HYSTERESIS LOOPS FOR TIMBER STRUCTURES

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ABSTRACT

This paper reviews experimentally determined hysteresis loops for timber structures, including moment-resisting joints with (i) steel and (ii) plywood side plates, (iii) shear walls clad with various materials, and (iv) push-pull tests on various connection details. The paper compares bending and push-pull hysteresis loops for nailed steel side-plate joints. An attempt is made to classify the above hysteretic behaviour for analytical purposes, and the available computer models are reviewed for applicability to these hysteresis shapes.

1. INTRODUCTION

This paper is one of a series of papers on the design of timber structures for wind and earthquake resistance, resulting from the work of a joint committee of the New Zealand Timber Design Society and the New Zealand National Society for Earthquake Engineering.

While of general interest to researchers and designers in the construction industry, this study had a specific purpose as the first stage in a series of studies for determining the SM product (S = Structural Type factor, M = Material Type factor) required for assessing the level of lateral seismic load using the provisions of the New Zealand Loadings Code.

2. EXPERIMENTALLY-DETERMINED HYSTERESIS LOOPS

2.1 Moment-Resisting Joints - Steel Side Plates

Section A of the references gives five sources of hysteresis loops for this situation, of which the first (Ref A1) is derived from A3 and A4. Hence the list reduces to four ultimate sources, of which two (A3, A4) concern the behaviour of single joints, and the other two (A2, A5) concern portal frame behaviour. These are discussed below.

2.1.1 Nail yielding joints

The two latter studies demonstrate similar frame behaviour under cyclic loads (ie similar loop shape) of the type shown in Fig 1 with moderate

pinching at a drift of $H/100$ (ie 1 percent). Because of the large influence of the elastic bending deformations of the timber members, the strength plateau is only reached at excessive deformations. Figure 2 shows the similarity of typical loop shapes from the two studies. The repeated slow cycling behaviour of single joints also showed similarity in loop shape.

Comparisons of individual loop shapes for single T joints and complete portal frames were made (Fig 2). The general similarity of shape exhibited may be expected because the timber member length per joint is roughly similar in all cases, ie the ratio of work done in the member to that done in the joint is similar in all cases.

The significant feature of the comparison between frame behaviour and joint behaviour is the fact that the high ductility of the yielding nails occurred at joint rotations implying excessive drift of the corresponding frames.

2.1.2 Yielding steel plate joint

The necked steel joint detail studied in Ref A4 was designed so that the steel plate yielded and not the nails. This ensured that the hysteretic behaviour of the joint followed the classical steel form of stable nearly elasto-plastic loops shown in Fig 3.

2.2 Moment-Resisting Joints - Plywood Side Plates

Section B of the references gives four sources of hysteresis loops for this situation, of which the first (Ref B1) concerns the behaviour of a complete portal frame, while the remainder examine single joints.

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Fig 1. LOAD DEFLECTION HYSTERESIS LOOPS FOR MOMENT-RESISTING JOINT WITH STEEL SIDE PLATES (REF A2)

Fig 2. COMPARISON OF LOAD-DEFLECTION HYSTERESIS LOOPS FOR MOMENT-RESISTING JOINTS WITH STEEL SIDE PLATES (REFS. A2 AND A4).

Fig 3. HYSTERESIS LOOPS FOR YIELDING STEEL PLATE JOINT (REF A4)

Fig 4. HYSTERESIS LOOPS FOR MOMENT-RESISTING JOINT WITH PLYWOOD SIDE PLATES (REF. B1)

Figure 4 shows the results of repeated slow cyclic loading tests from one of the studies, and typifies the general similarity of behaviour of the results of all four studies. While pinching is moderate in all tests, the single joint tests perhaps show less of this effect than does the portal frame. The reverse might normally be expected if the influence of timber bending deformations is less in the single joint tests, and suggests that the number of nails used may be excessive in the latter tests.

In contrast to the steel side plate specimen discussed above, flattening of the backbone curve is not displayed within the cycling load range, and the unloading curve tends to be close to parallel to the loading curve without any significant lengths of zero change in deflection, ie no fat loops have been reported. This may be because the nails bend in single curvature with plywood side plates and in double curvature with steel side plates, thus placing less ductility demand on the nails in the former case.

Also this thin loop behaviour of moment-resisting joints is in contrast to the push-pull behaviour of nailed plywood specimens (Refs D4, D7, D10) at modest nail deflection values, as shown in Fig 8.

2.3 Sheathed Walls - Various Materials

Section C of the references gives eight sources of hysteresis loops for timber sheathed walls, representing work by one Japanese, one American and three New Zealand organisations. The walls studies gained their shear resistance from:

- plywood cladding
- particle board cladding
- plasterboard cladding
- diagonal timber braces

A family of hysteresis curves from a repeated slow cyclic loading tests typical of the above research is given in Fig 5. As with moment-resisting joints, significant pinching of the loops occurs.

2.3.1 Plywood and particle board sheathed walls

Apart from the pinching effects, Fig 5 suggests useful energy absorbing behaviour as does the seminal work of Medearis (Ref C8). The significant difference between behaviour of the wall and that of moment-resisting frames is that nail ductility is utilised at much lower frame displacements. It can be seen that the load plateau is reached before or near permissible drift limits in all the cases shown.

Cyclic load tests (Ref C5) on walls in which plywood sheathing was glued to the framing using two non-elastomeric glues, ie Cascade 'K' glue and Selleys 'No More Nails' glue, found adequate strength but very thin hysteresis loops, behaviour being

essentially elastic up to failure, ie brittleness was exhibited.

2.3.2 Plasterboard sheathed walls

These walls tested in Japan (Ref C2) give similar style of loops to the ply and particle board walls, a result supported by small specimen tests carried out in New Zealand (Ref C3).

2.3.3 Sheathed walls with diagonal timber braces

The Japanese tests (Refs C1, C2) on this type of wall exhibited similar behaviour to the other shear walls. A point to note is the asymmetrical hysteretic behaviour caused by the use of a single diagonal bracing element. Unfortunately the above references give little detail of the test specimens used.

2.3.4 Typical loops

Figure 6 presents typical individual loops characteristic of interstorey drift of $H/100$ (1 percent), and the general similarity of shape may be observed.

2.4 Push-Pull Tests - Various Connection Details

Section D of the references gives ten sources of hysteresis loops for various connection details tested under push-pull cyclic loading. Some of these tests examined models of particular joints, some were to assess element behaviour, and some were intended to simulate the behaviour of elements of different geometry, eg shear walls.

Families of hysteresis curves from repeated slow cyclic loadings tests typical of the above research are given in Figs 7 and 8. These are for the following types of connection respectively:

- bolted timber strut
- nailed plywood side plates

The usual pinching of loops and the general similarity between Figs 7 and 8 may be readily seen.

2.5 Bending v Push-Pull Hysteresis Loops for Nailed Steel Side Plate Joints

Finally it is noted that the similarity between individual loops of the above types indicate why simple push-pull models give a good indication of the characteristics of other type element or action, as concluded elsewhere (Ref D4).

3.0 CLASSIFICATION AND COMPUTER MODELS OF JOINT HYSTERESIS

The evidence so far available gives broadly similar hysteretic behaviour for each element type. It thus is appropriate to classify and discuss the above material under the headings of

Fig 5. HYSTERESIS LOOPS FOR TIMBER FRAMED SHEAR WALLS

ALL LOOPS CHARACTERISTIC OF DRIFT = $H/100$

- - - REF C3 PARTICLE BOARD
- - - REF C4 PLYWOOD
- - - REF C4 PLYWOOD
- - - REF C6 PARTICLE BOARD

Fig 6. COMPARISON OF HYSTERESIS LOOPS FOR WALLS SHEATHED WITH DIFFERENT MATERIALS

Fig 7. HYSTERESIS LOOPS FOR BOLTED TIMBER STRUT CONNECTION UNDER PUSH-PULL LOADING (REF.D1).

Fig 8. HYSTERESIS LOOPS FOR JOINT WITH NAILED PLYWOOD SIDE PLATES UNDER PUSH-PULL LOADING (REF. D4).

the three items at which yielding occurs, ie

nails
nail-plates
bolts

3.1 Joints with Yielding Nails

As illustrated in Fig 9 there are three characteristic shapes of loop, dependent on the strain level and joint type. Figure 9(b) shows the familiar cigar shape with slight reverse curvature, which is common to all yielding nail elements at intermediate strain levels, and with moment-resisting frames it persists to very high strain levels because of the influence of the elastic bending deformations of the timber members. It is also noted that as usual the mean stiffness of the loop always decreases with increasing peak strain.

The loop in Fig 9(b) could be modelled with modest to fair accuracy by all of the five model shapes shown in Figs 10 and 11, which are discussed later.

The S-shaped loop for highly strained steel side plate joints (Fig 9c) could reasonably be modelled using any one of Figs 10(b), (c) (d) or Fig 11.

3.2 Joints with Yielding Nail Plates

The hysteresic behaviour for necked steel side plate joints (Fig 3) would be most accurately modelled by the familiar Ramberg-Osgood formulation (Fig 12(a)), although a bi-linear model could also be reasonably accurate.

3.3 Joints with Yielding Bolts

The bolt hysteresic behaviour for push-pull action shown in Fig 7 is simply

Fig 9. JOINTS WITH YIELDING NAILS

Fig 10. SIMPLIFIED HYSTERETIC MODELS FOR COMPUTER ANALYSIS

Fig 11. PINCHING HYSTERESIS MODEL (REF. M2)

Fig 12. FURTHER HYSTERESIS MODELS

modelled in Fig 12(b) or more systematically modelled using the same basic shape in Fig 11.

3.4 Computer Modelling

For the non-linear response-history analyses proposed for a subsequent study, two computer programs which are commercially available in New Zealand could be used, namely RUAUMOKO (University of Canterbury) and DRAIN-2D, and hysteresis models already mounted on these programs would therefore obviously be preferred unless they were technically unsatisfactory.

RUAUMOKO currently has models from Figs 10(b) and 12(a) available. Fig 10(b) comes from Kivell et al.

(Ref M1) while Fig 12(a) comes from current research by Stewart (Ref M2).

DRAIN-2D has Fig 10(c) and 12(a) currently available, but implementing further models is a major undertaking. Fig 10(c) is a recent addition to DRAIN-2D formulated by Thorn (Ref M3).

As Figures 10(b) and/or 11 are perhaps the most appropriate for modelling all but the necked steel plate joint, RUAUMOKO would appear to be the better of the two programs, at least for hysteretic modelling purposes, for the proposed analytical studies.

4. CONCLUSIONS

(1) The hysteresis loops for nail yielding connections in timber structures

may be classified into three shapes which develop from each other with change in strain level.

(2) The hysteretic loops for bolted connections have a form similar to, but simpler than, the high strain loops for nail yielding steel side-plate joints.

(3) Yielding steel side plate joints in bending have the hysteretic behaviour of stable steelwork beam members.

(4) The loop shapes considered to be typical of the experimental results can be modelled for dynamic analysis reasonably accurately by currently available computer models.

(5) Of the two programs considered, RUAUMOKO appears to have better loop models than DRAIN-2D, for the shapes required.

(6) All of the hysteresis loops so far produced have been derived from slow or relatively slow cyclic loading. Verification of results to data by real earthquake frequency loadings (Shake-table tests) is desirable.

(7) As the New Zealand earthquake code permits 2 percent interstorey drift under the design earthquake real loadings, hysteretic loops for up to that level of deformation may be considered in subsequent studies.

(8) Glued sheathed wall construction (using non-elastomeric glues) will behave in a brittle fashion, unless holding down connections are designed to yield first.

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