EXPERIMENTAL STUDY ON FLEXIBLE END PLATE CONNECTIONS IN FIRE

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INTRODUCTION

Over the last decade research has shown that steel and steel-composite structures can have a significantly greater fire resistance than is suggested by conventional tests on isolated components. Burgess [1] explains that this is largely due to the interaction between the beams and floor slabs in the fire compartment, and the restraint afforded by the surrounding structure. In the design of real projects, it is implicitly assumed that the connections have sufficient fire resistance because they are heated more slowly than the connecting members in fire situations. However, the evidence from the collapse of the WTC buildings suggests that the progressive collapse may have been triggered by the failure of steel connections [2], [3]. From full-scale fire tests, it has been found that steel connections may be the weakest components in fire conditions [4]. In research on the performance of large substructures in fire, non-linear three- dimensional analysis shows that the axial forces generated in beams are seen to reach very high values [5]. Typically theses forces can vary from compression in the early stages of a fire, when thermal expansion is restrained by the surrounding structure, to tension in the later stages due to the heated members hanging essentially in catenary. Consequently, the connections at the ends of these members are subjected in turn to these axial forces whilst also undergoing large rotations.

In 1987 a joint SCI/BCSA connection group was established to produce a series of publications which would standardise detailed design methods for commonly used steel connections. Owens and Moore [6] carried out a series of tests to investigate the ability of simple steel connections to resist tying forces, as specified in UK design codes to ensure a minimum level of robustness and prevent progressive collapse. The test programme comprised 11 tests for web cleat steel connections and 10 tests for flexible endplate beam-to-column connections. It was found that conventional steel connections have inherent robustness and may provide tensile ties to resist progressive collapse. It should be noted that Owens and Moore tested tying forces applied to simple steel connections as horizontal tie effects, as indicated by UK codes. But in a fire situation the tying force is most likely to be inclined due to the connections experiencing large rotations/deformations. Hence, the connection will be subjected to both horizontal and vertical force components. Furthermore, the strength of steel connections exposed to a fire will result in a reduction of resistance, thus an understanding of the tying resistance of simple steel connections in fire is essential in the investigation of robustness of steel structures.

The research group at the University of Sheffield developed a series of tests for steel connections, including three commonly used simple connections and one moment connection. This paper reports on the experiments conducted on flexible end plate connections and details of the other connections may be found in Yu *et al.* [7].

1 TEST PROGRAM

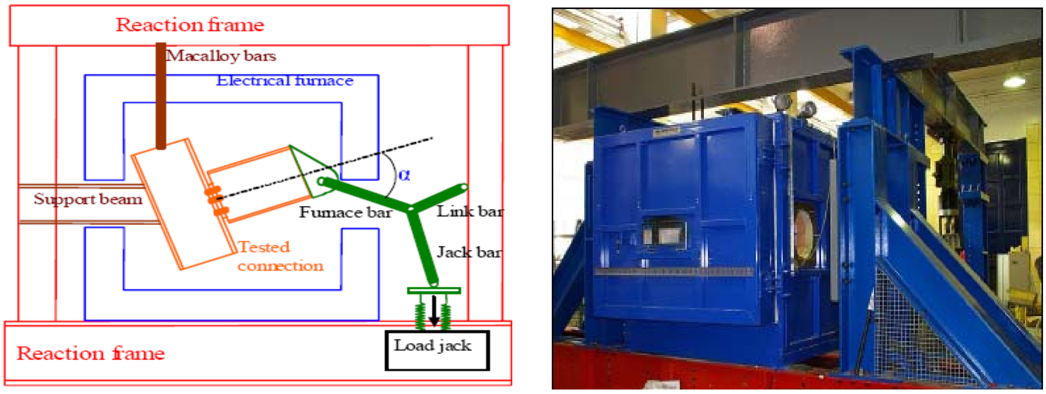
In this connection programme, twelve tests were separated into three classes according to initial loading angles (α): 35^o, 45^o and 55^o, which implicitly defined the horizontal and vertical components of tying forces applied to these connections. As a result of the loading mechanism, the angle of inclination of the applied tensile force varied during the test. The magnitude and angle of the force were monitored and recorded throughout the experiments. Flexible end plate (Fep) connections were tested at both ambient and elevated temperatures. The test schedule, test numbers and temperatures are as shown in *Table 1.*

Table 1. Test schedule

Temps \ Initial α	35°	45°	55°
20°C	Fep35-20	Fep45-20	Fep55-20
450 °C	Fep35-450	Fep45-450	Fep55-450
550 °C	Fep35-550	Fep45-550	Fep55-550
650 °C	Fep35-650	Fep45-650	Fep55-650

1.1 Test Arrangement and Instrumentation

Connection tests were performed in an electric furnace with the experimental set-up illustrated in *Fig. 1*. *Fig. 1(a)* shows a connection in the furnace and the load applied though three linked ϕ26.5 mm Macalloy bars. *Fig. 1(b)* is a photo of the electric furnace; note the small rectangular glass viewing panel in the door and the large circular hole through which the furnace bar was positioned.



(a) (b)

Fig. 1. (a) Experimental set up & (b) Electric furnace

The essential requirement in this test program was to obtain the resistances of steel connections against tying force at both normal and high temperatures. Measurement of the forces was achieved by using strain gauges on the loading system (three Macalloy bars: furnace bar, link bar and jack bar) at ambient temperatures. At high temperatures, the strain gauges close to or inside the furnace would be damaged. So in order to obtain the force in the furnace bar, strain gauges were fixed to the link and jack bars and the applied force was then calculated by resolving the system of forces. Any changes in inclination of the bars were recorded using three angular transducers.

To avoid the problems associated with cooling instrumentation in a furnace, Spyrou and Davison [8] developed an image-acquisition technique to measure the displacements and rotations for testing specimens at high temperatures. This approach was adopted and included image acquisition and processing software, and targets made of ceramic rods, embedded into the specimens before testing. A digital camera was fixed on the main door of the furnace to record the movements of the specimen through a 200 mm x100 mm viewpoint. The recorded photos were processed by software to obtain the rotations and displacements of the steel connection.

1.2 Fabrication and Assembly

Steel sections (beams and columns) were supplied by Corus and fabricated by Billington Structures Ltd. The holes in the end plates were punched according to current UK practice. Normal engineering procedures and standard tolerances were adopted during fabrication and no special effort was taken. All the specimens were assembled in the test rig and standard grade 8.8 M20 bolts were used for all tests.

1.3 Specimen Details

In this series of connection tests, a 254UC89 was used for the column and a 305x165UB40 for the beam. The thickness for the end plate was 10 mm and all the bolts were used in 22 mm clearance holes. The steel used was nominally S275 for universal beams and the column was S355. The design details and sizes of the specimens have been included in *Fig. 2.* and the numbers of ①-⑥ show the location of thermocouples used in testing. α is the initial or ending angle of external loading.

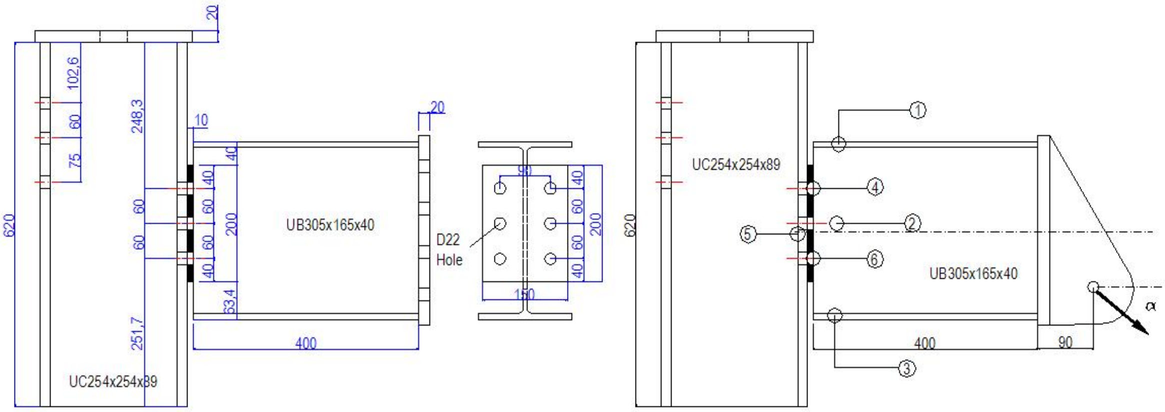


Fig. 2. Design details for flexible end plates

2 EXPERIMENTAL OBSERVATIONS

2.1 Failure Modes of Endplate Connections

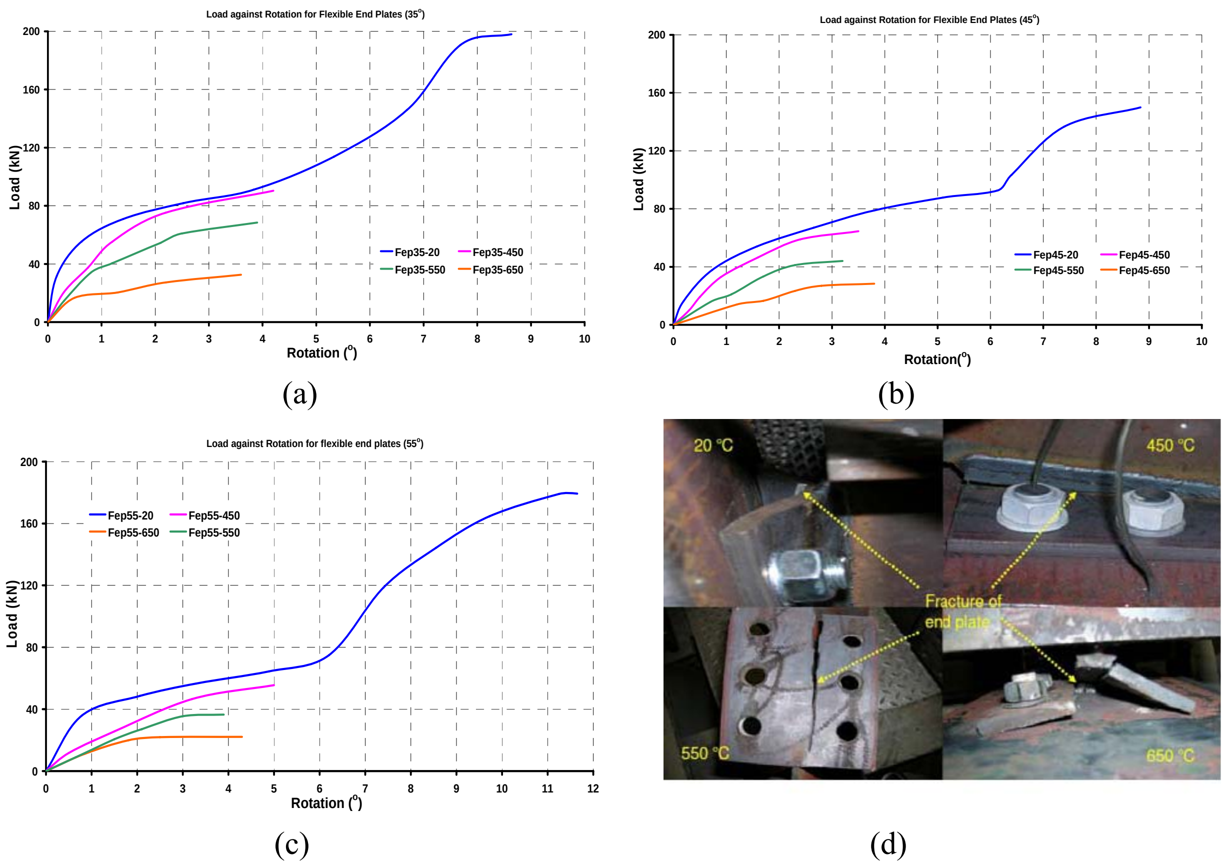


Fig. 3. Test results for flexible endplate connections (a) 35° (b) 45° (c) 55° (d) modes of failure

In the series of flexible endplate tests performed by Owens and Moore [6], two different modes of failure were reported: (a) bearing failure of the endplate and (b) fracture of the endplate close to the toe of the weld. The partial depth endplate experiments showed only one mode of failure at both ambient and elevated temperatures: fracture of the endplate close to the toe of the weld, shown in *Fig. 3* (d), which is very similar to the aforementioned finding by Owens and Moore [6].

2.2 Test Results

The experimental results for twelve connection tests have been summarised in *Table 2.* including testing temperatures, failure loads, rotations for each endplate connection and the variation of α for applied loads. As this research project is concerned with the ductility and resistance of simple connections, plots of variation of load-rotation characteristics are shown in *Fig.3* (a) (b) (c). The connections tested at both ambient and elevated temperatures demonstrated a non-linear response. It is clearly observed that the resistance and ductility (as measured by rotation capacity) of steel connections are both decreased at high temperatures. The reduced rotation capacity of simple connections at high temperatures is due to the rupture of the end plates occurring before the beam flange contacts with the column flange, which occurs at ambient temperatures as evidenced by the kink in the curve at about 6^o rotation.

Table 2. Summary of test results for flexible endplate connections

Test no.	Ending α (degree)	Connection rotation (degree)	Contact with column before failure	Max failure load (kN)	Tying capacity estimated by using EC3 (kN)		Minimum tying force (kN)
					$k_{y,\theta}$	$k_{p,\theta}$	
Fep35 - 20	43.49	8.6	yes	192	254.13	254.13	75
Fep35-450	38.71	4.2	no	90.36	226.18	99.11	75
Fep35-550	40.17	3.9	no	68.51	158.83	68.62	75
Fep35-650	39.62	3.6	no	32.55	88.95	33.04	75
Fep45 - 20	51.08	8.8	yes	150	254.13	254.13	75
Fep45-450	48.56	3.5	no	64.5	226.18	99.11	75
Fep45-550	47.86	3.2	no	44.1	158.83	68.62	75
Fep45-650	48.59	3.8	no	28.45	88.95	33.04	75
Fep55 - 20	56.10	11.2	yes	179.3	254.13	254.13	75
Fep55-450	55.90	4.8	no	55.56	226.18	99.11	75
Fep55-550	55.51	3.9	no	36.31	158.83	68.62	75
Fep55-650	55.67	4.5	no	22.09	88.95	33.04	75

3 ROBUSTNESS OF FLEXIBLE ENDPLATE CONNECTIONS

Robustness is the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause [9]. The partial collapse of Ronan Point in 1968 arose from a lack of positive attachment between structural elements; thereafter a minimum robustness to resist accidental loading was specified for designing structures in the UK. However, recent research [10] recognises factors such as (a) energy absorption capacity, (b) ductility and (c) redundancy (or alternate load paths), also need to be taken into account carefully, as indicators of structural robustness.

Two main approaches have now been recommended for structural robustness. The first strategy is tying a steel frame horizontally and vertically to increase its structural continuity and create a structure with a high level of robustness, named as *tying force approach*. Byfield and Paramasivam [11] note that the provision of horizontal and vertical tying provides a good level of robustness to buildings, particularly at resisting gas explosions. The other strategy is the so-called *alternate load path method*. In this approach, if part of a structure has been removed by an accidental action, the remaining members are still well connected to develop an alternative load path which transfers the load of the collapsed members to the surrounding stiffer members.

In the *tying force approach*, the *tying force* is the action which is generated within steel beams and passed on to steel connections. It is acknowledged that the tying forces are applied in a structure in both horizontal and vertical directions to help to achieve a good level of robustness. In a fire situation, utilization of catenary action is able to enhance the fire resistance of structural steel beams, if sufficient strength and ductility are assured in the design of key elements such as beams and connections [5],[7]. *Fig.4* shows the catenary action; the beam acts as a cable hanging from the surrounding cold structure, observed in experimental tests, performed by Allam *et al.* [5]. In the figure, note the large rotation and deflection at the connection zone and steel beam respectively. The tensile force generated within the beam is inclined to the horizontal direction, and this *inclined tying force*, is representative of the forces arising due to catenary actions.

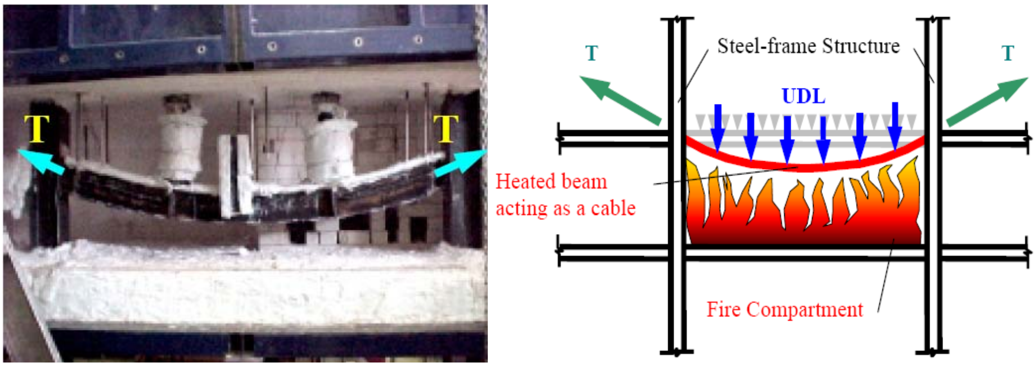


Fig.4. Tying force in catenary action

Tying resistance (or tying capacity) is the ability of steel connections to resist a horizontal force determined in accordance with an industry standard design manual [13]. *Table 2* summarises the resistance of each endplate connection when it failed, which is to be compared with the tying resistance anticipated by using Eurocodes. Obviously, the maximum capacities of these connections reduced very fast in the temperature range of 450 ^{o}C and 650 ^{o}C. In comparison with the minimum tying force in *Table 2*, the endplate connections might not provide sufficient connection resistance to satisfy the minimum robustness requirement at elevated temperatures; but an inherent robustness against progressive collapse can be assured at ambient temperatures.

The tying capacities determined by using the Eurocodes are likely to overestimate the connection resistances to tying forces at both ambient and elevated temperatures. The factors of $k_{y,\theta}$ and $k_{p,\theta}$ were introduced in estimation of tying capacities at elevated temperatures in *Table2*: $k_{y,\theta}$ standing for the reduction factors for effective yield strength and $k_{p,\theta}$ representing the factors for proportional limit. In *Table 2*, it is obvious that the tying capacities, calculated by using $k_{y,\theta}$ reduction factors, are higher than the connection resistances obtained in experiments, probably because the calculation of tying capacity in accordance with Eurocodes assumes zero beam rotation in the connection zone.

A post-September 11th report [12] states that it is insufficient merely to tie structural elements together and tying alone does not inherently provide a ductile structure or one with good energy absorption capability. Robustness may be achieved through the use of a structure that can absorb energy and structural elements such as connections are of particular importance.

The rotation capacity of an endplate connection is mainly produced by deformation in the plates, flanges and bolts. Note that 4^{o} as a maximum rotation in the joints was adopted in the analysis of catenary action by Byfield and Paramasivam [11]. It is obvious that the rotation capacities of these connections are reduced at elevated temperatures due to rupture of the end plates before the beam flange contacts with the column flange in the connection zone, whereas the endplate connections have already been found to be more ductile at ambient temperatures owing to the rupture occurring after contact with the column flange. In comparison with the maximum rotation, the connections tested at high temperatures might not satisfy this requirement for ductility. Moreover, it should be noted that the connections in catenary action are required to be much more ductile in rotating in comparison with the aforementioned maximum rotation from the experiments. As a result, the endplate connections can not be relied upon to have sufficient ductility, energy absorption or robustness for steel structures in a fire situation.

4 CONCLUSIONS AND ACKNOWLEDGMENT

The tying force approach, recommended by the Building Regulations, is a popular low-cost means to address concerns about structural integrity and resistance to progressive collapse. The tying capacity of connections is generally determined in the absence of beam rotations, by using an industry standard design manual. In a real structure, the inclined tying force may be produced within a steel beam owing to catenary action formed in a fire situation. As a result, the tying capacities estimated by using the EC3 are likely to overestimate the real resistances of connections. The review of experimental results indicates that the minimum tying resistance of 75 kN might not be assured for flexible end plate connections in a fire situation. As the rotation capacity of endplate connections is reduced as increasing temperatures, the connections may not possess the extensive ductility required for catenary action and may rupture before catenary action is fully developed. In consequence, specifying partial depth endplate connections seems inadvisable for robustness of steel structures where large connection rotations are anticipated.

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