The behaviour of hollow section connections under seismic loading

Sarah Hall writes, in conjunction with her supervisor Dr John Owen, about her undergraduate project at Nottingham University which won first prize in the 2003 Model Analysis Award

Steel structures are extensively used in regions of high seismic risk because it is assumed that their strength and ductility allows them to dissipate energy through hysteresis, thus reducing their response. However, the Northridge earthquake of 17 January 1994 exposed weaknesses in steel structures and prompted research into the behaviour of steel connections under seismic loading. That research has principally considered moment resisting frames and little work has been done on connections in tubular trusses, which are widely used offshore and in architecturally adventurous structures onshore.

The aim of this project was to investigate the seismic performance of square hollow section connections[1] and compare traditional X-joints with bird-beak joints, a novel joint configuration in which the chord and brace are rotated through 45°.

Table 1: Joint details

Joint No	T1	T2	BB1	BB2	BB1A
Chord	150×150×6.3	150×150×6.3	150×150×6.3	150×150×6.3	150×150×6.3
Braces	100×100×6.3	120×120×8.0	100×100×6.3	120×120×8.0	100×100×6.3
Welds	10mm fillet	10mm fillet	10mm fillet	10mm fillet	10mm fillet
Chord type	Hot rolled	Hot rolled	Cold rolled	Cold rolled	Hot rolled
Chord length	814mm	814mm	1010mm	1012mm	1000mm

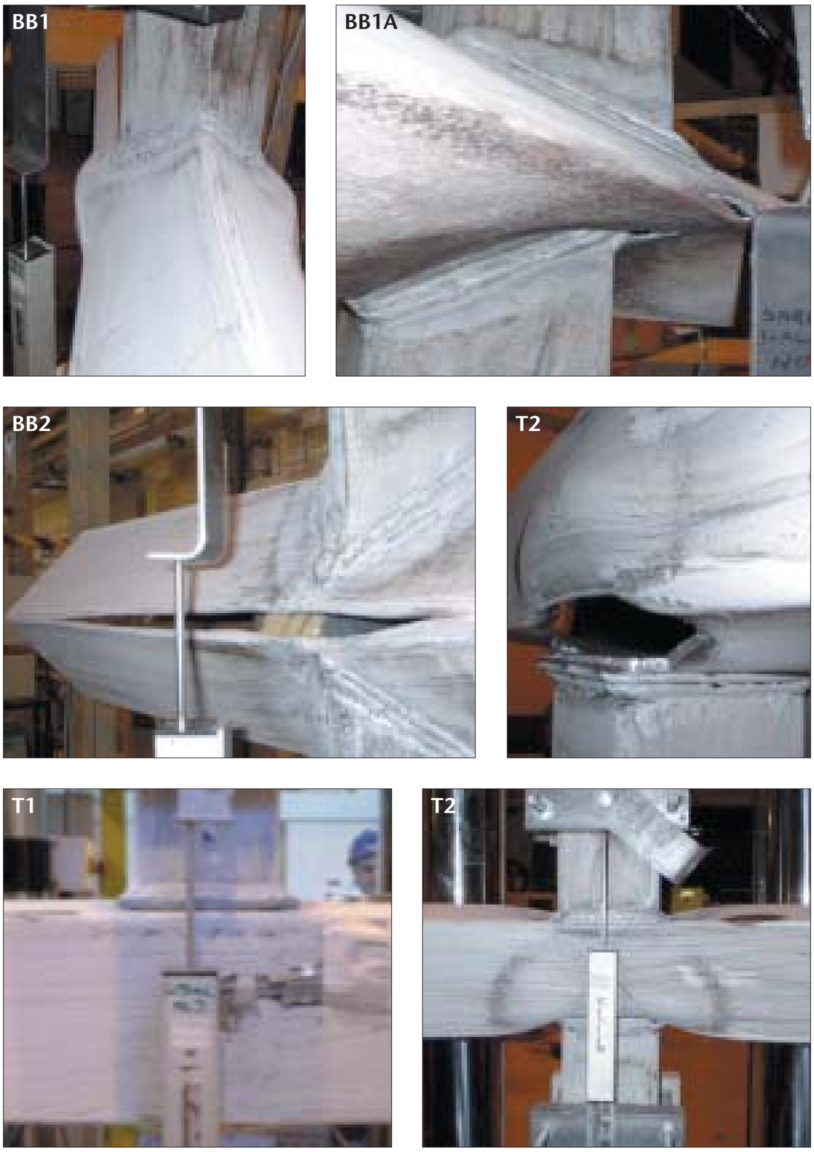

Fig 1. Observations during test

Testing methodology

Since the 1960s it has been generally accepted that the seismic performance of a structure depends principally on its inelastic cyclic response. Five RHS X-joints (Table 1) were manufactured and subjected to quasi-static inelastic cyclic loading under displacement control based on the SAC protocol[2] (Table 2). Each joint was white-washed so the formation of Lüder's lines could be observed and the lozenging of the chord and the indentation of the braces measured with potentiometers.

Observations and results

Observations. In all the joints, local failure occurred before significant plastic deformation of the chord was observed. In the traditional joints the braces punched into the upper face of the chord and cracks formed adjacent to the weld on diagonally opposite sides of the chord. These propagated along the length of the weld and the chord deformed causing the sidewalls to buckle. In the bird-beak joints local failure consisted of lozenging of the chord and fracture along the chord corners. The corners of the braces punched into the chord at diagonally opposite corners causing a misalignment of the braces (Fig 1).

Seismic performance indicators. Soh *et al* (2001) describe several indicators that can be used to assess the seismic

Table 2: Loading details

Multiple of Δ_0	1	2	3	4	6	8	12	16	20	SUM
Amplitude (mm)	2	4	6	8	12	16	24	32	40	
No of cycles	6	6	6	4	2	2	2	2	2	32
Load rate (mm/min)	2	2	4	4	4	4	6	6	6	

Table 3: Comparison of ductility ratios at first fracture for cyclic & monotonic tests

	m–monotonic	m–cyclic	m–ratio
T1	189.0	2.2	1.16
T2	189.0	3.2	1.69
BB1	38.5	2.5	6.49
BB2	38.5	1.4	3.64
BB1A	81.4	5.5	6.76

performance of structures. To calculate these, the displacement and load at first yield were determined for each joint using the method recommended by the European Convention for Constructional Steelwork[3].

Ductility ratio, μ, is defined as the ratio between displacement at a given load, δ, and the first yield displacement, δ_y:

$$\mu = \frac{\delta}{\delta_y} \qquad ...(1)$$

Strength resistance ratio, ω, is defined as the ratio between the load at the unloading point in the i^{th} cycle, P_i, and the load at first yield, P_y:

$$\omega = \frac{P_i}{P_y} \qquad ...(2)$$

Strength resistance ratios were calculated at each cycle for both tension, ω^+ and compression, ω^-. Some anomalies were noticed, but in general the joints initially had a higher strength resistance ratio in tension than compression, $\omega^+ > \omega^-$ until cracks form. The strength resistance ratio fell when significant yielding took place or when cracks formed and, after this, $\omega^- > \omega^+$ because the propagation of the cracks reduced the resistance in tension. For the traditional joints, deterioration occurred very rapidly once initial fractures had formed. The bird-beak joints maintained a more consistent ω despite fracture.

The ductility and strength resistance ratios can be used to plot normalised load-displacement curves (Fig 2). These curves show strong hysteresis indicating that energy is being dissipated. The amount of energy dissipated in each joint can be compared using the area within these curves, but a more quantitative measure is the energy dissipation ratio[4].

Energy dissipation ratio, η_a, is defined as:

$$\eta_a = \sum_{i=1}^{N_c}\left(E_i^+ + E_i^-\right)/E_y \qquad ...(3)$$

where E_i^+ and E_i^- are the energy dissipated in the i^{th} tension and compression half-cycles and E_y is the energy absorbed at first yield.

Both Fig 2 and a plot of energy dissipation ratio against ductility ratio (Fig 3) show that BB1A and BB1 dissipate more energy than T1. This suggests that bird-beak joints perform better than traditional joints under seismic loading. The hysteresis curves for the traditional joints are a very different shape to those for the bird-beak joints – indicating the loss of strength in the compression half-cycle when the braces are punching into the chord wall. The results also show that T2 dissipates more energy than BB2, which could be an effect of the higher β ratio or the cold formed chord in BB2; further investigations are needed.

Hot and cold rolling. From Figs 2 and 3, it can be seen that BB1A (hot rolled) dissipates more energy than BB1 and BB2 (cold-rolled). Compared with BB1, BB1A also has a higher ductility ratio and carries a much greater load at first fracture (Table 3), and has higher peak loads in both tension and compression. This illustrates the influence of cold forming on the behaviour of the joint, where residual stresses and strain hardening may mean that less load is needed to cause cracking in the chord corners and the ductility is reduced.

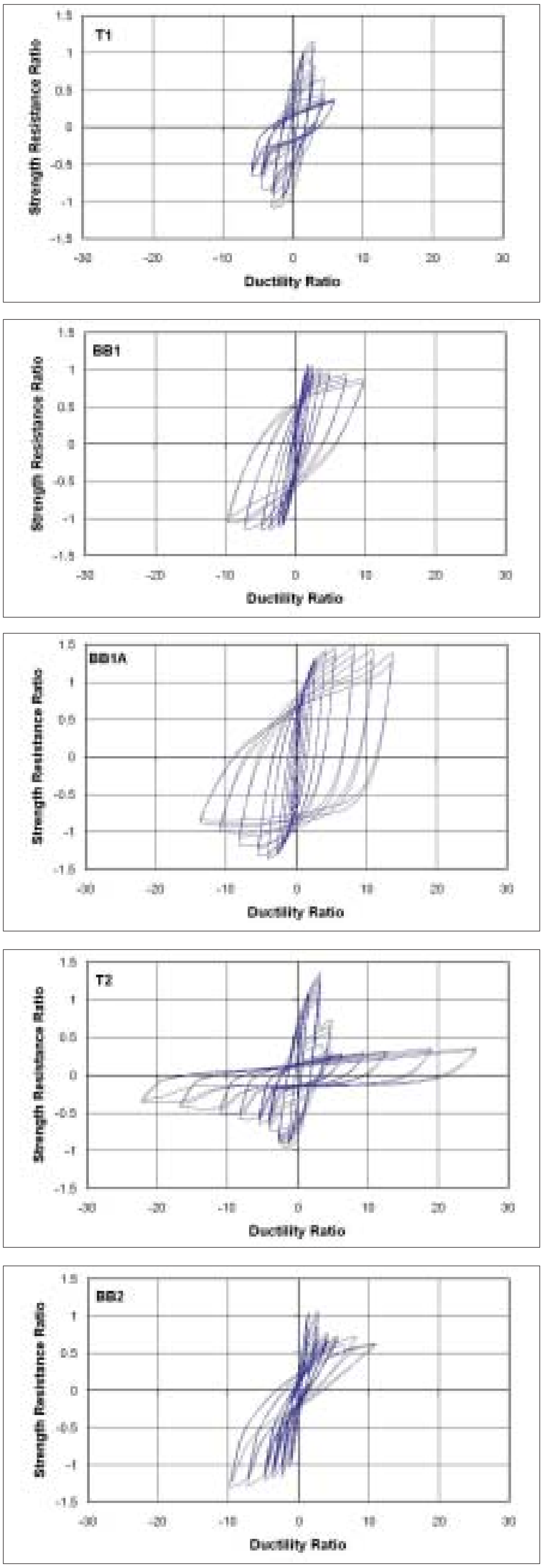

Fig 2. Normalised hysteresis curves

Finite element modelling

To draw more general conclusions about the behaviour of traditional and bird-beak joints under seismic loading, a finite element parametric study was planned. However, this requires material properties to be known. Table 3 shows a comparison of the ductility ratios at first fracture from the static coupon tests and the cyclic joint tests. The results suggest that the steel behaves differently under cyclic and monotonic loading and it would, therefore, not be suitable to use the material properties obtained from a monotonically loaded coupon test to calibrate a finite element model for modelling cyclic loading. The material properties under cyclic loading must be investigated further in order to calibrate the model appropriately, possibly using a cyclical coupon test.

Metallurgical investigation

In each of the specimens, fracture occurred close to the welds at lower strains and ductility than expected from coupon tests. To determine whether this was caused by the heat affected zone (HAZ) or was due to the cyclic loading, further metallurgical studies were carried out. Specimens were selected from the fracture surfaces and their microstructure studied using a metallurgical microscope and a scanning electron microscope (SEM). There are essentially two modes of fracture – ductile and brittle. A ductile fracture shows a rough, irregular, dull, dimpled surface due to the cup-and-cone nature of the fracture on both a macroscopic and microscopic scale. A brittle fracture exhibits a mass of minute facets, which reflect light and reveal the crystalline nature of the material.

The fractured end of the coupon from BB1A revealed perfectly ductile behaviour when studied under the SEM. The failure surfaces of the test joints did not always clearly resemble standard ductile or brittle surfaces, rather the characteristics of each could be recognised. In particular, some brittle sections were observed in T2, BB2 and BB1A although wear of the surfaces, due to the later load cycles did affect the surface features. The results suggest that failure could have been caused by ductile crack initiation, which in some cases may have resulted in a final brittle fracture. As all of the joints exhibited predominantly ductile behaviour it is unlikely that the premature fracture was due to the HAZ.

Conclusions

This investigation has shown the differences in behaviour between the traditional and bird-beak joints when tested under inelastic cyclic loading. The bird-beak joints generally showed better performance than the traditional joints as they:

- dissipated more energy,
- maintained their strength after fracture,
- had greater first yield displacements.

The main exception to these general conclusions was BB2 as its dimensions may have affected its behaviour and it demonstrated a different failure to the other bird-beak joints.

It has been seen that hot and cold rolling have a significant effect on the performance of the joints. When compared with a cold rolled joint, a hot rolled joint:

- dissipated more energy,
- had a higher ductility ratio and strength resistance ratio,
- had higher peak loads in tension and compression, as well as a higher load at fracture.

The metallurgical investigation has clearly indicated a predominantly ductile fracture in all the joints. Concern would have arisen if the fractures had a more brittle appearance as brittle crack growth is unstable once it starts and the component fractures catastrophically. The results from the metallurgical investigation have suggested that the fractures were caused by ductile crack initiation due to low cycle fatigue although the crack propagation has, in some cases, resulted in a final brittle fracture.

It must, however, be noted that all conclusions here are based on one full-scale test of each joint configuration. The results have shown that cyclic material models need to be developed for use in finite element modelling of inelastic cyclic behaviour. Once this has been done, the FE model could be used for further investigation in order to draw more general conclusions.

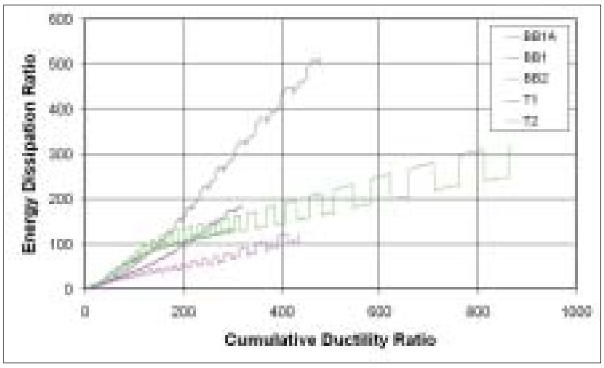

Fig 3. Energy dissipation ratio against cumulative ductility ratio for each joint

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The Model Analysis Award is an annual competition for experimental projects carried out by final year undergraduates and first year postgraduates. The competition is organised by the Institution's Study Group on Model Analysis as a Design Tool and is launched in March each year. se

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