EFFECTIVE BENDING CAPACITY OF DOWEL-TYPE FASTENERS

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Abstract

The design of connections with dowel-type fasteners according to Eurocode 5 is based on Johansen's yield theory. Here, the bending capacity of the fastener is an important parameter. Tests with timber connections with dowel-type fasteners show plastic deformations of fasteners in failure modes 2 and 3. The plastic hinge, however, is in most cases not fully developed and consequently the full plastic fastener bending moment is not reached. Depending on the moment-angle relation of fasteners in bending a modified equation was derived to determine the fastener bending capacity.

1. Introduction

The load-carrying capacity of connections with dowel-type fasteners like bolts, dowels or nails may be determined on the basis of Johansen [2]. According to Johansen the load-carrying capacity depends on the geometry of the connection, the bending resistance of the dowel and the embedding strength of the timber or wood-based material. For the bending resistance of the dowel, Johansen assumed the elastic moment capacity of the dowel's cross-section, the possible increase due to plastic deformations was disregarded. The design equations in Eurocode 5 [3], which are derived from Johansen's work, are based on a rigid-plastic behaviour of both, the dowel under bending moments and the wood under embedding stresses and take into account the plastic moment capacity of the dowel.

According to Johansen, three different failure modes are possible for timber-timber-connections in double shear (see **figure 1**). Failure mode 1 corresponds to the embedding failure of the middle or side member, respectively, where the embedding strength according to EN 383 [5] is defined as „an average compressive stress at maximum load in a specimen of timber or wood-based sheet product under the action of a stiff linear fastener“. In failure modes 2 and 3, apart from the embedding strength of the wood the

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bending capacity of the fastener is reached. Failure modes 2 and 3 of dowels loaded in double shear correspond to identical failure modes of dowels loaded in single shear.

According to EN 409 [6] the yield moment of a nail is determined at a bending angle of 45°. For such a large bending angle, the whole cross-section of the fastener is assumed to be under plastic strain. In [7] results of fastener bending tests are published where the bending capacity of fasteners with d > 8mm is also determined on the basis of EN 409.

For bending angles below 45° only the outer areas of the cross-section of a fastener are additional deforR/2med plastically. In this case, the plastic capacity can only be partially used and the fastener bending moment lies between the elastic and plastic bending capacity of the mostly circular dowel cross-section.

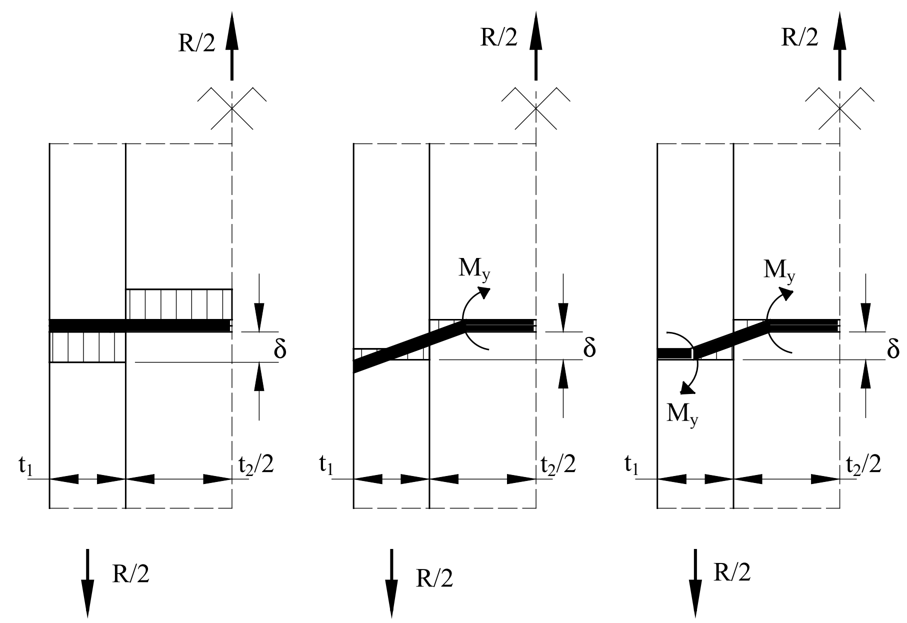

Figure 1 Failure modes of a double shear timber-to-timber connection

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2. Deformation behaviour of dowel-type fasteners

If the load-carrying capacity and the deformation behaviour of connections with dowel-type fasteners is determined by tests according to EN 26891 [8], the connection strength is defined as the maximum load before a deformation of δ = 15 mm parallel to the load direction is reached.

For a large number of connections tested at Delft University of Technology, Jorissen [7, 9] measured the bending angles α of dowels after the connection had reached the maximum load. In most cases where failure modes 2 or 3 occurred, the bending angles were significantly below α = 45°. This means that the plastic hinge was not fully developed and the plastic moment capacity of the dowel was not attained in the connection (see **Figure 2**).

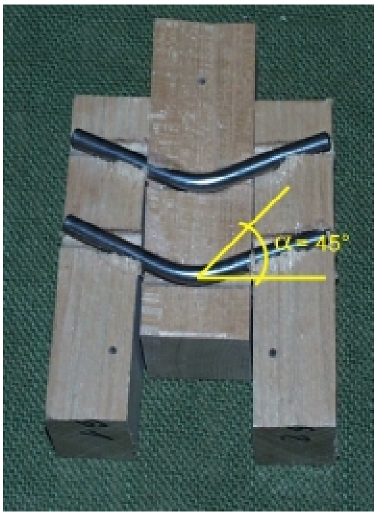

Figure 2 Test specimen opened after reaching maximum load

Since the fastener's cross-sections were only partially plasticised, their bending capacity was lower than according to EN 409. This lower bending capacity influences the load-carrying capacity of the connection for failure modes 2 and 3 and results in lower connection strength values. For a realistic connection design the actually reached bending moment is therefore important. If a deformation limit of 15 mm is assumed for the connection, the effective bending capacity depends on the yield strength of the fastener material, the fastener diameter and the shape of the moment-angle-diagram of the fastener.

In order to determine the moment-angle-diagrams of the fasteners bending tests with different fasteners were evaluated. Since different steel grades and different fastener diameters lead to large differences in absolute moment values, the moment-angle-diagrams were normalised by dividing the moment values by the moment capacity corresponding to a bending angle of α = 45° (see **Figure 3**):

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$$\overline{M}(\alpha,d)=\frac{M(\alpha,d)}{M(\alpha=45°,d)} \tag{1}$$

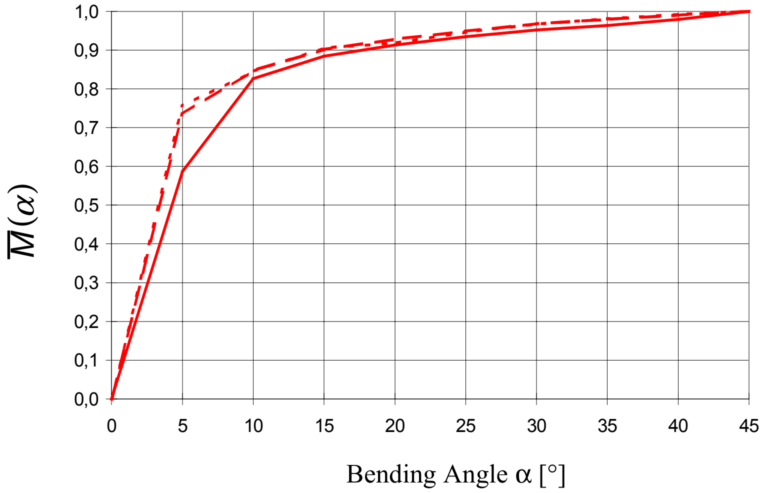

Figure 3 Normalised moment-angle-diagrams of dowel-type fasteners of different diameter *d*.

Since the shape of $\overline{M}(\alpha, d)$ is very similar for different fastener diameters d, a mean curve $\overline{M}(\alpha)$ was determined. This relation neither depends on the fastener diameter d nor on the fastener material properties and may be approximated by an exponential function (see **Figure 4**).

$$\overline{M}(\alpha)=(0{,}866+0{,}00295\cdot\alpha)\cdot\left(1-e^{\left(\frac{-0{,}248\cdot\alpha}{0{,}866}\right)}\right) \tag{2}$$

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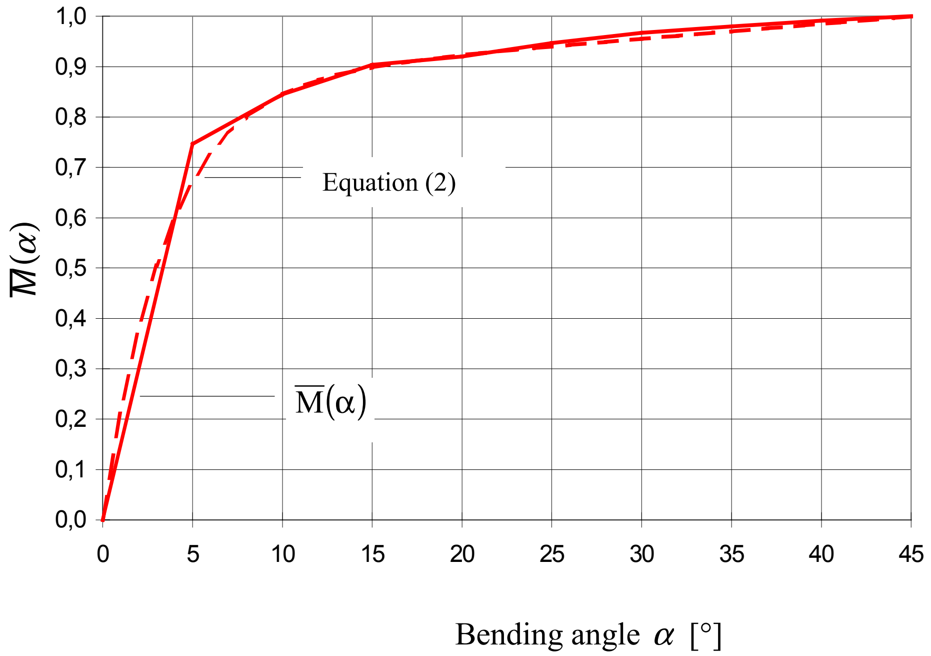

Figure 4 Mean normalised moment-angle-diagram of dowel-type fasteners and approximation

3. Theoretical bending angles in connections

Figure 5 shows the failure modes 2 and 3, where the angle α is defined as

$$\alpha = \arctan\left(\frac{\delta}{\ell}\right) \tag{3}$$

Here, δ is the maximum deformation of δ = 15 mm parallel to the load direction. The length ℓ corresponds to the length of the wood or wood-based material where the embedding strength is reached. For failure mode 2 the length ℓ results as

$$\ell = a_2 + b_1 + b_2 \tag{4.1}$$

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and failure mode 3 as

$$\ell = b_1 + b_2. \tag{4.2}$$

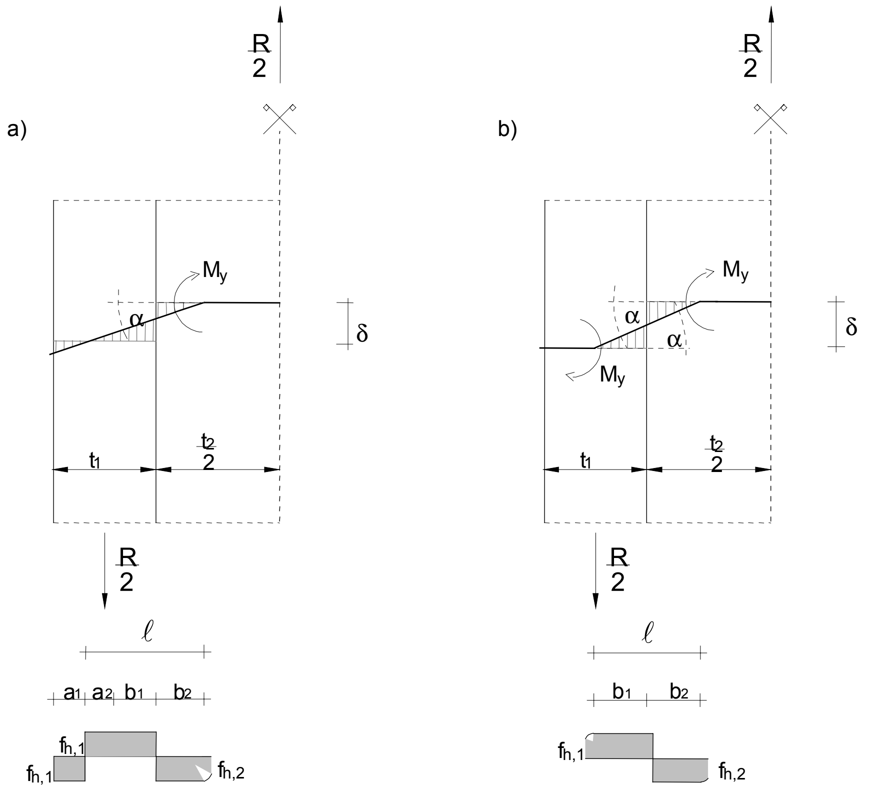

Figure 5 Failure mode 2 (left) and 3 (right) for a fastener in single or double shear

In both cases ℓ depends on the fastener diameter d, the embedding strength f_h and the yield moment M_y. The fastener yield moment itself depends on the fastener diameter d and the yield strength f_y of the fastener material, the embedding strength also is a function of d and of the density ρ.

Subsequently the derivation of α as a function of the fastener diameter d is shown as an example for failure mode 3. For a load-grain angle of 0° and for the same densities ρ of the middle and side member the embedding strength f_h is constant and the connection is

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symmetrical. Consequently $b_1 = b_2 = b$ and $\ell = 2 \cdot b$. The dimension b may now be determined from the equilibrium of forces (see **figure 5**) and results as

$$b=\sqrt{\frac{2\cdot M_y}{f_h\cdot d}}\ . \qquad (5)$$

The bending angle α consequently is calculated as

$$\alpha=\arctan\left(\frac{\delta}{2\cdot\sqrt{\frac{2\cdot M_y}{f_h\cdot d}}}\right). \qquad (6)$$

α depends on the fastener bending moment M_y. Since in general at maximum load $\alpha < 45°$, the full plastic bending capacity is not reached. Using equation (7), the dependence between the bending moment M_y and the bending angle α may be taken into account by an iterative procedure. $\alpha = 45°$ is taken as a first value. In the next step the normalised moment according to equation (2) is calculated and inserted in equation (7). After three iteration steps the difference $\Delta\alpha$ is generally less than 1°.

$$\alpha_{i+1}=\arctan\left(\frac{\delta}{2\cdot\sqrt{\frac{2\cdot M_{y,k}\cdot\overline{M}(\alpha)}{f_{h,k}\cdot d}}}\right) \qquad (7)$$

The parameters influencing α(d) depend on the fastener material and the embedding strength and therefore require a different determination of the effective bending capacity for different types of fastener. For bolts, dowels and nails in predrilled holes the embedding strength is determined as

$$f_{h,k}=0{,}082\cdot(1-0{,}01\cdot d)\cdot\rho_k \qquad (8)$$

The corresponding equation to calculate the embedding strength for nails in non predrilled members is:

$$f_{h,k}=0{,}082\cdot d^{-0{,}3}\cdot\rho_k\ . \qquad (9)$$

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The yield strength in bending f_y according to Eurocode 5 is 80% of the tensile strength $f_{u,k}$ of the steel grade used.

Scheer, Peil and Nölle (1988) have published the results of bending tests with bolts 4.6 and 5.6 and give a 5-percentile value of the yield strength in bending of 67% of the actual tensile strength. The value of 67% includes the strain hardening due to large strains in the outer areas of the circular cross-section and relates to a bending angle α = 10°. The plastic bending moment for α = 45° is 19% higher than for α = 10° (see **figure 4**). Consequently, for α = 45° a value for the yield strength in bending of 67% · 1,19 = 80% of $f_{u,k}$ results. This confirms the equation for the fastener yield moment for bolts and dowels given in Eurocode 5 independently of the steel grade:

$$M_{y,k} = 0{,}8 \cdot f_{u,k} \cdot \frac{d^3}{6}. \tag{10}$$

The yield moment of nails with circular cross-section with a minimum wire tensile strength of 600 N/mm^2 is according to Eurocode 5:

$$M_{y,k} = 180 \cdot d^{2,6}. \tag{11}$$

Figure 6 shows as an example the bending angle α depending on the fastener diameter d for failure modes 2 (fm2) and 3 (fm3) according to Johansen. The parameters tensile strength $f_{u,k}$ and characteristic density ρ_k were chosen as 1000 N/mm^2 and 350 kg/m^3, respectively. A large value of the tensile strength and a low value of the density lead to comparatively low values of the bending angle α and are therefore conservative.

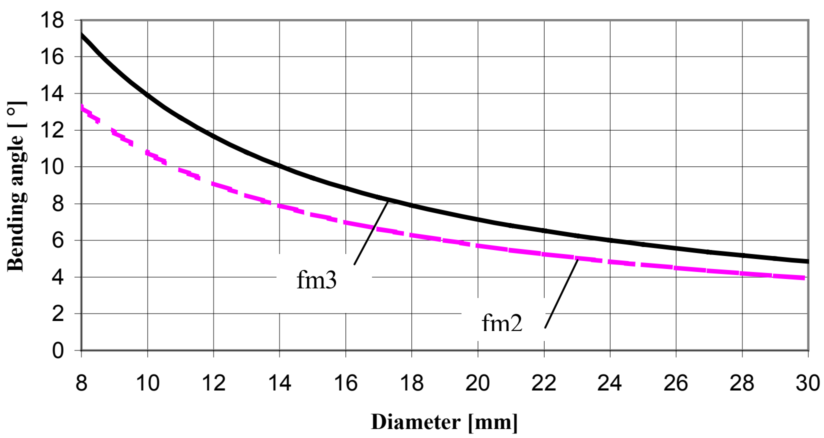

Figure 6 Bending angle α depending on fastener diameter d for failure modes 2 and 3.

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4. Effective bending capacity of dowel-type fasteners

For the different types of fastener the function $\alpha(d)$ was determined, resulting in minimum values of the bending angle α. For this purpose, the governing parameters were conservatively chosen, resulting in maximum values for the steel tensile strength and minimum values for the characteristic density. For connections with bolts or dowels, the tensile strength $f_{u,k}$ was chosen as 1000 N/mm^2 and the characteristic density ρ_k as 350 kg/m^3. Inserting these values in equation (2) results in a relation between the normalised moment and the fastener diameter d. Multiplying $\overline{M}(\alpha(d))$ and the yield moment according to equation (10), a simplified approximate expression for the effective bending capacity of dowel-type fasteners for a deformation δ = 15 mm results:

$$M_{y,k} = 0{,}3 \cdot f_{u,k} \cdot d^{2,6} \quad \text{Nmm} \tag{12}$$

where

$f_{u,k}$ fastener tensile strength in N/mm^2

d fastener diameter in mm

Equation (12) should be used for all dowel-type fasteners and gives about 10 % higher values than equation 10.20 (Dowels) in E DIN 1052. This is acceptable, since all unfavourable conditions mentioned above will only very rarely occur at the same time. The proposed equation is also identical to the one used for nails in the current version of the EC5 draft.

Using equation (12) for the bending capacity of dowel-type fasteners, the decreasing bending angle with increasing fastener diameter is implicitly taken into account.

5. Conclusion

The design of connections with dowel-type fasteners according to Eurocode 5 is based on Johansen's theory. Here, the bending capacity of the fastener is an important parameter. Tests with timber connections with dowel-type fasteners show plastic deformations of fasteners in failure modes 2 and 3. The plastic hinge, however, is in most cases not fully developed and consequently the full plastic fastener bending moment is not reached. Depending on the moment-angle relation of fasteners in bending a modified equation was derived to determine the fastener bending capacity. The bending capacity of dowel-type fasteners according to the proposed modified equation leads to significantly lower bending capacities especially for large fastener diameters. Using the

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modified equation results in a better agreement between test results and theoretically determined connection capacities.

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