Summary
This paper presents the results of preliminary tests conducted to compare the strength and stiffness of nail plate tooth embedment characteristics with those for smooth surface embedment, and goes on to probe the validity of using the Johansen equations derivatives to predict nail plate joint strength.

1. Introduction
Punched metal plate fasteners (nail plates) have been used for more than 30 years in the manufacture of trussed rafters for roof applications in Europe. Despite this, and the fact that they are manufactured by the thousand, their design appears to have developed essentially from trial and error. In principle the load transfer mechanism between a plate tooth and timber is similar to that of any other laterally loaded fastener such as a nail or bolt. It follows, therefore, that the Johansen equations or their derivatives, which are the near universally accepted analytical models for estimating ultimate joint strength, should apply to nail plate joints. This would, however, require that the assumed rigid plastic bearing behaviour of the timber, on which the equations are based, is achieved, that appropriate material properties are used, and that the sometimes complicated nail plate tooth geometry is incorporated accurately. The embedment stiffness and strength between tooth and timber are influential factors in these requirements and both are likely to be affected by any damage caused to the timber by the teeth during plate pressing. This paper presents the results of preliminary tests that were carried out to determine the bearing characteristics of both tooth damaged, and undamaged smooth surface timber, and in the light of the results speculates on the validity of the appropriate Johansen equations derivatives to predict the ultimate strength of nail plate joints.

2. Johansen Equations (derivatives)
There are many different nail plate geometries but probably the most common are those of rectangular plan shape made from steel of 1 mm nominal thickness with teeth aligned in rows and with either one or two teeth punched from a slot. Tooth profiles vary widely but a width of about 3 mm is common and where two teeth are punched from the same slot a length of 6-8 mm is usual. With these typical dimensions the two equations that best estimate the load capacity of a nail plate are those relating to a thick steel plate as illustrated in Figure 1.
Figure 1. Failure modes in steel to timber connections for thick steel plates.

In these equations the embedding stress distributions are based on assumptions of rigid plasticity in bearing and ultimate load is calculated from the existence of maximum embedding strength along the whole fastener length, and/or when the fastener forms a mechanism by developing sufficient plastic hinges in the nail plate teeth. The plastic hinges in a tooth are formed either at the root only, or both at the root and elsewhere along its length. The capacity of a tooth is given by (Blass, *et al* [eds], 1995):

\[ R_d = f_h d b_t \]

where:
- \( R_d \) = shear resistance of a tooth
- \( f_h \) = embedding strength of the timber
- \( d \) = diameter of the dowel (= width of the nail plate tooth)
- \( b_t \) = yielded timber stress block width as shown in Figure 1

The stress block width \( b_t \) is dependant upon the mode of failure in the joint. For Mode 2, equilibrium equations yield a stress block width given by (Blass, *et al* [eds], 1995):

\[ b_t = t_l \left[ \left( \frac{2 + \frac{4 M_p}{f_h d t_l^2}}{f_h} \right)^{-1} - 1 \right] \]

where:
- \( M_p \) = plastic moment capacity of the tooth
- \( t_l \) = length of tooth

In the case of Mode 3, the stress block width is given by (Blass, *et al* [eds], 1995):

\[ b_t = \frac{2 M_p}{f_h d} \]

In Eurocode 5, the corresponding equations for joint capacity also take into account the contribution of the rope effect but this is considered inappropriate for short nail plate teeth. From these equations it is seen that the dominant factor governing the shear resistance of a tooth is the embedding strength. In Europe, EN 383:1993 is the current test standard covering embedment testing for dowel type fasteners. The basis of the testing procedures indicated is to mimic as closely as possible, via the use of a stiff linear fastener, the real situation that exists when the fastener is used in practice. For nail plates this implies that tests should be conducted on teeth that have been pressed into timber in the way they would be in practice. However, with the relatively short tooth length described above, and the fact that one end of a tooth is integral with the plate there is no possibility of using the formalized procedures. In order to obtain relevant embedment data a different technique is required.
3. Experimental techniques

A non-standard technique was tried by Constantini (2004) in an undergraduate project at the University of Brighton. Tests involved pressing a small area of a plate into a timber specimen, cutting the plate to separate an individual tooth from the remainder, exposing the tooth by cutting off the timber on one side of it and then applying load directly to the tooth. The first method of tooth loading was by use of a rod held rigidly in the testing machine platen and aligned with the centre of the area of the tooth. One such rod had a concave end and another had a convex end, to be chosen as appropriate for different tooth surface profiles. The method was partially successful but problems of slipping due to metal to metal contact and tooth rotation made it unreliable. The second method used a similar principle but with a circular cross sectioned rod glued onto the tooth at its centre of area and simple contact between the free end of the rod and the testing machine platen. This method overcame the slipping problem but required considerable dexterity to position the rod on the tooth and to support it whilst the glue set. The third and most successful method involved preparing the specimen as mentioned above but leaving about 3mm of wood covering the nail on the side to be loaded. This covering was then carefully removed and the void filled with a filler paste. Once this had hardened the end of the specimen, including the filler paste, was sanded leaving a smooth true finish. The nail was then loaded with a flat ended rod of tooth profile cross section that was held rigidly by the testing machine platen. Generally the method worked well but it was difficult to keep the filler from adhering to the exposed edges of the wood in the void above the nail and sometimes the filler crushed during loading. Appropriate choice of filler and sanding to leave the thinnest possible, but competent, thickness of filler minimized these problems. In each of the above loading arrangements the eccentricity of load had the potential to cause the whole specimen as described to rotate about its base but this problem was foreseen, and solved by doubling the bottom width of the timber specimen such that concentric reactions were obtained.

4. Tests

Using the filler technique, tests were conducted on teeth taken from three different manufacturers’ plates, each with 25 replicates. The timber specimens used were approximately 45 mm x 25 mm in cross section and 135 mm long with a length of approximately 50 mm of the same cross section glued onto the lower part of the specimen to provide concentricity of load and reaction. A typical unfinished test specimen is shown in Figure 2. The timber was conditioned at 65±5 % RH and 20±2ºC before test. A constant rate of machine cross head movement of 0.8 mm per minute was used with cross head movement taken as displacement. On the smooth sanded end of each specimen an additional bearing test was conducted using a flat ended, nail profile cross sectioned, loading bar as mentioned above, appropriate to each tooth shape. A typical graph of stress versus displacement from a successful test is shown in Figure 3, however, in some tests there was a tendency for the nail to rotate beneath the loading rod due to unevenness of bearing on its underside, which made it difficult to ensure that results were always meaningful.

5. Results

Due to variability caused by problems with the test arrangement and lack of experience of the student, two data sets were analyzed. The first included the results of all tests, designated (A), and the second excluded test results in which errors were suspected, designated (B). Dividing the maximum embedment stress recorded for each tooth by that for the smooth surface timber test, yielded the following average ratios for the three different manufacturers’ plates: 0.71(A), 0.72(A) and 0.85(A) with an average of 0.76(A), and 0.80(B), 0.68(B) and 0.91(B) with an average of 0.80(B). Similarly the stiffnesses recorded over the 10-40 % ultimate load range were compared as above yielding: 0.19(A), 0.22(A) and 0.21(A) with an average of 0.21(A) and 0.22(B), 0.20(B) and 0.18(B) with an average of 0.20(B). Density related trends for these ratios of embedment stress and stiffness were also investigated but proved to be inconclusive.
6. Discussion

It appears from the results presented above that the maximum embedment stress beneath a nail plate tooth is of the order of 78% of that obtained from smooth surface bearing. Allowing for this in the Johansen equations derivatives, with typical tooth dimensions as indicated above, predicts ultimate tooth loads of about 83-89% of those calculated with smooth surface embedment values. On the face of it this is a relatively small reduction but a more revealing scenario is suggested from comparison of the two typical embedment characteristics shown in Figure 3. As can be seen, for the smooth surface bearing curve, ultimate strength is achieved at a displacement of about 0.25 mm, so the curve may be considered a reasonable portrayal of rigid plastic behaviour. However, for the nail plate tooth bearing curve, ultimate strength is not reached until a displacement of about 2.75 mm, which is a response far from that of rigid plastic behaviour. In a real nail plate joint such non rigid behaviour would raise the prospect of the displacement necessary to invoke full bearing resistance along the teeth, causing axial forces in the teeth, sufficient to cause them to withdraw from the timber before the failure mechanism visualized in the derivation of the Johansen equations derivatives could develop. Such a scenario could invalidate use of the Johansen equations derivatives or at the very least require a check to rule out premature failure by teeth withdrawal.

7. Conclusion

This paper has quantified (with reservation) the reduction in ultimate strength of a nail plate tooth indicated by the Johansen equations derivatives when taking account of reduced tooth embedment strength due to timber damage caused by teeth during plate pressing. It has also identified departure from the assumption of rigid plastic embedment behaviour as a factor that could invalidate use of the Johansen equations derivatives for the prediction of ultimate joint strength.

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9. References
