

Strength of inclined screw shear connections for timber and concrete composite construction

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Synopsis

This paper presents a model for the strength of inclined screws used as shear connectors in timber and concrete composite floors. Experiments show that both the stiffness and strength of screwed timber to concrete shear connections can be increased if the screws are inclined in the direction of shear; this model predicts the enhanced strength. The model is an upper bound plastic collapse model that assumes that the timber and screws behave perfectly plastically and that the concrete remains undamaged. Six failure modes are considered: yield of the screw, in tension or shear, and four modes which combine bending of the screw and timber. The four combined modes allow screw withdrawal, lateral crushing of the timber and the development of plastic hinges in the screw. A design chart is proposed which shows the expected strength and failure mode. The model is validated by comparison to two sets of experimental tests.

Notation

A_{α}	Cross-sectional area of screw at interface between concrete and timber.
$F_{ax,\alpha}$	Withdrawal load of inclined screw from timber.
M_y	Yield bending moment of screw.
R_i	Shear strength of the inclined screw timber to concrete connection; in mode i .
\widehat{R}	Non-dimensional shear strength ($\widehat{R} = 4R/f_{t0}\pi d^2$)
W_E	External work done.
$W_{i,i}$	Internal work done in mode i .
d	Diameter of screw.
d_{eff}	Effective diameter of screw.
f_{1cube}	Mean concrete cube strength.
$f_{h,\alpha}$	Embedment strength of the timber, at an angle α to the grain ($\widehat{f}_h = f_{h,0}/f_{t0}$).
$f_{a,\alpha}$	Withdrawal shear stress of screw inclined at an angle α to the vertical.
f_u	Yield stress of screw.
h	Length of screw head cast <i>in situ</i> in concrete.
i	Failure mode.
k_{90}	Embedment strength modification factor.
l_{ef}	Effective length of screw.
t	Length of screw inserted into timber ($\widehat{t} = t/d$).
x_i	Location of point of zero lateral translation in mode $i = 3$ or 4.
u	Lateral displacement of screw tip.
α	Angle of inclination of the screw axis with the vertical.
Δ_{ax}	Axial displacement of screw.

Δ_{lat}	Lateral displacement of screw at the material interface.
λ	Ratio of withdrawal to embedment strength ($\lambda = f_{a,0}/f_{h,0}$).
ρ_k	Characteristic density of timber.

Introduction

Composite timber and concrete floors consist of timber members in the tensile zone, a concrete slab in the compression zone and a shear connection between the timber and the concrete. The shear connection is usually achieved with dowels (or screws or nails) vertically inserted into the timber. The strength of the shear connection is one of the key parameters required to design the composite floor.

In order to predict the shear capacity of vertically inserted dowel type shear connectors the plasticity model first proposed by Johansen¹ can be used. Johansen reasoned that the shear capacity of jointed timber members is attained when the timber under the dowel attains its ultimate bearing strength, or when the dowel develops plastic hinges simultaneously with the timber attaining its bearing strength. Both the dowel and the wood are assumed to behave perfectly plastically at the ultimate limit state. The model is an upper-bound plasticity method and the governing mode of failure of the connection is given by the lowest upper bound.

Johansen validated his strength prediction model by conducting shear tests on timber to timber connections made with a single steel dowel shear connector. The geometry of the connection and the properties of the dowel were such that the modes of failure were limited to two types: the dowel either rotated in the jointed timber members without forming plastic hinges; or the dowel developed a plastic hinge in each of the connected members. The contribution of frictional resistance between the connected timber members to the shear capacity of the joint was neglected. It was also assumed that the members were initially in contact, there was a perfect fit between the shear connectors and the timber, and the connection did not fail prematurely by timber splitting. The lateral displacement (slip) of the members of the joint, relative to each other, was assumed to remain small in comparison to the length of the dowel inserted into the timber.

Johansen's 'yield theory' was subsequently developed and validated by other researchers. Smith² gives a detailed report on the development of Johansen's theory and its applicability to jointed timber connections. A further discussion on the development of Johansen's theory can be found in Aune and Patton-Mallory³. Their prediction model, based on cumulative research after Johansen's initial proposed theory, predicts a limit state load for several modes of failure which may occur in practice for vertically inserted dowels working in single and double shear between similar and dissimilar materials. The governing mode depends on the cross section and yield strength of the fasteners, the thicknesses of the connected components and the 'embedment strength' of the components.

Equations for Johansen's model are now given in section 8.2 of Eurocode 5 Part 1-14. These equations have been shown to give accurate predictions; see, for example, Persaud & Symons⁵. However, the equations are restricted to vertically inserted dowels or screws (i.e. perpendicular to the applied loading). Meierhofer⁶ and Bejtka & Blass⁷ have shown that the orientation of a screw can significantly influence the initial stiffness and ultimate strength of the connection. This observation is validated by push-off shear tests described in this paper. Unfortunately there is no design

guidance in the timber Eurocode for the ultimate strength of shear connections made with inclined screws. The Eurocode only recommends that the strength of unconventional connections should be determined from push-off shear tests.

Bejtka & Blass⁷ investigated the link between the angle of inclination of screws and the ultimate strength that can be attained, with the view of developing equations to predict the ultimate shear capacity of the connection. They limited their investigation to timber to timber joints connected with screws inserted into the timber at various angles to the grain direction. They proposed a prediction model for the ultimate shear capacity of the timber-timber joint, which consisted of a series of six failure modes, similar to the approach used by Johansen. The first two basic modes were bearing failure in either member. The third mode consists of the screw rotating in the timber without forming a plastic hinge. The fourth and fifth mode consisted of the dowel developing a plastic hinge in one member and rotating in the other. The sixth and final mode consisted of the screw forming a plastic hinge in both of the connected timber members. Each mode of failure is analysed using an equilibrium approach where external forces are considered to be balanced by a combination of the withdrawal strength of the screws, bearing strength of the timber and the plastic moment capacity of the screws. A contact force between the timber components is included to balance the vertical component of the tension in the screws (for the relevant modes). A frictional resistance proportional to this contact force is also considered in the equilibrium calculations. The model was validated by comparing the predicted ultimate shear strength of the joint with several experiments. They found that for timber-timber connections made with a single inclined screw the peak strength of the connection system was attained with screws inserted at 30° to the vertical. At this angle of inclination, the shear strength of the connection was about 50% higher than that attained if the screws were vertical.

Kavaliauskas *et al*⁸ also used an equilibrium approach to consider the case of a timber to concrete connection with inclined screws. They assume that the screw is rigidly embedded in the concrete and this simplifies the problem to three possible failure modes: simultaneous lateral crushing and withdrawal of the screw from the timber (i.e. bearing failure); the development of a single plastic hinge in the screw; and the development of two plastic hinges in the screw. A frictional force between the concrete and timber is included in the equilibrium calculations.

A criticism of the theoretical approaches presented by Bejtka & Blass⁷ and Kavaliauskas *et al*⁸ is the use of equilibrium relationships at the outset in modelling failure modes that will be treated as upper bounds. The model presented in this paper implements the kinematic theorem of plasticity (see, for example, Calladine⁹). Work equations are found for hypothetical collapse mechanisms so that the external work done during collapse is

equal to the energy dissipated in plastic deformation. The collapse loads are therefore upper bounds on the actual collapse load.

The prediction model outlined in this paper has been developed to predict the shear capacity of inclined screw shear connections in composite timber and concrete floors. We will consider the vertical direction to be perpendicular to the applied shear load, and also to the grain direction of the timber. Screws will be considered to be inserted into the timber at an angle to the vertical, with the screws all oriented in the direction of slip as shown in Fig 1. Following Johansen's theory, the timber and the connectors will be assumed to behave perfectly plastically at the ultimate limit state. However, in addition to crushing of the timber due to lateral displacement of the screw, withdrawal of the screw from the timber will also be considered. We will also consider the possibility of failure of the screw itself, in tension or shear. The embedment of the screw in the concrete is assumed to be sufficiently great such that no failure of the concrete occurs.

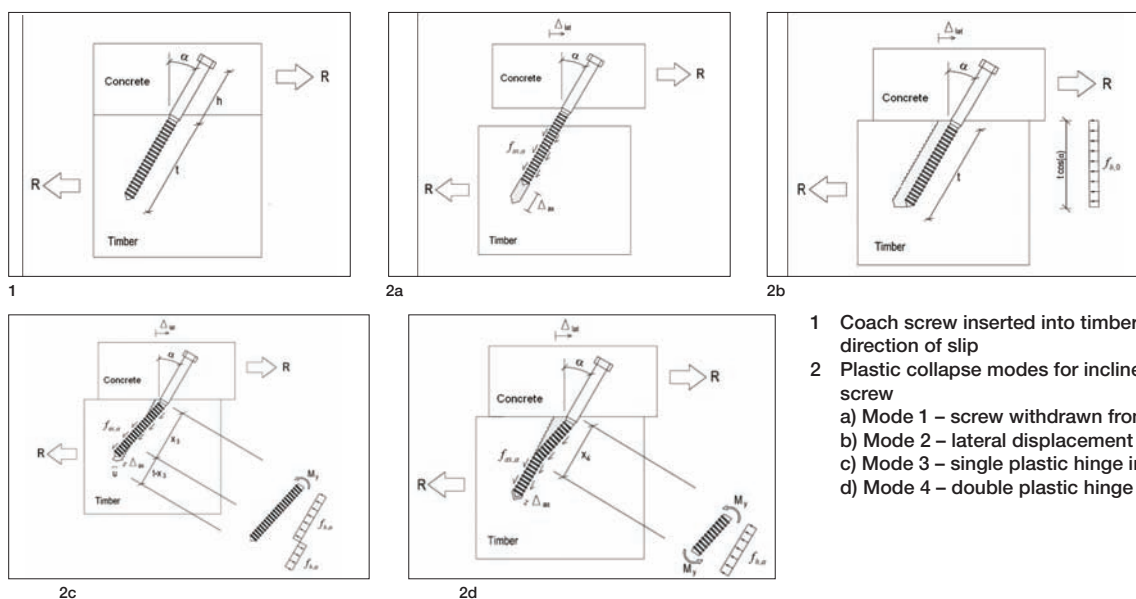
The model does not consider any contribution of friction between the two components. Friction is generally significant only when the connection slip is large, we examine only small displacements and initial yield. We also maintain that the magnitude of friction force that may occur in such screwed connections cannot be relied upon and it is therefore conservative to ignore it. This position may be supported by the work of Johansen¹, Aune and Patton-Mallory³, McLain and Thangjitham¹⁰ and Smith *et al*¹¹.

The first section of this paper describes the kinematic plastic collapse model. Each failure mode is considered in turn and the ultimate strength calculated. Two sets of experimental tests of inclined screw shear connections are then described. The results of these tests provide preliminary validation of the model. The paper concludes by presenting the plastic collapse model in the form of a failure map (design chart) which may be used to predict the mode of failure and strength of an inclined screw shear connection.

Plastic collapse model

This model follows a similar approach to Johansen's yield theory. Kinematic plastic collapse mechanisms are postulated and an upper bound on the collapse load is then determined from a work calculation. The assumption that the portion of the connector embedded in the concrete does not fail limits the possible modes of failure involving the timber to four, as shown in Figs 2a to 2d.

In mode 1 (Fig 2a), the screw is withdrawn from the timber without causing any crushing failure to occur in the timber. In mode 2 (Fig 2b) the screw displaces horizontally and crushes the timber without forming a plastic hinge. In mode 3 (Fig. 2c) a single plastic hinge forms in the screw at the interface between the timber and the concrete. In mode 4 (Fig 2d) the screw has two plastic hinges: one at the interface of the timber and the concrete; and the other



- 1 Coach screw inserted into timber in the direction of slip
- 2 Plastic collapse modes for inclined coach screw
 - a) Mode 1 – screw withdrawn from timber;
 - b) Mode 2 – lateral displacement of screw;
 - c) Mode 3 – single plastic hinge in screw;
 - d) Mode 4 – double plastic hinge in screw

in the portion embedded in the timber. In both modes 3 and 4, as the coach screw displaces laterally it is simultaneously being withdrawn from the timber.

There are also two additional failure modes which only involve the screw. These are shear or tensile failure of the screw at the interface between the timber and concrete. A work calculation for a small displacement of each failure mode provides an upper bound estimate of the shear capacity of the connection. Hence the governing mode of failure, and thus the strength of the connection, is given by the lowest upper bound. The work calculation assumes that the external work done by the applied load is equal to the energy absorbed by plastic deformation of the timber and any plastic hinges forming in the screw.

Unlike Johansen's equations, which predict the shear capacity of connections made with only vertically inserted screws/dowels, the model outlined in this paper can predict the shear capacity of connections with screws at any angle of inclination to the vertical. It also takes into account the contribution of the withdrawal strength of the screws from timber.

The model differs from the inclined screw models proposed by Bejtka & Blass⁷ and Kavaliauskas⁸ in two respects. Firstly, a kinematic work calculation is used to derive equations for the shear capacity of the relevant modes of failure without considering equilibrium. Secondly, in this model screw withdrawal (mode 1) and lateral displacement (mode 2) are considered as independent possible failure modes, rather than as a single combined timber bearing failure mode.

Material and component strengths

The material properties required for the model are the embedment and withdrawal strength of the screw in the timber and the yield strength of the screw (and hence its tensile, shear and bending strength). The contribution of inter-member friction to the shear capacity of the connection is neglected in the plastic collapse calculations.

The embedment strength f_h (or crushing stress) is a measure of the resistance of the timber to lateral displacement of the screw. This stress has a maximum value when the timber grain is axially crushed. When the timber is indented at an angle to the grain direction the embedment strength is reduced. Section 8.5 of Eurocode 5⁴ recommends equation (1) to determine the embedment strength of timber $f_{h,\alpha}$ at an angle α to the grain direction. This expression has its origins in work by Hankinson¹².

$$f_{h,\alpha} = \frac{f_{h,0}}{k_{90} \sin^2 \alpha + \cos^2 \alpha} \quad (1)$$

In equation (1) $f_{h,0}$ is the embedment strength parallel to the grain (i.e. for $\alpha = 0$). Note that in this context of a horizontal timber beam to concrete slab shear connection the grain direction is assumed to be parallel to the beam/slab interface. Consequently for a screw inclined at an angle α to the vertical the lateral embedding direction is also at an angle α to the horizontal grain direction.

The modification factor k_{90} determines the knockdown effect on the embedment strength. For softwood the Eurocode recommends that k_{90} should be determined as a function of the screw effective diameter d_{eff} (the lesser of either the smooth shank diameter of the screw or 1.1 times the inner thread diameter, in mm), from equation (2) below. For simplicity we will assume that $k_{90} = 1.5$ for all d .

$$k_{90} = 1.35 + 0.015d_{\text{eff}} \quad (2)$$

The characteristic embedment strength of the timber parallel to the grain may be determined from an embedment test in which a dowel is forced against the grains of the timber. Alternatively, it can be obtained (in N/mm²) from the empirical relationship in section 8.3 of Eurocode 5 for predrilled holes:

$$f_{h,0,k} = 0.082\rho_k(1 - 0.01d_{\text{eff}}) \quad (3)$$

where d_{eff} is the effective screw diameter (in mm) and ρ_k is the density of the timber (in kg/m³).

The withdrawal strength of screws also depends on the angle of insertion. Screws inserted into the end grain of timber have lower withdrawal strength than screws inserted perpendicular to the grain direction. We follow the recommendation of section 8.7.2 of Eurocode 5 for calculating the withdrawal strength of screws inserted at an angle to the grain in equation (4).

$$f_{a,\alpha} = \frac{f_{a,0}}{\cos^2 \alpha + 1.5 \sin^2 \alpha} \quad (4)$$

$f_{a,\alpha}$ is the axial withdrawal shear stress for a screw inclined at an angle α to the vertical and $f_{a,0}$ is the withdrawal strength of a screw perpendicular to the timber grain (noting again that for a horizontal timber beam to concrete slab shear connection we have assumed that the grain direction runs parallel to the beam/slab interface). The net axial withdrawal load $F_{ax,\alpha}$ will be calculated straightforwardly according to equation (5), where t is the length of screw embedded in the timber.

$$F_{ax,\alpha} = \pi dt f_{a,\alpha} \quad (5)$$

However, we note that this differs slightly from the empirical Eurocode equation (6)

$$F_{ax,\alpha} = (\pi d l_{\text{ef}})^{0.8} f_{a,\alpha} \quad (6)$$

where the effective length $l_{\text{ef}} = t - d$ and d is the thread diameter (and the correct units of N/mm² and mm must be adopted). In the absence of experimental data the Eurocode recommends that the perpendicular characteristic withdrawal strength $f_{a,0}$ should be based on the timber density ρ_k (in kg/m³) according to eqn (7).

$$f_{a,0} = 3.6 \times 10^{-3} \rho_k^{1.5} \quad (7)$$

To determine the yield moment of the screw or dowel we adopt classical mechanics and use equation (8).

$$M_y = \frac{\pi}{32} f_u d^3 \quad (8)$$

where f_u is the yield stress and d the diameter of the screw (for simplicity we will take d as the outer diameter of the screw thread throughout but note that this may slightly overestimate the yield moment). Note that section 8.5 of Eurocode 5 provides an empirical equation (9) for calculating the yield strength of a screw. However, the values of M_y obtained from (8) and (9) differ by less than 20% for screws with 10mm < d < 25 mm.

$$M_y = 0.3f_u d^{2.6} \quad (9)$$

Mode 1

In all modes the external work W_E done by the shear force R is:

$$W_E = R \Delta_{\text{lat}} \quad (10)$$

In mode 1 the screw is withdrawn from the timber without lateral movement (see Fig. 2a). The lateral (slip) displacement of the joint Δ_{lat} is the horizontal component of the axial displacement Δ_{ax} and therefore depends on the angle of inclination α of the screw to the vertical:

$$\Delta_{\text{lat},1} = \Delta_{\text{ax},1} \sin \alpha \quad (11)$$

The internal energy $W_{I,1}$ dissipated by failure of the timber as the screw is withdrawn is:

$$W_{I,1} = F_{ax,\alpha} \Delta_{\text{ax},1} \quad (12)$$

where $F_{ax,\alpha}$ is the withdrawal load of the screw from timber. Equating the internal work $W_{I,1}$ with the external work W_E , and

substituting for the lateral displacement $\Delta_{lat,1}$, gives the ultimate shear force in mode 1 as:

$$R_1 = \frac{F_{ax,\alpha}}{\sin \alpha} \quad (13)$$

Mode 2

Mode 2 is characterised by the screw crushing the timber fibres in front of it as it is rigidly displaced laterally in the timber (see Fig 2b). There is no separation of the timber and concrete and no withdrawal of the screw.

The internal energy dissipated in compression of the timber is:

$$W_{1,2} = f_{h,0} dt \cos \alpha \Delta_{lat} \quad (14)$$

where d is the diameter of the screw, $f_{h,0}$ the embedment strength of the timber parallel to the timber grain direction and t is the depth of penetration of the screw into the timber.

Equating the internal and external work gives the ultimate shear force in mode 2 as:

$$R_2 = f_{h,0} dt \cos \alpha \quad (15)$$

Mode 3

In both modes 3 and 4 the axial withdrawal component of the screw is mobilised while the screw simultaneously develops one, or two, plastic hinges as it laterally displaces. For infinitesimal displacements, the axial displacement of the screw $\Delta_{ax,34}$ in both modes 3 and 4 is given by:

$$\Delta_{ax,34} = \Delta_{lat,34} \sin \alpha \quad (16)$$

In mode 3 the screw develops a single plastic hinge at the interface between the timber and the concrete as the concrete is displaced relative to the timber. The screw tends to rotate in the timber, about some point along its embedded length, crushing the timber fibres in front of the screw above the point of rotation and behind the screw below the point of rotation (see Fig 2c). The location of this point of rotation from the timber/concrete interface is x_3 along the length t of the screw inserted into the timber. The lateral displacement of the tip of the screw u is:

$$u = \frac{\Delta_{lat,34}(t - x_3)}{x_3} \quad (17)$$

The energy dissipated by crushing of the timber, rotation of the plastic hinge in the screw and withdrawal of the screw is:

$$W_{1,3} = f_{h,\alpha} dx_3 \cos \alpha \frac{\Delta_{lat,34}}{2} + f_{h,\alpha} d(t - x_3) \cos \alpha \frac{u}{2} + M_y \frac{\Delta_{lat,34} \cos \alpha}{x_3} + F_{ax,\alpha} \Delta_{ax,34} \quad (18)$$

Substituting for $\Delta_{ax,34}$ and u in equation (18) and equating the internal and external work gives:

$$R_3 = \frac{f_{h,\alpha} dx_3 \cos \alpha}{2} \left[x_3 + \frac{(t - x_3)^2}{x_3} \right] + \frac{M_y \cos \alpha}{x_3} + F_{ax,\alpha} \sin \alpha \quad (19)$$

Because we are seeking the lowest upper bound estimate of the shear capacity of the connection we find the value of x_3 that minimises R_3 . Thus we set the differential:

$$\frac{dR_3}{dx_3} = 0 \quad (20)$$

This leads to an expression for the location of the point of rotation of the screw in the timber as:

$$x_3 = \sqrt{\frac{M_y}{f_{h,\alpha} d} + \frac{t^2}{2}} \quad (21)$$

If we substitute for x_3 in equation (19) we obtain the ultimate shear force R_3 for mode 3 as:

$$R_3 = f_{h,\alpha} d \cos \alpha \left(2\sqrt{\frac{M_y}{f_{h,\alpha} d} + \frac{t^2}{2}} - t \right) + F_{ax,\alpha} \sin \alpha \quad (22)$$

Mode 4

In mode 4 the screw develops two plastic hinges. One at the interface between the timber and the concrete, and a second plastic hinge at some point along its embedded length (see Fig 2d). The location of the plastic hinge from the timber/concrete interface is x_4 along the length t of the screw inserted into the timber.

The energy dissipated by the timber in compression, the plastic hinges in the screw and from withdrawal of the screw is:

$$W_{1,4} = f_{h,\alpha} dx_4 \cos \alpha \frac{\Delta_{lat,34}}{2} + 2M_y \frac{\Delta_{lat,34} \cos \alpha}{x_4} + F_{ax,\alpha} \Delta_{ax,34} \quad (23)$$

Substituting for $\Delta_{ax,34}$ in equation (20) and equating the internal and external work gives:

$$R_4 = \frac{f_{h,\alpha} dx_4 \cos \alpha}{2} + \frac{2M_y \cos \alpha}{x_4} + F_{ax,\alpha} \sin \alpha \quad (24)$$

Again, because we are seeking the lowest upper bound estimate of the shear capacity of the connection we find the value of x_4 that minimises R :

$$x_4 = \sqrt{\frac{4M_y}{f_{h,\alpha} d}} \quad (25)$$

If we substitute for x_4 in equation (24) we obtain the ultimate shear force R_4 for mode 4 :

$$R_4 = \cos \alpha \sqrt{4M_y f_{h,\alpha} d} + F_{ax,\alpha} \sin \alpha \quad (26)$$

Screw tensile failure

We will now consider the first of two failure modes involving only the screw. Tensile failure of the screw may be analysed using the same approach used for Mode 1 (screw withdrawal). This gives the ultimate shear force for tensile failure of the screw as:

$$R_{tensile} = \frac{f_u \pi d^2}{4 \sin \alpha} \quad (27)$$

Screw shear failure

The second screw failure mode to be considered is shear failure of the screw at the interface between timber and concrete. The cross-sectional area A_α of the screw on this interface increases with screw inclination α such that

$$A_\alpha = \frac{\pi d^2}{4 \cos \alpha} \quad (28)$$

If the shear yield stress of the screw is taken to be $0.6f_u$ then the ultimate shear force for shear failure of the screw is:

$$R_{shear} = 0.6f_u A_\alpha = \frac{0.6f_u \pi d^2}{4 \cos \alpha} \quad (29)$$

Summary of model

The predicted strength of an inclined screw shear connector is given by the minimum predicted strength of all six modes described above. It is convenient to normalise the ultimate shear load R by the tensile strength of the screw to give a non-dimensional strength $\hat{R} = 4R/f_u \pi d^2$. The failure model can then be

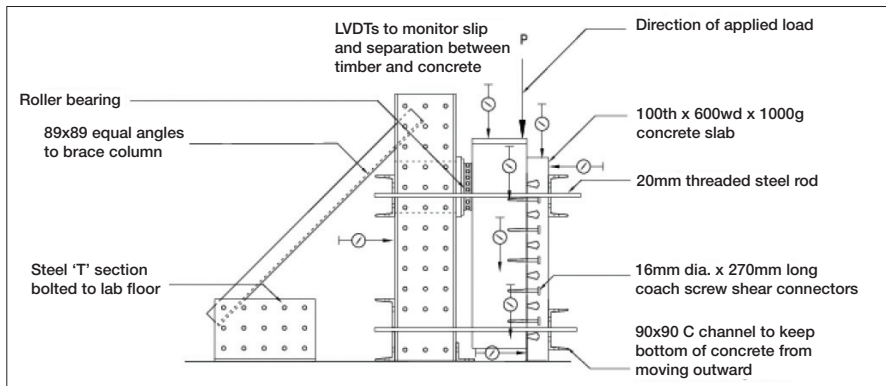
summarised as in eq 30 (see next page).

where the non-dimensional screw length $\hat{t} = t/d$ embedment strength $\hat{f}_h = f_{h,0}/f_u$ and withdrawal strength $\lambda = f_{a,0}/f_{h,0}$. The parameters \hat{t} , \hat{f}_h , λ , and the inclination angle α determine which failure mode will dominate and the strength of a particular screw connection. The parameter λ (ratio of withdrawal to embedment strength) is expected to be broadly constant for a wide range of timbers.

$$\widehat{R} = \frac{4}{f_u \pi d^2} \min \left\{ \begin{array}{l} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_{tensile} \\ R_{shear} \end{array} \right\} =$$

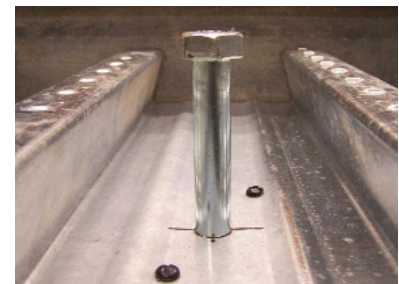
(30)

$$\min \left\{ \begin{array}{l} \frac{4\widehat{t}\widehat{f}_h}{\sin \alpha (\cos^2 \alpha + 1.5 \sin^2 \alpha)} \\ \frac{4\cos \alpha \widehat{t}\widehat{f}_h}{\pi} \\ \frac{4\widehat{t}\widehat{f}_h}{\cos^2 \alpha + 1.5 \sin^2 \alpha} \left[\frac{\cos \alpha}{\pi} \left(\sqrt{\frac{\pi(\cos^2 \alpha + 1.5 \sin^2 \alpha)}{8\widehat{t}^2\widehat{f}_h}} + 2 \right) - 1 \right] + \lambda \sin \alpha \\ \frac{4\widehat{t}\widehat{f}_h}{\cos^2 \alpha + 1.5 \sin^2 \alpha} \left[\frac{\cos \alpha}{\pi} \sqrt{\frac{\pi(\cos^2 \alpha + 1.5 \sin^2 \alpha)}{8\widehat{t}^2\widehat{f}_h}} + \lambda \sin \alpha \right] \\ \frac{1}{\frac{\sin \alpha}{0.6}} \\ \frac{1}{\cos \alpha} \end{array} \right\}$$



3

- 3 Schematic of single sided push-out test rig
 4 16 x 230mm coach screw shear connector, RLSD Holorib decking and 4.5 mm temporary fixings. 4a) Vertical 16mm screw; 4b) 16mm screw at 20° to the vertical; 4c) 16mm screw at 40° to the vertical; 4d) 16mm screw at 50° to the vertical



4a



4b



4c



4d

However, the value of \widehat{f}_h will depend on the particular timber and screw material in use.

Shear tests of inclined screw shear connections

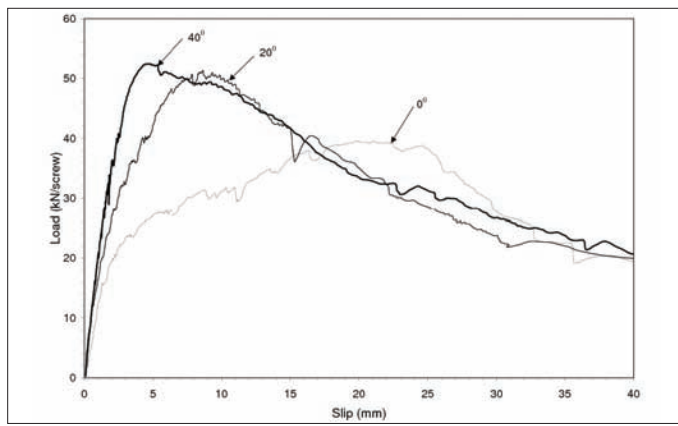
Two sets of experimental shear tests of inclined screws have been conducted to provide preliminary validation of the failure model. The first set used large 16mm diameter, 230mm long coach screws connecting structural glulam timber to a concrete slab. These tests were intended to be representative of a practical application of inclined screw shear connectors in a timber and concrete composite floor. The screws failed in either mode 3 or 4. The second set of tests used smaller 6mm diameter, 50mm long coach screws in balsa wood. The choice of a much softer wood caused these tests to fail in either mode 1 or 2.

Large scale tests – 16 x 230mm coach screws in glulam timber
Experimental method

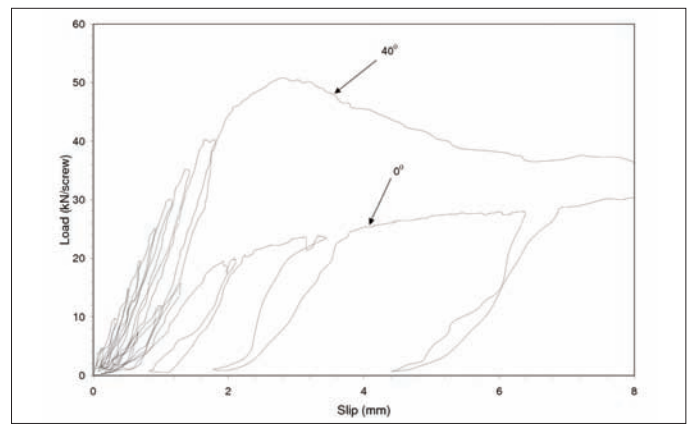
The load-slip response of timber to concrete shear connections using inclined coach screws has been investigated through a series of single sided push-out shear tests. The push-out shear test has become the standard method of establishing the strength and fatigue performance of shear connectors for steel and concrete composite beams and is also suitable for testing shear connections for timber and concrete composite construction. The

typical form consists of a short section of beam connected to two small concrete slabs by the shear connectors. The slabs are bedded down onto a reaction floor and a load is applied to the upper end of the beam. The relative slip between beam and slab is then monitored. In experiments presented in this paper a modified version of the test with only a single concrete slab was used (see Fig 3). This configuration is referred to as the single sided push-off shear test. The purpose of the experiments was to quantify the load-slip relationship of the shear connectors, and in particular to determine the initial stiffness (slip modulus), the yield strength and the ultimate strength of the connectors in single shear.

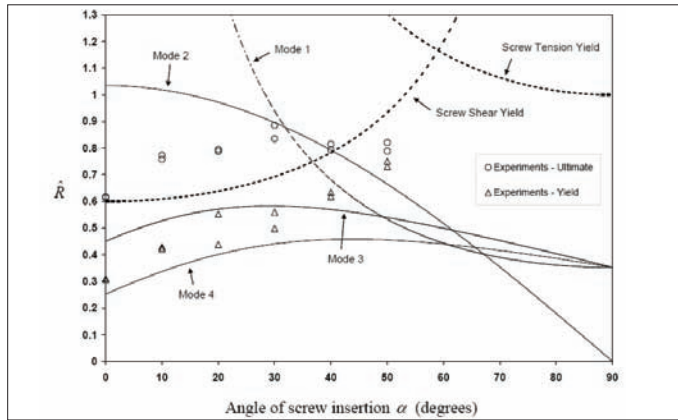
The specimens tested were of a composite timber and concrete floor system utilising steel decking as permanent formwork for the concrete floor slab. Such a system was previously tested by the authors with vertically inserted coach screws (see Persaud and Symons⁵). To construct each specimen a 1000mm long, 600mm wide and 100mm deep concrete slab was cast on Richard Lees Holorib S280 0.9mm permanent formwork steel decking. Each steel decking sheet was initially fixed to the timber beam with 4.5mm x 20mm long self drilling, self tapping screws, two per trough. In each trough of the decking, an ordinary 16mm diameter, 230mm long, coach screw was screwed into a pilot hole (pre-drilled in the timber to a depth $t = 130$ mm) to serve as a shear connector between the timber and concrete. There were a total of



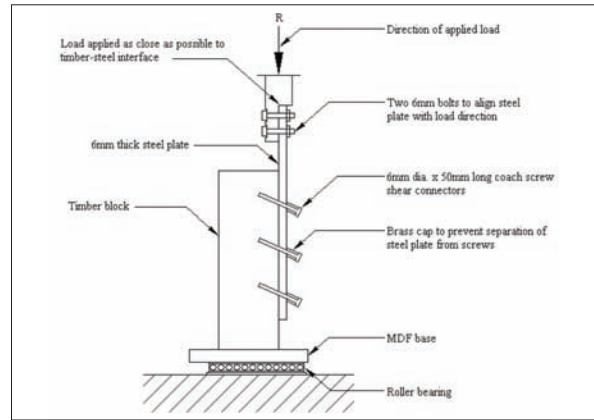
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6



7



8

- 5 Load/slip response for 16 x 230mm coach screws (no reloading cycles shown)
- 6 Load/slip response for 16 x 230mm coach screws (with unload/reload cycles)
- 7 Shear capacity for 16 x 230mm coach screws in GL28 glulam ($\hat{f}_{h,0} = 0.1$, $\hat{t} = 8.1$, $\lambda = 0.16$)
- 8 Test configuration for 6 x 50mm coach screws in balsa wood

five coach screws in each specimen. Specimens were prepared with the coach screws inserted at angles of 0°, 10°, 20°, 30°, 40° and 50° to the vertical (see Fig 4). Two identical specimens were made and tested for each angle. A layer of A142 mesh reinforcement was placed at a depth of 30mm from the surface of the concrete to control any potential cracking. The concrete cube strength $f_{1\text{cube}}$ at the time of testing was 38.6 MPa (an average of 36 tests). The glulam timber beam was Grade GL28, 270 x 160mm in section and 1000mm long. The timber moisture content was 9.5% (an average of 36 tests). Further details of the experimental method are given by Persaud¹³.

Results of experiments

The two specimens tested at each angle of inclination gave almost identical responses; the elastic stiffness and ultimate strength recorded for each pair differed by no more than 2%. Fig 5 shows the load per connector against slip response of specimens with screws at 0°, 20° and 40° (plots for the other angles tested are omitted for clarity). The load was applied in repeated loading and unloading cycles of increasing amplitude; however, these cycles are removed from Fig 5 for clarity. Fig 6 shows details of the initial load per connector against slip response of specimens with screws at 0° and 40°; the loading and unloading cycles are included in Fig 6.

Comparison of model with experimental results

We now compare the predictions of the plastic collapse model with the experimental results of the large scale push-off shear tests of inclined coach screws. Measured and derived material properties used as inputs to the model are given in Table 1. The yield moment M_y of the coach screws was determined from three

point bend tests of screws. Indentation and withdrawal tests of the screws with timber samples were used to determine the embedment $f_{h,0}$ and withdrawal strengths $f_{a,0}$ of the timber. The non-dimensional parameters for screw length $\hat{t} = t/d = 130/16 = 8.13$, embedment strength $\hat{f}_h = f_{h,0} / f_u = 32 / 320 = 0.1$, and withdrawal strength $\lambda = f_{a,0} / f_{h,0} = 0.163$.

Table 2 summarises the key results of the large scale push-off shear tests and includes the model predictions of yield load and failure mode. The experimental yield point was taken as the 5% diameter offset point, following the method of McLain¹³. Figure 7 shows the predicted non-dimensional shearing resistance \hat{R} of each of the proposed failure modes plotted against the angle of insertion α of the screws to the vertical. The experimentally measured yield loads and ultimate strengths for the inclined screw shear tests are also plotted in Fig 7 (represented by triangular and circular markers respectively). It can be observed from Fig 7 that the proposed model predicts failure in Mode 4 over the whole range of screw inclinations tested. Examination of the screws after testing revealed that for inclinations up to 30° the screws did indeed fail in Mode 4 (double hinge), although screws inclined at 40° and 50° appeared to have failed in Mode 3 (single hinge). The model gives slightly conservative predictions of the shear capacity at yield of the connectors. However, the ultimate strengths of the screwed shear connections are significantly greater (up to a factor of two higher) than the yield loads and much higher than the model.

Small scale tests – 6 x 50mm coach screws in balsa wood

Experimental method

Single sided shear tests were conducted in balsa specimens with three 6 x 50mm coach screws inserted at an angle α to the normal of the grain direction. Tests were conducted for the range $\alpha = 0^\circ$ to 60° , in increments of 10° . A minimum of five tests were conducted at each angle. The test configuration is shown in Fig 8. For these small scale tests a 6mm thick steel plate was substituted for the *in situ* cast concrete slab used in the large scale tests. This plate provided the equivalent moment fixity required for the head of the screws. The use of a roller bearing support for the balsa block ensured that Mode 1 failure (screw withdrawal) could freely occur.

	Unit	Large scale tests 16 × 230mm coach screws in GL28 glulam	Small scale tests 6 × 50mm coach screws in balsa
Measured embedment strength $f_{h,0}$	MPa	32	6.7
Measured withdrawal load $F_{ax,0}$	kN	34.1	0.514
Insertion depth t	mm	130	25
Axial withdrawal strength $f_{a,0}$	MPa	5.2	1.1
Yield moment (in bending) M_y	Nm	129	11.6
Calculated yield stress f_u	MPa	320	547
$\lambda = f_{a,0}/f_{h,0}$		0.163	0.163
$\hat{t} = t/d$		8.13	4.17
$\hat{f}_h = f_{h,0}/f_u$		0.10	0.012

Table 1 Summary of material properties

Property	α	0°	10°	20°	30°	40°	50°
<i>Experimental (mean of two tests)</i>							
Load at yield R	kN/screw	19.8	27.4	31.9	34.0	40.3	47.6
Slip at yield	mm	2.1	2.2	2.3	2.3	2.4	2.4
Ultimate strength	kN/screw	39.6	49.2	50.9	55.3	51.7	51.5
Slip at ultimate strength	mm	19.6	12.2	7.8	6.3	4.1	3.8
Observed failure mode		4	4	4	4	3	3
<i>Model predictions</i>							
Predicted load at yield R	kN/screw	16.3	21.7	25.8	28.3	29.4	29.3
Predicted failure mode		4	4	4	4	4	4

Table 2 Summary of push-off shear test results and predictions for 16 × 230mm coach screws in GL28 timber

Property	Unit	0°	10°	20°	30°	40°	50°	60°
<i>Experimental (mean of 5 or 6 tests)</i>								
Load at yield	N/screw	697	840	760	739	666	531	552
Ultimate strength	N/screw	881	926	918	943	806	790	649
Observed failure mode		2	2	2	2	1	1	1
<i>Model predictions</i>								
Predicted load at yield	N/screw	967	990	945	871	662	518	431
Predicted failure mode		3	2	2	2	1	1	1

Table 3 Summary of push-off shear test results and predictions for 6 × 50mm coach screws in balsa wood

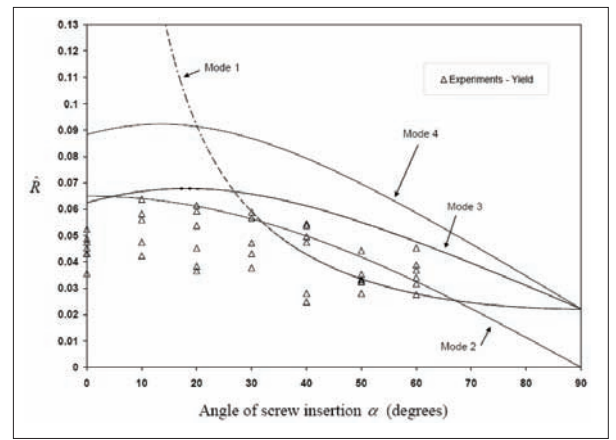
Further details of these small scale tests are given by Stanislaus¹⁵.

Comparison of model with experimental results

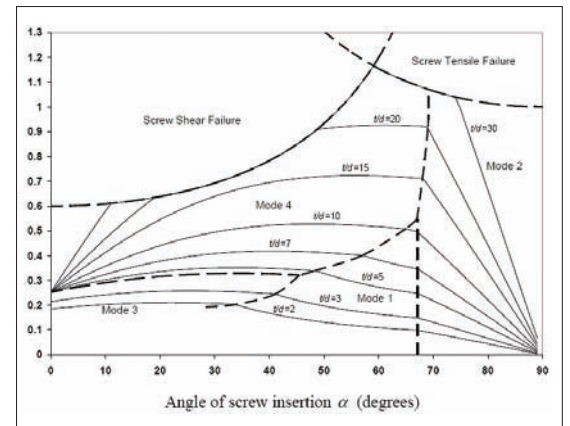
Embedment and withdrawal tests were conducted to determine the strength of the balsa wood. Bending tests were used to determine the yield moment of the screws. The measured and derived material properties for the balsa wood and screws are summarised in Table 1.

The non-dimensional parameters for screw length $\hat{t} = t/d = 25/6 = 4.17$, embedment strength $\hat{f}_h = f_{h,0}/f_u = 6.7 / 547 = 0.012$, and withdrawal strength $\lambda = f_{a,0}/f_{h,0} = 1.09 / 6.7 = 0.163$. We note that the value of λ for the balsa wood was virtually identical to that measured for the GL28 glulam structural timber.

Table 3 allows a comparison of the experimental results of the small scale push-off shear tests with the predictions of the model for yield load and failure mode. In Fig 9 the predicted non-dimensional shear strength \hat{R} for each failure mode is plotted for varying angle of screw insertion α . Note that the screw tension and screw shear failure modes are off the scale of Fig 9 and so are not visible ($\hat{R}_{shear} > 0.6$ for all α , $\hat{R}_{tension} > 1$ for all α). The model predicts



9



10

- 9 Shear capacity for 6mm screws in balsa wood ($\hat{f}_h = 0.01$, $\hat{t} = 4.2$, $\lambda = 0.16$)
 10 Design chart for steel screws in structural timber ($\hat{f}_h = 0.1$, $\lambda = 0.16$)

that either Mode 1 or Mode 2 should occur over virtually the entire range of α (the overlap of Mode 3 and Mode 2 at $\alpha = 0^\circ$ is very slight). The experimentally measured yield loads for the small scale tests are also plotted in Fig 9. The measured yield loads fall, on average, slightly below the predicted strengths. However, the model did provide a good prediction of the failure mode. The majority of tests for $\alpha = 0^\circ$ to 30° appeared to have failed in Mode 2, whereas the majority of tests for 40° to 60° had apparently failed in mode 1. For clarity the measured ultimate strengths measured from the tests are not plotted in Fig 9. The ultimate load at each inclination was, on average, 25% higher than the yield load and is given in Table 3.

Failure map / design chart

Figure 10 shows a proposed failure map, or design chart, for inclined screw shear connectors. The map shows a set of curves of the non-dimensional shear strength \hat{R} of a screw, plotted against the screw inclination angle α , for a range of selected values of $\hat{t} = t/d$ between 2 and 30. Each curve shows the minimum value of \hat{R} for all six failure modes considered in the model presented in this paper. Dashed lines on the map separate different modes of

failure. The map shown in Fig 10 is drawn for the particular choice of non-dimensional timber embedment strength $\widehat{f}_k = 0.1$ and withdrawal strength $\lambda = 0.16$. These values of \widehat{f}_k and λ are appropriate for mild steel coach screws in GL28 glulam structural timber (as tested and described above).

The map may be used as a design chart to determine the expected strength and mode of failure of a particular connection, or to choose the optimum length of angle of inclination of a screw. For example: if a screw must be inserted vertically ($\alpha = 0^\circ$) the map shows that there should be no benefit in strength in using a screw longer than $t = 5d$. The map also indicates that for a screw with, say, embedded length $t = 10d$, the optimum angle of inclination $\alpha = 48^\circ$. This inclination angle should give a connection twice as strong as if the screw was inserted vertically. The maximum possible strength available, from a particular diameter of screw, is for a screw embedment length $t = 25d$ and inclination angle $\alpha = 60^\circ$. At this point the double hinge failure (mode 4), screw tensile failure and screw shear failure modes are expected to coincide. Such a connection would be expected to be 4.5 times stronger than the same screw inserted vertically.

Conclusions

The shear capacity of an inclined coach screw shear connection at yield can be predicted using the model and failure map presented in this paper. The model has been shown to be reasonably accurate in prediction of both failure mode and magnitude of yield load by comparison with two sets of experimental data. It is hoped that the model and failure map will facilitate the design of inclined screw shear connections for timber and concrete composite construction.

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