVD adopt. Easy to re-assemble by dry joint. Max span is 25m.

Photo 14:
Kibi Kogen Kindergarden (architect: Masao Koizumi)
Only one project using European White Wood as structural member. One way joist system is adopted for roof.

Photo 15:
Yoshidamachi gymnasium (archtitect: Yuji Noga)
Typical traditional style sports hall with slope roof. Roof area is 1000m^2