Experimental and numerical tests of clinch connections strength

M Dudziak¹, K Talaśka¹ and D Wilczyński ²

¹The President Stanisław Wojciechowski State University of Applied Sciences in Kalisz, Nowy Świat Street 4, 62-800 Kalisz, Poland
²Chair of Basics of Machine Design, Poznan University of Technology, Piotrowo Street 3, 60-965 Poznan, Poland

E-mail: marian.dudziak@put.poznan.pl

Abstract. The work presents experimental investigations of clinch connections of structural wooden elements. The tests were carried out using the MTS Insight 50 kN laboratory testing machine. The influence of changing parameters such as the angle of sharpening γ staples, which values were successively 30° and 60°, and the mutual positioning of the staple legs, which was parallel, divergent and convergent, were investigated. The presented results gave information on which parameters, the connection strength is the highest. Experimental research was also supported by numerical studies in which the phenomenon of destruction of this type of connection was simulated. The built-in numerical model gives the opportunity to examine the connection strength for a larger number of cases of change in the value of the angle γ and the angle of mutual positioning of the staple legs.

1. Introduction

An important solution of the method of permanent and inseparable connection of two of pieces of wood together is a connection of these pieces by using the friction-shaped inseparable connection. The connecting element is a nail, after passing through the connecting elements the end of nail is clinching [1, 2]. This method of combining the two layers is used for the production of spool discs. Nailing technique is effective and efficient only during the construction of large spools. This applies to the size range from Ø1000 mm to Ø2500 mm and a weight of electric line from 400 kg to 1 ton. Nailing technique has several disadvantages [3–5]:

• the phenomenon of cracking and damage to the wooden material at the point of contact with the nail,
• damage to the face surface of the disc particularly in the area of contact between two elements,
• object weight increase due to the weight of steel nails
• laborious process of hammering nails and wrapping of ends in the opposite direction and their clinching.

The process of clinching of nails is incomplete. It has a reduced tensile and shear strength. An attempt was made to use the clamps to connect the disc layers of spool. Figure 1 shows a view of the clamps with the typical geometrical parameters. Figure 2 shows a view of the spool made using the clamps.
Figure 1. View of the clamp with characteristic geometrical parameters: b – the width of cross-section of the wire, h – the height of cross-section of the wire, d – wire diameter, H – height of the clamp, B – width of the clamp.

Figure 2. The spool: a) traces of stitching on the circumference, b) recessed clamp – inner side of the spool disc, c) recessed clamp – outer side of the spool disc.

2. Modeling of clamps connections
Studies were done for clamps with the length which did not exceed the total thickness of the joined elements (figure 3) and which exceeded the total thickness of the joined elements (figure 4). Figure 3 shows a view of a recessed clamps with symmetrical "nominal" tightening angle – \( \alpha = 90^\circ \). This way of tightening the legs of clamps ensures the perpendicularity to the surface of the connected elements (or close to a perpendicular angle \( \gamma < 5^\circ \)). The increase of thickness of the connected elements enforces the longer clamps. During the tests it was observed that clamps from company PREBENA (wire cross section: rectangular with dimensions of 1.4 \( \times \) 1.6 mm) have insufficient stability and buckling prior to complete recess in the material (figure 4). The graphs show the waveforms of destructive force of connection as a function of displacement during the test on the MTS testing machine. The horizontal axis of the graph determines the relative displacement of the connected elements during their separation. The graphs contain 3 tests and their average.
Figure 3. a) View of recessed clamps; b) Ratio of height of the clamp to thickness of connection: $K$ – total thickness of the joined elements, $H$ – height of the clamp; c) Destructive force of connection in function of displacement.

Figure 4. a) View of recessed clamp; b) Ratio of height of the clamp to thickness of connection; c) Destructive force of connection in function of displacement.
The next stage of the study was associated with the search for the more effective connection by shaping the geometry of the blade. Tests were taken on clamps with two angles of sharpening of the blades (\(\gamma = 30^\circ\) and \(\gamma = 60^\circ\)) and three types of arrangement of the blades (one direction, convergent, divergent). Length of clamps did not exceed the total thickness of the joined elements. Schemes, illustrations and graphs are shown in figures 5–7. In figures 8 and 9 are shown results of tests with use of clamps with length exceeded the total thickness of joint.

**Figure 5.** a) View of recessed clamp b) Geometry of the clamp, c) Destructive force of connection in function of displacement (arrangement of the blades in one direction).

**Figure 6.** a) View of recessed clamp; b) Geometry of the clamp; c) Destructive force of connection in function of displacement (divergent arrangement of blades).
Figure 7. Views of recessed clamp and geometry of the clamps: a) $\gamma = 30^\circ$, convergent arrangement of blades, b) $\gamma = 60^\circ$, divergent arrangement of blades, c) $\gamma = 60^\circ$, convergent arrangement of blades, d) $\gamma = 60^\circ$, arrangement of the blades in one direction.

Figure 8. a) View of recessed clamp; b) Geometry of the clamp; c) Destructive force of connection in function of displacement (arrangement of the blades in one direction).
3. Conclusions from experimental research

1. If the length of the clamp legs does not exceed the total thickness of the connected elements, the most favorable case is the use of clamps sharpened symmetrically – this allows to recess the material surface in a perpendicular way.

2. Increasing the length of the legs has not positive effect on increasing the value of destructive force – buckling.

3. Shaping the blades on the ends of the clamp legs does not increase the destructive force of the connection.

4. Plastic deformation (flexing) of the clamp legs after perforation connected elements, create a clinching connection with a positive effect on increasing the value of destructive force of the connection.

4. Numerical research

Abaqus Explicit allows to model contact phenomena with the application of the principle of virtual work [6–12]. It is equipped with two algorithms. First one is so-called "General Contact" – it is an automatic algorithm with a very simple definition of contact and it has a low number of restrictions concerning types of mating surfaces. Second one is so-called "contact pairs" algorithm – it has much more restrictions concerning types of mating surfaces and it often requires much more attention during defining the contact, but it allows to model some cases of mating surfaces which cannot be modelled with the standard procedure of "General Contact".

The above presented two procedures allow to model:

- contact between a rigid body (nondeformable) and/or a deformable body,
- contact phenomena during self-contact of a body,
- phenomena of finite or small sliding,
- contact between bodies which are susceptible to damage.

In case of the procedure "contact pairs" one should use datum surface at nodes in order to model a body which is susceptible to damage. The application of procedure "General Contact" allows to model such type of body with the use of datum surface at finite elements.

In effect it allows to model contact phenomenon between any number of such bodies. It allows to:
- define contact phenomenon by user with the application of general constitutive models,
- model temperature reactions between surfaces, for example heat conduction,
- model contact phenomena between Euler materials and Lagrange bodies,
- define coefficient of friction for the condition of mean temperature of a surface and/or in a scope of other variables which have an effect on its values [5].

These features were applied in order to perform numerical simulations of contact in a wedge-clamp connection which is used to connect constructional elements made of wood.

The finite element method was used for simulations of strength of a clamp connection. During simulation the clamp connection strength was tested for the cases where the value of the angle $\gamma = 0^\circ$, $\gamma \neq 0^\circ$ – clamp legs had a divergent orientation in the timber; and $\gamma \neq 0^\circ$ – clamp legs had a convergent orientation in the timber. For each case of the angle $\gamma$ the force was measured which is required to

![Figure 9. Views of recessed clamp and geometry of the clamps: a) $\gamma = 30^\circ$, divergent arrangement of blades, b) $\gamma = 30^\circ$, convergent arrangement of blades.](image)
destroy the connection. In order to make numerical simulation the model was simplified by treating the connected elements as a rigid body. For the projection of the contact phenomenon between the clamp and the material (where the clamp is sunk), the holes were made with a fillet radius which was equal to the bend radius of the clamp legs. To reduce the calculation time, the models of connection components have been discretized by using the shell elements. Maintaining the geometric parameters of these elements allows to reflect the actual size of the cross-section of clamps. The following figures show the phases of numerical simulations.

Figure 10. Initial phase of the simulation strength of the clamp connection

Figure 11. Clamp connection during simulation of disconnection – phase of plastic deformation of the clamp ends.

Figure 12. The final phase of the simulation strength of the clamp connection.

Figure 10 shows the initial phase of the simulation for the case of disconnection when the angle $\gamma = 0^\circ$. In this phase a rapid growth of the destructive force of the connection is present.
Figure 11 shows the phase of plastic deformation of the clamp ends to their original form. The apparent stress indicates exceeding the maximum value of the yield point for the material from which the clamp is made. In this phase a combination of the destructive force reaches its maximum value.

Figure 12 shows the phase where the destructive force of the connection is decreased. The clamp legs are deformed plastically (they are straight) because the force required to pull them out has a lower value.

**Figure 13.** Characteristic changes of the destructive force of the connection for the case $\gamma = 0^\circ$.

**Figure 14.** Characteristic changes of the destructive force of the connection for the case $\gamma \neq 0^\circ$ where the clamp is divergent.

**Figure 15.** Characteristic changes of the destructive force of the connection for the case $\gamma \neq 0^\circ$ where the clamp is convergent.
In Figure 13 we can see a rapid increase of the force from the value 0 N to the value about 285 N. Exceeding the value 285 N is equivalent to the excess of the yield strength of the clamp material which takes its plastic deformation (figure 3).

Figure 14 shows the destructive force changes of the clamp connection obtained from the numerical simulation for the case $\gamma \neq 0^\circ$ where the clamp is divergent.

Figure 15 presents the destructive force changes of the clamp connection obtained from the numerical simulation for the case $\gamma \neq 0^\circ$ where the clamp is convergent.

5. Conclusions from numerical research
The experimental investigations have shown higher strength of the clamp connection when the clamp length is greater than the total thickness of the connected elements. The performed numerical simulations of the connection strength have confirmed the validity of the practical application of this connection. The results convergence between experimental and numerical studies was obtained. Numerical simulations have confirmed high strength of the connection for the case when the angle of the clamp legs is equal $\gamma = 0^\circ$.

6. References
[1] ASCE 1996 Mechanical connections in wood structures Washington DC: American Society of Civil Engineers
[2] Rammer D R and Mendez A M 2008 Withdrawal Strength of Post-frame Ring Shank Nails Frame Building News April pp 59–67
[3] Soltis L A and Wilkinson T L 1987 Bolted Connection Design Gen. Tech. Rep. FPL–GTR–54 (Madison WI: Forest Products Laboratory, U.S. Department of Agriculture, Forest Service)
[4] Forest Products Laboratory 2010 Wood Handbook: Wood as an Engineering Material – General Technical Report FPL–GTR 190 (Madison WI: Forest Products Laboratory, U.S. Department of Agriculture, Forest Service)
[5] Zahn J J 1991 Design equation for multiple-fastener wood connections Journal of Structural Engineering 117 3477–3485
[6] Hughes T J R, Taylor R L, Sackman JL, Curnier A and Kanoknukulchai W 1976 A Finite Element Method for a class of contact-impact problems Computer Methods in Applied Mechanics and Engineering 8 249–276
[7] Bathe K J and Chaudhary A 1985 A solution method for planar and axisymmetric contact problems International Journal Numerical Method and Engineering 21 65–88
[8] Hallquist J O, Goudreau G L and Benson D J 1985 Sliding interfaces with contact impact inlarge-scale Lagrangian computations Computer Methods in Applied Mechanics and Engineering 51 107–137
[9] Simo J C, Wriggers P and Taylor R L 1985 A perturbed Lagrangian formulation for the finite element solution if contact problems Computer Methods in Applied Mechanics and Engineering 50 163–180
[10] Giannakopoulos A E 1989 The return mapping method for the integration of friction constitutive relations Computers and Structures 32 157–167
[11] Zhong Z H 1993 Finite Element Procedures for Contact-impact Problems (New York: Oxford University Press)
[12] Abaqus Documentation