Assessment of Semi-Rigidity of Dowel Type Knee Joint between Timber Elements

Lilita Ozola 1, Janis Fabriciuss 1

1 Department of Structural Engineering, Faculty of Environment and Civil Engineering, Latvia University of Life Sciences and Technologies, 19 Akademijas Str, Jelgava, LV-3001, Latvia

Lilita.ozola@llu.lv

Abstract. Creation of a moment resisting connection between column and beam elements in knee joints is the core problem in portal frame design of structural timber. The main performance requirement for rigid joints is to avoid any rotation between the members connected. Withstanding this condition by using glued finger joints, the knee joint can be classified as a rigid one and the bending moment produced by external loads can be transferred safely. Nevertheless, the solution of knee joints with mechanical fasteners is an effective way to overcome transportation limitations. Knee joints with mechanical fasteners exhibit a relevant semi-rigidity when some rotational movement develops between beam and column members connected due to the embedment of the fasteners in the wood and their bending deformation. The aim of the current study is to examine the rotational stiffness of semi-rigid joints. The rotational stiffness of the connection was determined in terms of design moment capacity to radians of rotation. The calculation methods for design of semi-rigid structural timber connections developed during recent years were used for the calculation of the bearing capacity. L-shape connection models of softwood lumber assembled by normal strength dowels were tested under a stepwise static load. The analysis of the test data testifies that connections with dowels located around a single circle demonstrate an intensive development of rotational movement. For design purposes the semi-rigidity of these connections may be characterised by the rotational stiffness value $K_\phi = 10 \frac{M_d}{\text{rad}}$. Moment resisting joints of dowels located in double circles behave almost as rigid, and their stiffness may be characterised by rotational stiffness value $K_\phi = 65 \frac{M_d}{\text{rad}}$. It is found from comparison of embedment deformations that dowels located around external circle transfer more than four times bigger reactive shear force than dowels around inner circle.

1. Introduction

Portal frame structures have gained an increasing popularity in the modern construction industry. They take less time for assembling compared with the conventional truss-column type structural systems. Because of the demands of aesthetics and the continuing need to achieve structural efficiency and cost competitiveness, portal frames are steadily evolving. Creation of a moment resisting connection between column and beam elements in knee joints of a portal frame is the core problem in structural timber design. It is the main performance requirement for rigid joints to avoid any rotation between the members connected. Withstanding this condition, the knee joint can be classified as a rigid one and the bending moment produced by external loads can be transferred safely. The only type of connection to be defined as rigid in structural timber design is a glued one. The requirements for a rigid corner
joint of high reliability are certainly fulfilled by using large scale glued finger joints produced in a factory. Nevertheless, the use of glued knee joints is limited due to the conditions of transportation of big montage units from factory to building site. Knee joints with mechanical fasteners are an effective way of overcoming transport limitations. However, knee joints with mechanical fasteners exhibit a relevant semi-rigidity when some rotational movement develops between the members connected due to both the embedment of the fasteners in wood and their deformations in bending. The effects of semi-rigidity become significant for the assessment of the anticipated deformations of a portal frame under service load. For example, rotational movement predicted in knee joints produces sharp increase of corner displacements of the portal frame, see results of the worked example in figure 1. It is found that the horizontal displacement increases four times due to the semi-rigid behaviour of connection compared with the rigid one.

During the last two decades the researchers Racher [1], Kermani [2], [3] and others [4], [5], [6] made a significant contribution to the investigation of the behaviour of semi-rigid dowel type connections, and developed a calculation methodology. Nevertheless, the results of worked examples of portal frames show an extreme horizontal movement in the knee joints. The majority of investigations have been carried out in a short duration loading. The aim of the current study is to assess the effects of rotational deformations developed in knee joint to the behaviour of a portal frame under load. It has been predicted that the assessment effect of semi-rigidity of knee joints with mechanical fasteners enables one to develop design conditions reflecting the exhibitions of structural behaviour more realistically regarding deformations in particularly.

![Figure 1. Design model of portal frame (worked example)](image)

**Table 1. Deformation in portal frame**

|        | Horizontal displacement rigid knee joint $\Delta_1$ mm | Vertical displacement rigid knee joint $\Delta_2$ mm | Horizontal displacement semi-rigid knee joint $\Delta_3$ mm | Vertical displacement semi-rigid knee joint $\Delta_4$ mm | $\Delta_3 / \Delta_1$ | $\Delta_4 / \Delta_2$ |
|--------|-------------------------------------------------------|---------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|------------------------|------------------------|
| 1      | 0                                                     | 0                                                 | 0                                                        | 0                                                        | 1                      | 1                      |
| 2      | -24.37                                               | -0.34                                             | -93.2                                                    | -0.34                                                    | 3.82                   | 1                      |
| 3      | 0                                                     | -70.25                                            | 0                                                        | -262.36                                                   | 1                      | 6.51                   |
| 4      | 24.37                                                | -0.34                                             | 93.2                                                     | -0.34                                                    | 3.82                   | 1                      |
2. State of art in knee joint design
The calculation methodology currently used for the design of portal frames with mechanical fasteners is briefly presented here.

In the case of symmetrically arranged fasteners of an equal diameter point C can be assumed as the possible centre of the rotation, see figure 2a. The bending moment produced by external forces attached to the frame, generates the reactive forces $F_{M,ext}$ and $F_{M,int}$, acting on the fasteners arranged at the external and internal circles correspondingly. Basing on a linear relationship between the forces and deformations, the lateral movement for fasteners of external and internal circles, correspondingly is expressed as a ratio of reactive force and slip modulus ($K$):

$$\delta_{ext} = F_{M,ext} / K, \quad (1)$$

$$\delta_{int} = F_{M,int} / K, \quad (2)$$

For the small rotation angle values the following equations may be written based on the previous assumptions and geometric relationships:

$$d\varphi = \delta_{ext} = -\frac{F_{M,ext}}{K \cdot r_{max}} \cdot \frac{r_i}{r_{max}}, \quad (3)$$

$$F_{M,ext} = K \cdot r_{max} \cdot d\varphi, \quad (4)$$

Generally, assuming that lateral movements of fasteners in different circles are directly proportional, the shear force ($F_{M,i}$) attached to any fastener of a connection, irrespectively of the external or internal circle, may be expressed by the following equation:

$$F_{M,i} = K \cdot \delta_i = K \cdot r_{max} \cdot d\varphi \cdot -\frac{r_i}{r_{max}}, \quad (5)$$

where $r_i$ is the radial distance of the fastener from the centre point C of the rotation or lever of the shear force ($F_{M,i}$). The resisting moment produced by an individual fastener is expressed as follows:

$$M_i = F_{M,i} \cdot r_i = K \cdot r_{max} \cdot d\varphi \cdot -\frac{r_i^2}{r_{max}}, \quad (6)$$

While the total moment is ($M$) compensated by the sum of resisting moments produced by the bearing capacities (assuming $F_{v,ext} = F_{M,i}$) of individual fasteners the force system retains balance, which is expressed by the following equation:

$$M = \sum_{i=1}^{n_c} \frac{n_c \cdot F_{v,ext} \cdot \sum_{i=1}^{n} r_i^2}{r_{max}}, \quad (7)$$

where $n_c$ is the number of shear planes in the connection, and $n$ is the number of fasteners.

Equation (7) is valid for the connection where an equal number of fasteners is arranged in one or two circles at equal distances.

![Figure 2. Knee joint with mechanical fasteners: (a) structural solution, (b) proposed linear force – deformation model of the fasteners.](image-url)
3. Materials and Methods

Two different groups of models were prepared for the tests. The first group of models (figure 3a) clearly and directly represents loading conditions of a moment connection. The moment connections of these L-shape models were made by placing five fasteners in single circle (figure 3b) and seventeen fasteners in double circles: 12 dowels around the outer circle and 5 dowels around the inner circle (figure 3c). The second type of models (figure 3d) were made in a shape of a real portal frame including two semi-rigid knee joints. Moment connections of portal frame were made using dowel type fasteners, in the same way as described before, were placed around two circles (figure 3e). Metric threaded rods of diameter d= 6 mm (grade 4.8 DIN 976) were used as fasteners. Before the tests the theoretical bearing capacity \( (M_d) \) using Eurocode 5 [7] conditions were calculated according to the assumption of the linear behaviour of dowels located around the circle (equation (7)).

Both models were made of softwood lumber (pine Pinus Sylvestris or spruce Picea Abies) with moisture content of 5%. The lumber was free of knots, cracks, and it had straight grain. The average mass density of the wood 420 kg/m\(^3\) in dry condition. The moisture content of the wood was measured using the Wood Moisture Meter MD-2G. All connection models were subjected to stepwise loading in test frame. Linear displacements representing rotational movement of members connected were measured with an accuracy of 0.01 mm employing dial gauges mounted on a rigid frame (figure 4a, figure 4b).

**Figure 3.** Test models: (a) Static scheme, (b) L-shape model with dowels in single circle, (c) L-shape model with dowels in double circles, (d) design model, (e) portal model.
4. Results and Discussion

The development of rotational movement in L-shape models with fasteners located in a single circle is shown in figure 5. The relative bending moment on the ordinate axis represents the ratio of moment applied to the design bearing capacity. A linear relationship between the load and rotational movement is observed up to 50-60% of the design capacity. During the next loading cycles deformation of the connections develops more intensively with increasing the load, and a non-linear dependence exhibits when load increases above 60% from the design bearing capacity. Generally, dowel type connections with fasteners in single circle exhibit a highly non-linear behaviour due to the deformations of steel fasteners in bending and of the wood under the embedment stresses of the last, approximately a third part of the capacity range.

It can be concluded that the joint solution with dowels in a single circle is subjected to an extremely high value of rotational movement. It is suggested to evaluating the semi-rigidity of dowel type moment resisting joints at the load level when the linear relationship transfers to a non-linear (figure 5). The average rotational movement (0.0749 radians with standard deviation 0.019) is found at seventy-five percent load level. Consequently, semi-rigidity of single circle type connection may be characterized by rotational stiffness modulus $K_{\phi} = 0.75 \cdot M_d/0.0749 = 10 \ M_d/\text{rad}$.

The development of rotational deformations in L-shape models with fasteners located in a double circle is shown in figure 5. It may be concluded that the joint solution with dowels in double circles is not efficient due to the fact that an important part of bearing capacities is not utilized by the fasteners.
arranged around the internal circle. However, this joint is almost rigid. Evaluating the semi-rigidity in the same way as for a single circle connection, the results are as follows: linear behaviour continues up to full design load level corresponding to average rotational movement of 0.025 radians. Nevertheless, the variation is very big, coefficient of variation exceed 40%. Due to that the rotational stiffness modulus was evaluated at rotational movement level of 0.01 radians, up to that variation of both variables remains under 25%. Average it is the 55 percent load level (with coefficient of variation 25%) and average rotational movement 0.01 radians with coefficient of variation 9%. Consequently rotational stiffness modulus For connection with dowels located around double circles my be defined as $K_\phi = 0.65 \cdot \frac{M_d}{0.01}$ or $K_\phi = 65 \cdot \frac{M_d}{\text{rad}}$.

Figure 5. Relationships between rotational movement and moment applied for L-shape models with dowels around single circle

Figure 6. Relationships between rotational movement and moment applied for L-shape models with dowels around double circles.
There is a good chance to examine the relationship between the angle of reactive force of dowel and grain direction according to the measurements of embedment deformations of holes (figure 7). It is clear that variation of data is very large as it is illustrated by x-y scatter graphs in figure 8. The coefficient of correlation between force and angle data samples is negative (Correl= -0.2), that suggests that relatively large angle values tend to occur with relatively lower reactive force values. Also value of correlation coefficient suggests that relationship between reactive force values and angle data is found very weak in this case.

An average value of hole deformations in outer circle under failure load is more than four times bigger than the one for holes around inner circle that confirm the similar ratio of reactive forces.

Figure 7. Each fasteners deformation connections. Left side are first type model, right side second type model.

Figure 8. Embedment deformation depending on force direction regarding grain orientation
5. Conclusions

- Moment resisting joints of dowels located in the single circle demonstrate an intensive
development of rotational movement. Semi-rigidity of these connections may be characterised
by the rotational stiffness value \( K_\phi = 10 \frac{M_d}{\text{rad}} \).
- Moment resisting joints of dowels located in double circles behaves almost as rigid, and the
rotational stiffness value found is \( K_\phi = 65 \frac{M_d}{\text{rad}} \).
- It is found from the comparison of embedment deformations that dowels located around the
external circle transfer approximately four times higher shear force than the ones located
around the inner circle.
- It is reasonably safe to suggest assessing embedment deformations of holes that the angle
between the reactive force of dowel and grain direction does not influence significantly force
distribution between dowels.

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