The stiffness contribution of mortice and tenon joints in traditional timber frames

Gareth Berridge of the University of Bath writes about his undergraduate project that won first prize in the 2005 Model Analysis Award

Unlike steel frame buildings, the behaviour of which can be satisfactorily predicted using analytical methods taught in all structural engineering courses, modern green oak timber frame buildings have, to date, been constructed based on precedence. A history of trial and error has defined their arrangement and form, such that the most successful have then gone on to become commonplace. Since the behaviour of timber members in shear and flexure can be relatively easily predicted using Codes of Practice, based on empirical evidence, it is the traditional joints in these frames that prohibit the determination of a frame's behaviour. These, in the majority of cases, are one of a variety of single or double pegged mortice and tenon joints. Although these joints are often simplified in analysis as pin-jointed connections they are in fact semi-rigid moment connections with tensile or 'pull-out' capacity. Knowledge of the moment-rotation and pullout behaviour of these joints is necessary for the development of frame design methods.

This technical note outlines the results of an initial investigation into a practical way of predicting frame behaviour under service loading, considering the effect of moment-rotation response of the mortice and tenon connections. Tests were carried out on 1:5 scale timber frames and joints, results from the latter were used in a computer analysis that successfully predicted the behaviour of the frames.

Joint testing and results

A series of 1:5 scale timber frames were fabricated using Scots Pine sections connected by single pegged mortice and tenon joints (using Scots Pine pegs) with 'draw-bore'. This is a process commonly used in traditional timber frames in which holes in the tenon and mortice are offset, pulling the two connected members together upon insertion of the peg, creating a tight fitting joint (see Fig 1 and Tables 1 & 2). The drawbore in a full-scale timber frame is typically 3mm. Since the joints were at 1:5 scale, obtaining a scaled drawbore was not practical. A drawbore of roughly 1mm was therefore used.

Five replicas of the joints in these frames were then constructed and tested to determine their rotational and pullout stiffness for use in the computer model (Fig 2).

To test rotational stiffness, four joints were subjected to relative opening and closing of their component members via the application of a gravity load acting perpendicular to

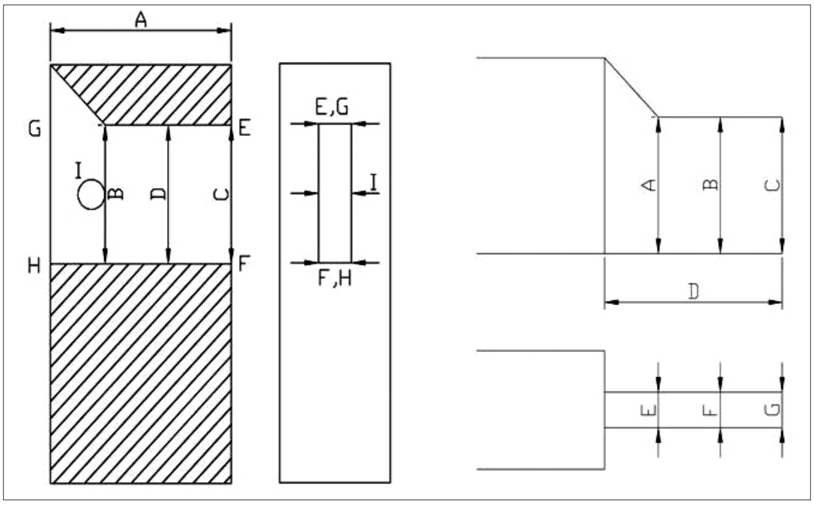

Fig 1. (left) Diagram showing section, elevation and plan of mortice and tenon members

Table 1: Test Connection Dimensions for Tenons corresponding to Fig 1

	Measurements (mm)						
Joints	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	22.74	22.56	22.28	34.06	5.81	5.81	5.65
2	22.71	22.62	22.63	33.89	5.70	5.74	5.82
3	22.91	22.89	22.81	33.82	5.86	5.83	5.82
4	22.81	22.63	22.29	34.25	5.42	5.62	5.60
5	22.89	22.85	22.76	33.89	5.73	5.69	5.69

Table 2: Test Connection Dimensions for Mortices corresponding to Fig 1

	Measurements (mm)								
Joints	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
1	32.69	24.24	23.15	23.02	6.80	6.46	6.14	6.39	6.18
2	32.98	22.91	22.92	22.78	7.00	7.00	6.51	6.31	6.69
3	33.03	23.04	23.68	23.10	7.38	6.71	6.11	6.16	6.02
4	32.78	22.42	22.89	22.90	6.11	6.50	6.84	6.27	6.59
5	32.94	23.18	23.30	23.09	6.84	6.55	6.41	6.76	6.92

Fig 2. (below) Joint test set up

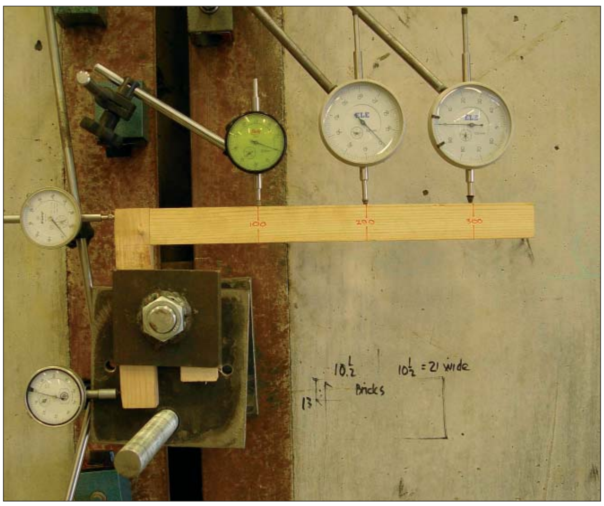

Table 3: Values of K1 and K2

Rotational Stiffness	K1 (kNm/rad)	K2 (kNm/rad)
Joint 1	0.375	0.125
Joint 2	0.42	0.09
Pull out Stiffness	**K1 (kN/m)**	**K2 (kN/m)**
Joint 3	1350	190

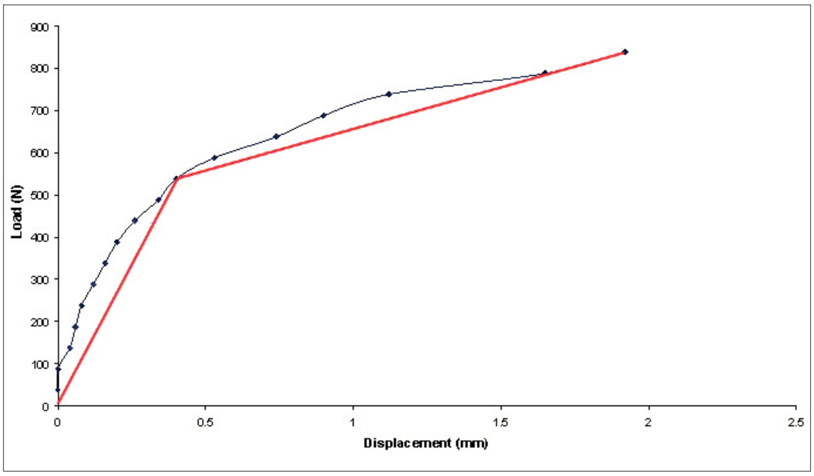

Fig 3. (right) Graph with bilinear approximation

the tenon member. The term 'opening' describes the relative rotation of the mortice and tenon members, resulting in the angle formed by them moving from a right angle to an obtuse one. 'Closing' describes the internal angle moving from a right angle to an acute one.

The fifth joint was subjected to a gravity load acting parallel to the tenon member through the centreline of the peg, loading the joint in 'pull-out', allowing its pull-out modulus to be determined.

It was considered that the shear stiffness of the joints (loading the tenon in bearing perpendicular to grain) would be much greater than that of bending or pull-out and would, therefore, have negligible contribution to the mode of frame deformation or failure. For this reason shear stiffness of the joints was not tested.

Results from joint tests revealed two distinct gradients for the moment-rotation and pull-out response. These were due to initial bearing of the joint components and their subsequent yielding.

Bilinear approximations

The rotational and pull-out stiffness of the joints were not linear elastic. A method of modelling connection response in a stiffness based structural analysis programme was required which is discussed below and shown in Fig 3. Two lines of best fit were applied to the moment rotation response that approximated the true gradients as linear, resulting in an overall bi-linear response.

These values for initial and subsequent stiffness, termed 'K1' and 'K2', (see Table 3) could then be entered into the computer programme.

Results for tests on joints 4 and 5 are not included here since these joints were used to establish that there was no discernable elastic limit in rotation or pullout.

Timber frame tests

The timber frames were fabricated with the same timber sections as the joints discussed. Nine transducers were positioned, three on each member (Fig 4) so that their deformed shapes could be seen in the test results.

Three frames were tested. Two were subject to a racking load and one to a gravity load applied to the midpoint of the 'beam' member with a hand operated hydraulic loading jack. Two of the frames were braced, as shown in Fig 4, and one was a simple portal frame. All frame supports were pinned. The transducers were connected to a computerised data acquisition system that logged load and displacement at one second intervals.

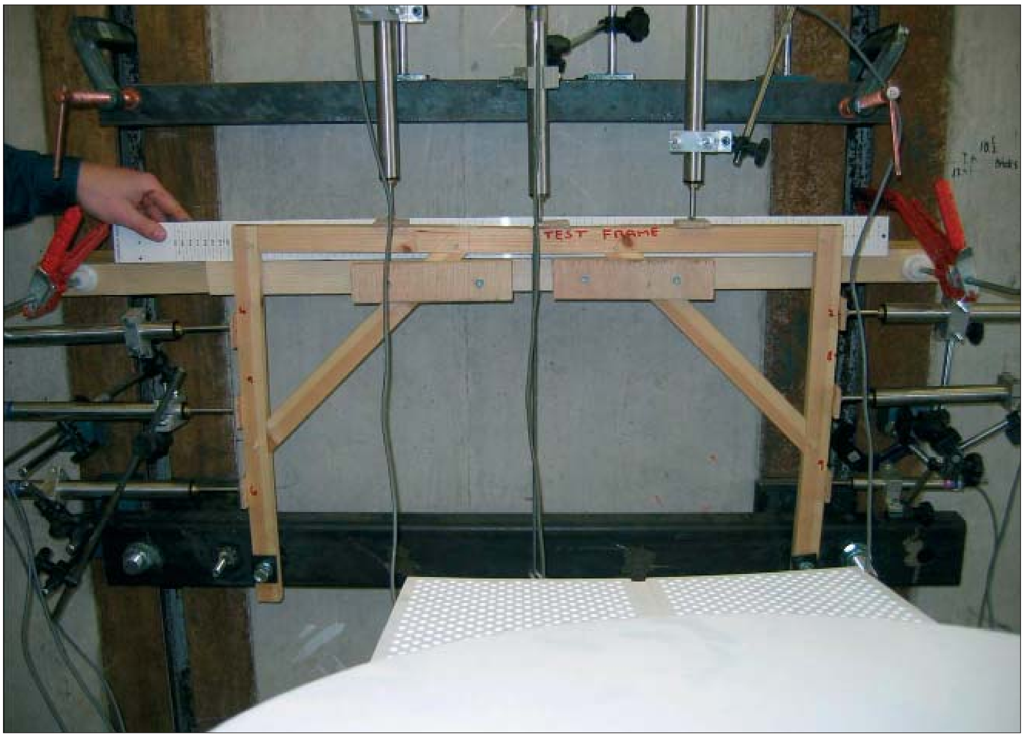

Fig 4. Test frame set-up

Timber frame results

There were nine displacement results for each frame, with the transducer closest to the loading point in each case measuring overall frame displacement,

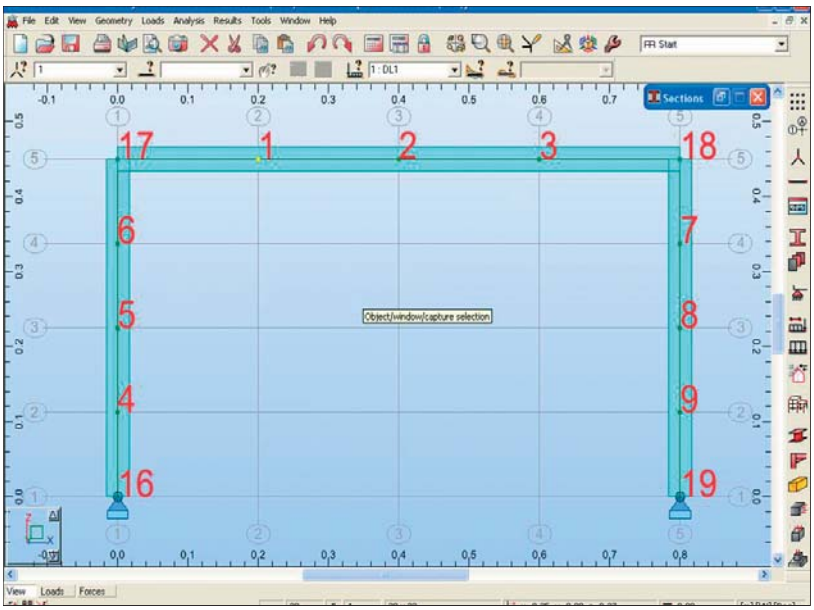

Fig 5. Computer model set-up

and hence stiffness. All the frames deformed in a predictable manner. In the case of the racking load applied to a knee braced frame, the joint of the brace that went into tension failed at a relatively early stage.

Computer model set up

Connection releases were defined in the stiffness based structural analysis software based upon connection modulus determined from tests (Fig 5). If the joints were released in the model's 'X' and 'Z' directions they were allowed to move horizontally and vertically respectively with a release about the 'Y' axis allowing rotation. The bilinear approximations for pull-out and rotation determined from the joint tests were entered for the releases at the corner joints.

However, due to the coordinate system used by the program a release cannot be defined along an inclined line. This meant that the pull-out resistance for the diagonal knee braces could not be directly defined. Hence the bilinear approximation for pullout stiffness had to be resolved into the 'X' and 'Z' directions and then entered into the program.

Model prediction results

The predictions made by the software model were compared by superimposing equivalent nodal load-displacement plots onto those of the frame tests (Figs 6,7, and 8)

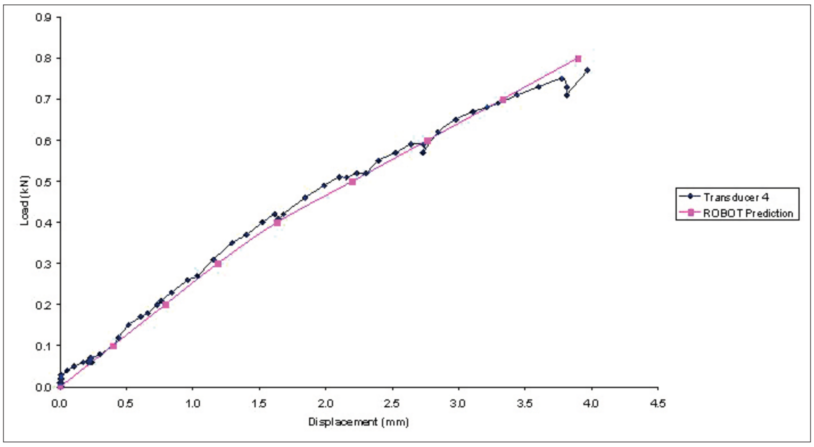

Fig 6. Prediction superimposed upon test frame result

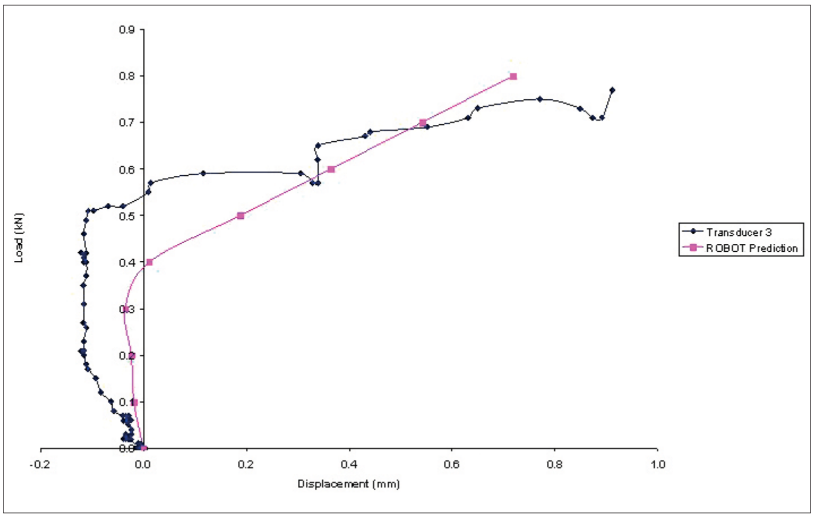

Fig 7. Prediction superimposed upon test frame result

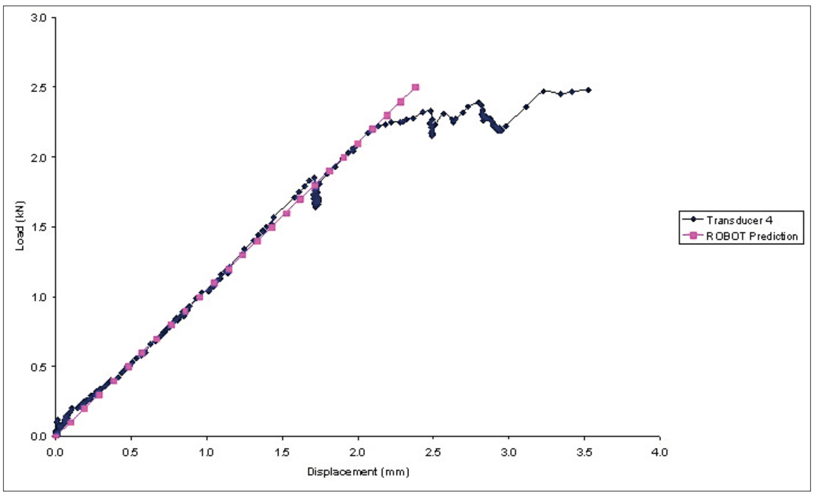

Fig 8. Prediction superimposed upon test frame result

Stiffness predictions made by the model are in good agreement with experimental results. However, in the case of the knee braced frame undergoing a vertical load, representing symmetrical live or dead load, predictions of the deformed post shape did not agree with the test results. The reason for this was that the model considered the upright to be a member with uniform, homogenous, cross-section where as the material removed for the knee braced connection mortice and peg hole violated this continuity. Since the section modulus of the member was locally lowered at the site of the connection, instead of the member taking on the parabolic shape predicted by the software, it actually deformed into a curve with increased curvature at the connection.

'Despite some inaccurate nodal predictions... all of the predictions of global stiffness were in good agreement at serviceability levels...'

Despite some inaccurate nodal predictions, like the above case which could be accounted for and corrected in the model, all of the predictions of global stiffness were in good agreement at serviceability levels (assumed to be 1/400 of the frame height).

Other work

Similar methods to those outlined herein have since been applied to full scale timber sub frames, by Shanks and Walker at the University of Bath, with very good correlation between theoretical prediction and test results. Unlike this body of work, Shanks and Walker took account of moisture content which affects the results to some extent. se

REFERENCES

1. Harris, R.: *Discovering timber-framed buildings*, Shire Publications, 1995
2. Brungraber, R.: 'Traditional timber joinery: A modern analysis', PhD Thesis, University of Stamford, 1985
3. Erikson, R., and Schmidt, R.: 'Laterally loaded timber frames', *Timber Framing*, Journal of Timber Framers Guild, North America, 62, pp 6-10, 2001.
4. Perry, S.: 'An investigation into mortise failure in traditional green oak carpentry', BEng Thesis, Department of Architecture & Civil Engineering, University of Bath, May 2004