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Nailed Steel Plate Connections: Strength and Ductile Failure Modes

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ABSTRACT

This paper deals with theoretical and experimental investigations of nailed steel plate connections. For the experimental part, a total of 99 laboratory tests have been carried out in order to study failure mechanism and shear capacity of nailed steel plate connections. The testing programme comprised two nail lengths, two steel plate thicknesses and five nailing patterns. All tests related to loading of the plate in the direction of the grain of the wood. The nail patterns were designed to give ductile joint failure by yielding of the nails and/or bearing failure of the wood. The failure load was recorded and the mode and course of failure noted. For some of the specimens, deformation of the nails during loading was studied by means of an X-ray equipment.
Deviations between the test results and contemporary consensus as manifested in the SS-EN 1995-1-1:2004 and the Johansen theory for ductile failure were found in several respects: development of the plastic hinges in the nails, influence of nail length, steel plate thickness and nail-to-nail and edge distances.
The paper also presents an empirical equation based on multiple regression analysis of the test results was proposed as an attempt to predict the load-carrying capacity of nailed connections in shear.

1. Introduction

Connections are usually critical parts of timber structures. Conventional types of joints with bolts or lag screws, sometimes used in conjunction with split rings or shear plates provide good load transfer. However, such types of connections have some weaknesses, e.g. stiffness properties which in some circumstances might be not adequate from a structural standpoint. The nailed plate connection, on the other hand, if provided with sufficient number of nails, exhibits excellent stiffness properties. The joint is easy to fabricate and install, and it can provide savings in the overall structure. Moreover, due to the tapered head, nails are tight-fit, which means that they exhibit minimal initial slip under load and as such can develop their design loads without inacceptable deformation of the structure. This is particularly important in the case of structures which are sensitive to second order effects.

Nailed steel plate connections or steel-to-timber connections as discussed in this paper are efficient types of connections with respect to both strength and stiffness. They are often used in long-span timber structures subjected to large forces and/or bending moments.

Correct understanding of the behaviour and adequate design methods for these types of connections are, therefore, of crucial importance. Certain types of timber structures, e.g. large span roofs, may exhibit low inherent strength redundancy. In such structures, a possible failure of a connection will often lead to catastrophic collapses. Smith and Foliente [14] report that one of the major causes for damages in timber buildings as a consequence of extreme winds and earthquakes is due to inadequately designed connections.

Nails are generally regarded as ductile connectors due to their size and high slenderness ratios. Mechanical fasteners for timber structures in Europe are regulated by SS-EN 1995-1-1:2004 [15]. For the different kind of cylindrical connectors, e.g. nails, bolts and screws, the code provides the load bearing capacity of the joint based on geometrical and mechanical properties of the fastener, mechanical properties of the timber and number of shear planes. Finally, a distinction is made among timber-to-timber and steel-to-timber connections, with further possibility to use thin or thick steel plates to connect the timber elements belonging to the joint.

The principles contained in SS-EN 1995-1-1:2004 [15] for cylindrical fasteners are based on extensive investigations led by Johansen and published in 1949. Johansen based his research on the primary hypothesis of a rigid-plastic behaviour for both materials. While for steel the post-elastic properties are due to plastic deformations, for timber they

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are due to the embedment capacity. Under this assumption, the load carrying resistance can be obtained with simple considerations of limit-equilibrium. The failure modes are named I, II and III, where the number of plastic hinges in the fastener is one less the mode number.

Möller [12] applied the Johansen plastic theory and developed equations for the load-carrying capacity for single- and double-shear joints. His work was the basis for the early Scandinavian codes. The theory was extended by Meyer [11] and Norén [13] by taking the residual withdrawal resistance or the rope effect into account. An experimental campaign on the shear capacity of nailed joints was carried out by Aune [2]. The main objective of his study was to validate and further improve Johansen's yield theory. Based on the test results, Aune et al. [1] published a comprehensive and complete theoretical description of the yield model in 1986.

Larsen [9] gave wider exposure of Johansen's yield load model to the international research community. For example, McLain and Thangjitham [10], USA, reviewed and evaluated this model with regards to bolted joints. Johansen put particular focus on nailed joints and some of his investigations on the topic were unfinished. Therefore, Larsen [8] completed and published his work.

A comprehensive survey of the status of nailed joints design in wood structures was made by Ehlbeck [5]. He summarized the research of the previous decades concerning different theories of joint performance, design criteria, national codes, and test methods. An extensive reference list and an additional relevant literature made his investigation exhaustive and applicable to Standard regulations.

Finally, thorough studies on group effect of multiple nails were carried out by Blass [3]. Some basic studies in this field of load distribution in rows of fasteners parallel to load was conducted by Cramer [4], Lantos [7] and Wilkinson [16]. Attention was given to ultimate load of joints with different number of nail rows and nails per row. The outcome of his work is that, provided nail spacing is sufficiently large, the ultimate load per nail is independent from the number of nails per row. His overall results confirm the ductile behaviour of nails in a timber connection.

The ultimate failure modes of nailed connections are referred to:

i) plug or block shear – i.e. a group tear-out of the wooden piece within the nailed area;
ii) bearing or embedment failure – with or without nail yielding;
iii) splitting – along the row of nails, especially in case of no pre-drilling or from the wedge effect from larger bolts.

Nailed steel plate timber connections are widely used in timber structures. When the number of nails to be driven tends to be large, adequate automatic nailers are utilized. Typical dimensions of a nail, which are adopted in practice and that are suitable for insertion by e.g. gas nailer are $d = 4$ mm and $L = 40$ mm to 60 mm, where d and L are the nail diameter and the nail length, respectively. Common steel plate thickness varies in the range 2.0 mm to 5.0 mm.

In this study only the ductile failure mode of nailed plate connections – i.e. failure mode *iii*) –is investigated. Ring shank nails with diameter $d = 4$ mm, length $L = 40$ mm to 60 mm and tensile strength $f_u > 600$ MPa were investigated. The steel plates adopted in the tests had thickness either $t = 2.5$ mm or $t = 5$ mm. The ductile failure mode is attained when *a*) the number of connectors is comparatively small and *b*) both spacing and end distances of the connectors are sufficiently large. In such situation, the determination of the load bearing capacity, can be conducted according to the model proposed by K. W. Johansen [6], which is also the basis of the design method recommended by SS-EN 1995-1-1:2004 [15]. According to this model – which assumes ideal rigid-plastic behaviour of both steel and wood – the load bearing capacity of a single nail is achieved *either* when the stress in the timber reaches the plastic failure stress (embedment strength) *or* when a combination of plastic failure in both nail (achievement of yield moment) and timber is attained.

There are also other parameters, besides embedment strength of the wood and yield moment of the nail that may influence the shear capacity of nailed plate connection, e.g. the thickness of the steel plate and both number and spacing of nails in the grain direction.

The main purpose of this study is to investigate the influence of nail length, nail pattern, density of the wood, moisture content, steel plate thickness and spacing of the nails on the shear capacity of nailed connections. Finally, an empirical equation to predict the shear capacity of nailed plate connections is proposed.

2. Materials and test methods

2.1. Materials

Softwood spruce timber (*Picea Abies*) with the strength grade of C30 was used for the manufacturing of all joints. According to EN 338, the principal characteristic strength values of grade C30 grade are: $f_{t,0,k} =$ 18 MPa, $f_{m,k} = 30$ MPa, $f_{v,k} = 4$ MPa, for parallel to grain tension, bending and shear, respectively. Moisture and density readings were taken on all timber members prior to testing. However, no strength tests were conducted in order to determine the mechanical properties of the timber.

Most of the specimens of the test series had an average moisture content (MC) of approximately 10% with the exception of five test series, which were conditioned to an average moisture content of approximately 17%, see Table 1. The MC was measured by means of pin-type moisture meter. The mean density at 10% was 452 kg/m^3, obtained by measuring gross weight and volume of wood members at the time of assembly. Member lengths varied from 300–900 mm. The cross section was 70 × 195 mm^2 for all specimens. The steel plates used in the joints had a strength grade of S235 (with yield strength $f_{y,k} = 235$ MPa, according to European standard EN 10025:2004) thickness of 2.5 mm and standard hole pattern, i.e. staggered holes with diameter 5 mm, spacing 40 mm in the grain direction and 20 mm in the direction perpendicular to the grain. Some joints used two overlapping steel plates, which is equivalent to a 5 mm thick steel plate. Ring-shank anchor nails and widened conical head, manufactured by cold-drawn material with dimension 40 × 4 mm and 60 × 4 mm were utilized as fasteners. The nails were hammer driven without pre-drilling the wood.

Three point bending tests were performed on twenty randomly selected nails in order to evaluate their yield strength. The mean value of yield strength was $f_y = 876$ MPa (CoV = 3.78%). The ratio between ultimate strength and yield strength can be assumed $f_u/f_y \approx 1.1$. Some

Table 1
Overview of the test series and principle characteristics of the specimens. MC is the moisture content of the tested specimen.

Specimen type	Test series n	Number of specimens	Plate thickness t [mm]	Nail length L [mm]	Number of nails	MC [%]
	1	8	2.5	40	1	10
(1 × 1)	2	9	5.0	40	1	10
	3	9	2.5	60	1	10
	4	9	5.0	60	1	10
	5	6	2.5	40	5	10
(1 × 5)-a	6	6	5.0	40	5	10
	7	6	2.5	40	5	10
(1 × 5)-b	8	6	5.0	40	5	10
	9	6	2.5	60	5	10
	10	6	5.0	60	5	10
	11	5	2.5	40	9	10
(3 × 3)	12	5	5.0	40	9	10
	13	3	2.5	40	1	17
(1 × 1)	14	3	5.0	40	1	17
	15	3	2.5	60	1	17
	16	3	5.0	60	1	17
	17	3	2.5	40	5	17
(1 × 5)-a	18	3	5.0	40	5	17

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