Methods of improving the survival temperature in fire of steel beam connected to CFT column using reverse channel connection

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A R T I C L E   I N F O

Article history:
Received 9 May 2011
Revised 2 August 2011
Accepted 1 September 2011
Available online 4 November 2011

Keywords:
Connection
Joint
Fire resistance
Catenary action
Numerical modelling
Concrete filled tubes
Reverse channel connection
Fire-resistant (FR) steel
Fire protection
Joint detailing

A B S T R A C T

This paper presents the results of a numerical study, using ABAQUS, of the behaviour and methods of improving the survival temperatures in fire of steel beams to concrete filled tubular (CFT) columns using reverse channel connection. The beams are axially restrained by the connected columns and develop catenary action so their survival temperatures are primarily controlled by the joint tensile resistance and deformation capacity. Therefore, improving the beam survival temperature mainly relies on improving the joint performance. This study investigates five different joint types of reverse channel connection: extended endplate, flush endplate, flexible endplate, hybrid flush/flexible endplate and hybrid extended/flexible endplate. The connection details investigated include reverse channel web thickness, bolt diameter and grade, using fire-resistant (FR) steel for different joint components (reverse channel, end plate and bolts) and joint temperature control. The effects of changing the applied beam and column loads are also considered. It is concluded that by adopting some of the joint details to improve the joint tensile strength and deformation capacity, it is possible for the beams to develop substantial catenary action to survive very high temperatures. However, it is important that the additional catenary force in the beam is resisted by the connected columns.

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1. Introduction

Concrete filled tubular (CFT) columns have a number of advantages including attractive appearance, high structural load carrying capacity and high fire resistance. However, the use of CFT columns has to overcome the problem of making connections due to difficult access from within the steel tube. As a result, the reverse channel connection has been developed. In this method, the two legs of a channel are welded to the tubular column face and the channel web is connected to a conventional endplate on the beam side. Fig. 1 shows a sketch of reverse channel connection. Detailed studies of reverse channel connection performance in fire were first reported by Ding and Wang [1] who carried out fire tests and reported that using reverse channel connection could allow the beam to develop substantial fire resistance. The authors [2] undertook detailed numerical simulations of the fire tests by Ding and Wang to validate their numerical simulation model. The validated numerical model is used to conduct the parametric studies reported in this paper.

Although making use of joint bending moment resistance can enhance fire resistance of the connected beam under bending, the emphasis of this paper is on the development of catenary action in the steel beam under fire attack. As a response to the collapse of the World Trade Center buildings on September 11, 2001, developing methods of controlling fire-induced progressive structural failure is now one of the most important aspects of the structural fire engineering research agenda and catenary action has now been identified as a feasible method [3].

Catenary action in a beam occurs when the beam's temperature is above its conventional limiting temperature, which refers to the temperature at which the beam's bending resistance is reached [4]. Catenary action has been investigated by a number of researchers, including Yin and Wang [5–7], Guo and Li [8], Yu [9]. The results of numerical studies by Yin and Wang [5–7] suggest that if the joints have sufficient tensile resistance and rotational capacity, the connected steel beam can survive very high temperatures without failure. As with other numerical studies, Yin and Wang [5] assumed infinite joint deformation capacity. The results of recent research studies on realistic joints to open section columns [10,11,17,18] indicate that conventional realistic joints have limited deformation capacities. Furthermore, the fire test results of Ding and Wang [1] on restrained beam–CFT column assemblies also confirm that conventional connections to CFT columns would not have sufficient strength or deformation capacity to allow substantial catenary action to develop in the beams. The main objective of the research reported in this paper is to find ways of enhancing the strength and deformational capacities of reverse channel connections to CFT...
columns to prolong the development of catenary action in the connected beam.

To achieve the above objective, this paper will investigate the feasibility of the following methods:

1. Using hybrid connections.
2. Using fire-resistant steel in joint components.
3. Fire protection of joint components.
4. Joint detailing.

Whilst some of the methods investigated in this paper may not be immediately feasible, it is important to identify the potential solutions to aid future developments for practical use.

2. Simulation methodology

Fig. 2 shows the structural arrangement to be simulated in this research. It represents a steel beam connected to two concrete filled tubular (CFT) columns. The top and bottom of the columns are rotationally unrestrained but are horizontally restrained to simulate the lateral stability system in a real structure. This structural arrangement is the same as used in the fire tests of Ding and Wang [1]. The simulation methodology to be summarised below has been validated by the authors [2] by comparison against the fire test results of Ding and Wang [1].

- Three-dimensional solid elements (C3D8) were used to model the main structural members (beam, steel tube, concrete fill, connection components).
- Boundary conditions: half of the structure was modelled due to symmetry. The bottom of the columns was pinned in all three directions and the top of the columns was pinned in two directions but movement along the column axis was allowed; because half of the structure was modelled due to symmetry, all nodes at the beam mid-section were fixed in the axial direction, which effectively prevented rotation about the two principal axes of the beam cross-section, but allowed the beam to twist about its longitudinal axis. To represent the effect of the concrete slab, the beam was assumed to be fully restrained in the lateral direction;
- To reduce the number of elements and nodes in the FE model, the column was divided into three parts and only the central part connected by the joint (90 cm) was actually modelled using the solid elements. The other two parts away from the joint zone were modelled using general beam elements with “box” cross section for the steel tube and “rectangular” cross section for the concrete infill. The ABAQUS “Coupling” function was used to join the three column parts [12].
- The reduction factors for strength and elastic modulus of carbon steel at elevated temperatures were the same as in EC3 (EN 1993-1-2) [13].
- The ABAQUS contact function was used to simulate interactions between many contact pairs, including the interface between the wall of the SHS and the concrete fill, between the bolt head and the web of the reverse channel, between the bolt nuts and endplate, between the bolt shanks and the web of the reverse channel, between the bolt shanks and the endplate, and between the web of the reverse channel and the endplate. In order to reduce computational cost, a contact was defined as
surface to surface contact with a small sliding option. “Hard contact” was assumed for the normal contact behaviour and a friction coefficient of 0.3 was used in the tangential direction of the contact pairs.

- The welds were simulated using the “tie” type constraint in ABAQUS. It was assumed that the weld would not fail.
- The loads were applied in two steps: (i) two point structural loads were applied to the beam at ambient temperature; (ii) while maintaining the structural loads, the structural temperatures were increased until structural failure.

- In the FE model, six different temperature curves were adopted for the different parts of the structure, as shown in Fig. 3: a total of three temperature curves for the bottom flange, web and top flange of the beam; one temperature curve for the joint zone which included all the bolts, nuts and connection components; one temperature curve for the steel tubular column in the joint region (90 cm); one temperature curve for concrete fill in the joint region (90 cm). The temperature of the other two parts away from the joint zone was set at ambient temperature. The time–temperature curves were based on the time–temperature curves of test 4 of the Ding and Wang [1] fire tests. In their test, the structural assembly failed at 30 min so the time–temperature curves adopted in this parametric study were extended proportionally and artificially for the bottom flange of the beam to reach 1000 °C at 60 min, as shown in Fig. 3. According to Annex D of EN 1993-1-2 [12], the temperatures in the joint region at different heights may be assumed to be proportional to that of the bottom flange of the beam at mid span. In this research, the temperatures in the joint were assumed to be uniform, being the average over the connection height, which gives 0.82 times the temperature at the bottom flange of the beam at mid span.

- The survival temperature of the beam was defined as the bottom flange temperature at which the beam failed to support the applied load.
- Simulation of the restrained structural subassemblies studied in this paper represents a highly nonlinear problem and the numerical model can sometimes become unstable. This unstable behaviour may be temporary when the structure changes from one load carrying mechanism (e.g. bending) to an alternative one (e.g. catenary action) or permanent when the structure is physically incapable of sustaining the applied load. If it is the former, the structure is able to recover and continue to resist the applied load. In this research, a damping factor was used to overcome the numerical non-convergence problem. The authors [2] proposed a method to determine how an appropriate damping factor may be chosen. Whether or not the damping factor was appropriate was assessed by comparing the reaction force with the applied load. If the reaction force fell below the applied load but then returned to the applied load after overcoming the numerical non-convergence problem, it was considered that the drop in the reaction force was taken by an artificial damping force when the structure was experiencing rapid movement caused by temporary loss of stability. If the reaction force fell below the applied load but continued to do so, then the structure was considered to have failed.

### 3. Parametric studies

To investigate methods of developing reverse channel connection to CFT columns to enhance catenary action in the connected beam, an extensive set of numerical parametric studies was carried out. The basic parameters were:

- Beam section size: \( 457 \times 152 \times 67 \) UB (flange width 153.8 mm, overall height 458 mm, flange thickness 15 mm, web thickness 9 mm).
- CFT column size: Square Hollow Section \( 300 \times 12.5 \) mm.
- Beam span: 10 m; the total column height: 8 m (two storeys of 4 m).
- Channel section size: \( 230 \times 90 \) (overall depth 230 mm, overall width 90 mm, leg thickness 14 mm, web thickness 7.5 mm).
- Endplate thickness: 10 mm.
- Material properties: the stress–strain constitutive relationships adopted in the FE models for the steel beams, columns and connection components were based on the steel tensile coupon tests at ambient temperature (Table 1) of test 4 of the fire test results of Ding and Wang [1]. For ABAQUS simulation, the nominal engineering stress–strain model obtained from the steel tensile coupon test was converted to the true stress–strain relationship.

- Temperature profiles: see Fig. 3, based on extending the time–temperature curves of test 4 of the Ding and Wang [1] fire tests.
- The applied load ratio is defined as the ratio of the maximum bending moment of the simply supported beam to the plastic moment capacity of the beam at ambient temperature. In the parametric study, the base load ratio was 0.4.

The numerical studies investigated the effects of the following parameters:

- Connection configuration: during catenary action, the connection is subjected to hogging bending moment and tension from the connected beam, putting the topmost connection

### Table 1

Mechanical property values for different steel components at ambient temperature.

<table>
<thead>
<tr>
<th>Component</th>
<th>Beam web</th>
<th>Beam flange</th>
<th>Column</th>
<th>End plate; reverse channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (MPa)</td>
<td>210,050</td>
<td>226,690</td>
<td>203,210</td>
<td>210,000</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>396</td>
<td>379</td>
<td>492</td>
<td>355</td>
</tr>
<tr>
<td>Maximum strength (MPa)</td>
<td>550</td>
<td>572</td>
<td>536</td>
<td>560</td>
</tr>
<tr>
<td>Ultimate strain (%)</td>
<td>25.3</td>
<td>27.2</td>
<td>19.4</td>
<td>27</td>
</tr>
</tbody>
</table>

![Fig. 3. Assumed time–temperature curves for parts of the structural arrangement.](image-url)
component under the maximum tensile force. Deformation capacity requires the connection to be as flexible as possible and connection resistance requires the topmost components to be as strong as possible. Different connection configurations may achieve different combinations of strength and deformation capacity and this parametric study investigated the following five configurations: flexible endplate (Fig. 4a), hybrid flush/flexible endplate (Fig. 4b) with flush endplate at the top providing tensile resistance and flexible endplate at the bottom to enhance deformation capacity, hybrid extended/flexible endplate (Fig. 4c) with the same reasoning as for a hybrid flush/flexible endplate; flush endplate (Fig. 4d) and extended endplate (Fig. 4e).

- Reverse channel web thickness: in the fire tests by Ding and Wang [1], test 8 using a flush endplate reverse channel connection failed by fracture of the front face of the reverse channel. Due to shear fracture of the reverse channel, the failure mode was brittle and therefore, the catenary action phase was very short. This parametric study investigated the effect of increasing the thickness of the reverse channel web to prevent its fracture and achieve a prolonged phase of catenary action.

- Bolt grade and bolt diameter: in reverse channel connections the bolts must be strong enough to prevent failure of the connection due to bolt fracture under combined bending and tension. In this parametric study two bolt grades 8.8 and 10.9 were used to investigate the effect of bolt strength. Three bolt diameters M20, M24 and M27 were also examined. Table 2 shows the ambient temperature properties used for bolt grades 8.8 and 10.9.

- Joint fire protection regime: since joint components are the key in controlling structural failure during the beam catenary action phase, this study investigated methods of changing the relative strength and ductility of the joint components relative to the beam by varying the joint fire protection (temperature) regime.
Fire resistant (FR) steel: another method of potentially increasing joint performance is to use fire resistant steel which could achieve better retention in strength and better ductility at elevated temperatures compared to normal carbon steel. In this parametric study, the reduction factors for FR steel at elevated temperatures were according to those suggested by Kelly and Sha [14] (as shown in Fig. 5). However, the elevated temperature properties of FR bolts were from Sakumoto et al. [15]. Table 3 compares the FR bolt properties with those of bolts made of conventional carbon steel.

(c) Hybrid extended/flexible endplate

(d) Flush endplate

(e) Extended endplate

Fig. 4 (continued)
Table 2
Mechanical property values for bolts at ambient temperature.

<table>
<thead>
<tr>
<th>Component</th>
<th>Grade 8.8</th>
<th>Grade 10.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (MPa)</td>
<td>210,000</td>
<td>210,000</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>640</td>
<td>900</td>
</tr>
<tr>
<td>Maximum strength (MPa)</td>
<td>800</td>
<td>1000</td>
</tr>
<tr>
<td>Ultimate strain (%)</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 3
Strength reduction factors and elongation% for FR steel bolts grade 10.9 [14].

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Reduction factors</th>
<th>Elongation%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tensile strength</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>Carbon steel bolts</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>FR bolts</td>
<td>0.903</td>
<td>0.959</td>
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<tr>
<td>FR bolts</td>
<td>0.775</td>
<td>0.874</td>
</tr>
<tr>
<td>FR bolts</td>
<td>0.550</td>
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<td>FR bolts</td>
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<tr>
<td>FR bolts</td>
<td>0.000</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 5. Strength reduction factors for the FR steels [13] and the carbon steel [12].

Fig. 6. Stress–strain relationships of steel at elevated temperatures: EN 1993-1-2 values and artificial values of a “ductile” steel.

4. Parametric study results

Table 4 lists all the simulations carried out in the parametric study. In this section, the simulation results will be presented by considering the effects of the six parameters identified in the previous section: (1) connection configuration; (2) reverse channel connection web thickness; (3) bolt grade and bolt diameter; (4) joint fire protection scheme (temperature); (5) FR steel for connection components, and (6) ductility (ultimate strain) of steel. Table 4 also compares the beam’s limiting temperature, the mode of failure and the survival temperatures of all the simulations, the survival temperature being defined as the maximum steel beam lower flange temperature above which the applied load on the structure could not be sustained.

4.1. Effect of joint configuration

Fig. 7 compares the effects of using the following different joint configurations: flexible endplate, extended endplate, hybrid extended/flexible endplate, flush endplate and hybrid flush/flexible endplate. All the other parameters are according to simulation 6 in Table 4. Owing to a slight increase in axial stiffness of the extended or flush endplate connection compared to the other joint types, the beam’s compression force is slightly higher during the restrained thermal expansion stage. Also the extended or flush endplate connections have higher rotational stiffness than the other connections, so the beam’s axial buckling capacity is higher resulting in a higher maximum compression force. The temperature at which the beam’s axial force changes from compression to tension is the beam’s limiting temperature, defined by the bending resistance of the beam and the connections. Fig. 7a indicates that the beams using flush, extended endplate connections and hybrid connection types reached similar, but higher limiting temperatures than the flexible endplate connection, which is expected.

The main interest of this research is the beam’s survival temperature under catenary action above the beam limiting temperature defined on the basis of the beam’s bending moment resistance. Fig. 7b shows that once the beam is in the catenary action phase, the rate of the beam’s vertical deflection slows down. The beam’s survival temperature depends on the strength and ductility of the joint. Without any other modification to the joint details, the beams survival temperatures are higher than the beam’s limiting temperatures by about 40 °C. This level of increase in the beam’s survival temperature is low. Nevertheless, Fig. 7a shows that using the extended or hybrid extended/flexible endplate connection resulted in better performance than using other joint types. In contrast, using the flush or hybrid flush/flexible endplate connection gave little increase in the beam’s survival temperature over the beam’s limiting temperature.

Fig. 8 shows the deformation patterns and failure modes of the different joints. It can be clearly seen that, the common failure mode of extended, extended/flexible and flexible endplate connections was fracture of the bolts by compound tension and bending moment, as shown in Fig. 8a–c; however, in the case of flush or...
<table>
<thead>
<tr>
<th>Simulation ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>7</th>
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<td>11</td>
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<td>11</td>
<td>11</td>
<td>11</td>
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<td>8.8</td>
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<td>M20</td>
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<td>Channel web</td>
<td>Bolts</td>
<td>Bolts</td>
<td>Bolts</td>
<td>Bolts</td>
<td>Beam</td>
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<td>–</td>
<td>Bolts</td>
<td>Bolts</td>
<td>Bolts</td>
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<td>Channel web &amp; endplate</td>
<td>Endplate</td>
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<td>Failure mode</td>
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<td>–</td>
<td>Web around bolts holes</td>
<td>Web around bolts holes</td>
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<td>–</td>
<td>Web around bolts holes</td>
<td>Bolts &amp; web around bolts</td>
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</tr>
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</table>
flush/flexible endplate connection, the fracture of the reverse channel web around the bolt holes compound with fracture of the reverse channel web corners near the flanges, was the common mode of failure, as shown in Fig. 8d and e.

4.2. Effect of reverse channel web thickness (Simulations 1, 2 and 3)

Having shown that the structural assembly may fail due to the reverse channel, this section investigates the effect of strengthening the reverse channel by increasing the reverse channel thickness. Fig. 9 compares the simulated failure modes for three reverse channel web thicknesses: 7.5, 9 and 11 mm, in all cases using the extended endplate connection. Increasing the reverse channel web thickness changed the connection failure mode from fracture of the reverse channel web around the bolt holes (7.5 mm) to the junction between the web and the flanges (9 mm) to the bolts (11 mm).

4.3. Effect of bolts grade and bolt diameter

By increasing the reverse channel web thickness, the connection failure mode moved to the bolts. One method of improving the bolt performance is to increase the bolt diameter or the bolt strength or both. In Simulation 3, the bolts were grade 8.8 and the beam failure temperature was at 718 °C. As the simulation results in Table 4 for Simulations 4–6 show, increasing the bolt strength grade and bolt diameter gave some increase in the beam’s survival temperature. However, this strategy is unlikely to be effective, because even when changing bolt size/grade from M20 Grade 8.8 (Simulation 3) to M27 Grade 10.9 (Simulation 6), the increase in the beam’s survival temperature was only 72 °C.

When using the other joint types, changing the bolt size/grade resulted in similar changes in the beam’s survival temperature. However, when using the hybrid extended/flexible endplate connection, the beam’s survival temperatures were higher than using extended endplate connection, owing to the increased connection deformation capacity in the compression zone.

4.4. Effect of FR bolts

In this set of simulations, bolt fracture was the governing failure mode. Therefore, if the bolt performance was improved, it would be possible to further increase the beam’s survival temperature. One method of improving bolt performance is to use fire resistant (FR) steel bolts. Fig. 10 indicates that changing the bolts with FR steel bolts prevented the pull out of bolts and enabled the beam to develop a more prolonged phase of catenary action and was able to increase the beam failure temperature by 98 °C from 727 °C (Simulation 4) to 825 °C (Simulation 8) for extended endplate connection compared to carbon steel bolts. The failure in this case moved from the bolts to reverse channel web and the endplate, as shown in Fig. 10a. In Simulation 9, the reverse channel web and the end plate thickness were increased to 13 and 12 mm, respectively. These improvements prevented the reverse channel web and the endplate failure. This change allowed the beam to survive very high temperature at 942 and 920 °C for extended and extended/flexible endplate connections respectively. Fig 10b shows that the connection failed by fracture of the bolts but at very high temperature. It is important to mention that, the failure temperature in the FE model was defined as the bottom flange temperature at which the beam failed to support the applied load due to fracture of some of the connection components under combined bending and tension where excessive plastic strain occurred. The ultimate strains at elevated temperatures were taken according to Table 3.

The results of Simulation 9 of all connection types are shown in Fig. 11. The results in Fig. 11 show that when using extended and extended/flexible endplate connections, the beam’s survival temperature increased by 102 and 152 °C to 920 and 942 °C, respectively compared to their carbon steel bolt counterparts (Fig. 7). However, when using flush or hybrid flush/flexible endplate connection, the beam’s survival temperature did not experience any improvement. In the case of flexible endplates, using FR bolts contributed in improving beam survival temperature by only about 40 °C from 756 to 795 °C.

This may be explained by the different failure modes of the extended (including hybrid extended/flexible) endplate and the flush (including hybrid flush/flexible) endplate connections, which are shown in Fig. 10. It can be clearly seen that, the common failure mode of the extended endplate connections was fracture of the bolts by combined tension and bending moment, whilst in the case of flush endplate connection, the failure mode was fracture of the reverse channel web around the bolt holes (see Fig. 8d and e). This happened as a result of the flush endplate connection’s combination of high force (due to lower lever arm) but low ductility. The inability of flush endplate connections to develop substantial catenary action due to limited ductility was clearly observed by other researchers [17,18].

4.5. Effect of fire protection for the connection zone

Bolt failure was clearly critical in determining the beam survival temperature. The results in Section 4.4 suggest that using FR bolts was able to achieve great enhancement to the beam’s survival temperature, yet the results in Section 4.3 indicate increasing the bolt size/grade achieved much lower increases in the beam’s survival temperature. This may be explained by the rate of reduction in
the bolt's tensile strengths and the bolt's deformation capacity. From the results of Simulation 6, when extended and extended/flexible endplate connections were used, connection fracture occurred at the upper bolt row where the tensile stress was the highest. The temperature in the bottom flange of the beam was about 790 °C and the corresponding connection temperature.

Fig. 8. Deformation patterns and failure modes of different joints (Simulation 6).

Fig. 9. Comparison of failure modes of extended endplate connection with different reverse channel web thickness (Simulations 1, 2 and 3).
(0.82 times the beam bottom flange temperature) was about 645 °C. As shown in Table 3, at this temperature, the conventional steel bolt retains very little (16.5%) of its ambient temperature strength but the FR bolt retains a substantial amount (27.3%) of its ambient temperature strength. Merely increasing the bolt size/grade would not be able to compensate for the substantial reduction in the bolt’s mechanical properties in the case of conventional steel bolts. Because of this, controlling the bolt (connection) temperature do not exceed the temperature above which the bolt reduces its strength substantially may achieve the same results as using FR bolts.

This is demonstrated by Simulation 7 in Table 4, which used connection fire protection (CFP) to limit the maximum temperature in the connection (including 20 cm of the beam connected to the connection) to 600 °C. In the finite element model, the connection temperatures increased to 600 °C and then were kept con-
stant while the temperature of the beam was still increasing. Fig. 12 compares the failure mode of the protected and unprotected extended end plate connections. It can be seen that using fire protection prevented fracture of any of the connection components and moved the failure zone from the connection to the beam at the boundary between the protected and unprotected beam zone. As a result, the beam survival temperature was increased by about 125 °C from 818 to 943 °C when using extended/flexible endplate connection and by about 153 °C from 790 to 943 °C in case of extended endplate connection. Fig. 13 compares the beam’s axial force–temperature and vertical deflection–temperature relationships, clearly showing the prolonged period of catenary action development in the CFP cases.

4.6. Effects of using FR steel for other connection components

In Section 4.4, it was shown that by using FR bolts in conjunction with extended and hybrid extended/flexible endplate connections, the beam’s survival temperature increased drastically. However, in case of flush and hybrid flush/flexible the increase in the beam’s survival temperature was much less. This was attributed to failure occurring in the web of the reverse channel. An attempt was made to increase the beam’s survival temperature by using FR steel for all the connection components (Simulation 10 in Table 4). However, the results for this simulation suggest that although using FR steel for all connection components prevented failure of the web of the reverse channel around the bolts hole; it did not increase the beam’s survival temperature significantly. This was due to bolt failure (as shown in Fig. 14) when reaching their plastic strain limits at 756 °C, as shown in Fig. 15. In contrast, due to the increased deformation capacity and lever arm when using the extended endplate, the bolt forces were much lower at the same beam lower flange temperature, allowing the beams to survive much higher temperatures. Figs. 15 and 16 compare the different maximum plastic strain of the critical connection components and the bolt forces between Simulations 4 (normal steel) and 9 (FR steel) for extended endplate connections and between Simulations 4 (normal steel) and 10 (FR steel) for flush endplate connections.

Fig. 14. Failure modes of flush endplate connection using FR steel (Simulation 10).

Fig. 15. Plastic strains in different connection components–temperature relationships.

Fig. 16. Bolt forces–temperature relationships.

Fig. 17. Effects of bolt strength retention factor and strain limit on beam axial force–temperature behaviour.

(a) Based on simulation 6, using conventional bolt strength retention factors

(b) Based on simulation 9
4.7. Effects of increasing the ductility of the steel beam and bolts

The mechanical properties of steel at elevated temperatures currently in use are based on experimental research of many years ago (Kirby [16]) when there was no interest in robustness of steel framed structures in fire. Therefore, there was little accurate information on the deformation capacity of steel at elevated temperatures. In the simulations using ordinary bolts, the maximum strain was 16% at ambient and elevated temperatures. However, for FR bolts, the variable strain limits at different temperatures in Table 3 were used. If ordinary bolts were to have the same deformation capacity as in Table 3 for FR bolts, it is expected that the beam survival temperature would be increased. This is shown in Fig 17a, which compares the beam axial force–temperature relationship

![Graph](image1)

(a) Beam axial forces – temperature relationships

![Graph](image2)

(b) Beam mid-span deflections – temperature relationships

Fig. 18. Effects of steel strain limit on beam behaviour, based on Simulation 7.

![Graph](image3)

(a) Beam axial forces – temperature relationships

![Graph](image4)

(b) Beam mid-span deflections – temperature relationships

Fig. 19. Effects of beam load ratio on beam behaviour.

![Graph](image5)

Fig. 20. Deformation pattern and failure mode of extended endplate connection with applied load ratio in the beam = 0.7, based on Simulation 9.

![Graph](image6)

Fig. 21. Deformation pattern and failure mode of extended endplate connection with applied beam load ratio = 0.7, based on Simulation 9, using FR steel for connection components.
tionships using extended endplate connection with different ordinary bolt deformation capacities, either constant at 16% (Simulation 6) or variable (Simulation 6A) as given in Table 3. Fig. 17b further shows the increase in the beam’s survival temperature in two steps. The first step compares the effect of using FR bolt strength retention factors (Table 3) but with a constant strain limit of 16% (Simulation 9A) with using normal bolt strength reduction factor and constant strain limit of 16% (Simulation 4). The second step compares the enhancement effect of using FR bolt retention factors with variable strain limits (Table 3), shown as Simulation 9. These comparisons clearly demonstrate the most important features of enhancing robustness of steel framed structures in fire: improving bolt ductility and strength (Simulation 6A or 9A).

In fact, by preventing bolt failure (e.g. limiting connection temperature), failure of the structure moved to the beam due to limited ductility of the steel. Currently, EN 1993-1-2 limits the steel strain at 20%. Fig. 18 compares the simulation results for mid-span deflections and axial force in the beam if using extended endplate connections with different steel strain limits: 20% as recommended in EN 1993-1-2, 27% as obtained by Ding and Wang [1] and an artificial level of 50%. The increases in the beam’s survival temperature were quite impressive. For example, if the steel strain limit was 50%, the steel beam survival temperature was as high as 990 °C. Nevertheless, it must be said that a strain level of 50% may not be achievable for carbon steel.

4.8. Effects of applied load ratio

From the results obtained so far, the extended and hybrid extended/flexible endplate connections allowed the beam to achieve the highest survival temperatures. The extended endplate connec-

![Fig. 22. Effects of using FR steel bolts (BFR) or FR steel for all connection components (CFR), based on Simulation 9 for steel beam load ratio 0.7.](image)

![Fig. 23. Effects of column temperature on beam behaviour, based on Simulation 9.](image)

![Fig. 19 compares the simulation results. At the lower load ratio of 0.4, the beam's limiting temperature was higher as expected. However, what is more remarkable is that at the lower load ratio, the beam was able to develop prolonged catenary action and achieve very high survival temperatures, whereas at the load ratio of 0.7, the increase in the beam's survival temperature from the beam's limiting temperature was quite modest. This is because at the high load ratio, the beam's catenary force and deflections were very high. The high catenary force and deformation induced failure in all the connection components: the reverse channel web, the endplate and the bolts, as shown in Fig. 20.

![Table 5](image)

<table>
<thead>
<tr>
<th>Case</th>
<th>Steel tube size</th>
<th>Column load ratio</th>
<th>Na (kN)</th>
<th>Np (kN)</th>
<th>Ma (kN m)</th>
<th>Mp (kN m)</th>
<th>Beam catenary action force included in calculation of column load ratio?</th>
<th>Column temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SHS 300 x 12.5</td>
<td>Unloaded</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>No</td>
<td>90 cm connected to beam heated</td>
</tr>
<tr>
<td>2</td>
<td>SHS 300 x 12.5</td>
<td>Na/Np = 0.5</td>
<td>2500</td>
<td>5000</td>
<td>–</td>
<td>–</td>
<td>Lower column heated</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>SHS 300 x 12.5</td>
<td>Na/Np = 0.5</td>
<td>2500</td>
<td>10,500</td>
<td>268.8</td>
<td>900</td>
<td>Yes</td>
<td>Lower column heated up to 500 °C</td>
</tr>
<tr>
<td>4</td>
<td>SHS 300 x 35</td>
<td>Na/Np x Ma/Mp = 0.5</td>
<td>2500</td>
<td>10,500</td>
<td>268.8</td>
<td>900</td>
<td>Yes</td>
<td>Lower column heated up to 500 °C</td>
</tr>
<tr>
<td>5</td>
<td>SHS 300 x 35</td>
<td>Na/Np x Ma/Mp = 0.5</td>
<td>2500</td>
<td>10,500</td>
<td>268.8</td>
<td>900</td>
<td>Yes</td>
<td>Lower column heated up to 500 °C</td>
</tr>
<tr>
<td>6</td>
<td>SHS 300 x 35</td>
<td>Na/Np x Ma/Mp = 0.5</td>
<td>2500</td>
<td>10,500</td>
<td>268.8</td>
<td>900</td>
<td>Yes</td>
<td>Lower column heated up to 500 °C</td>
</tr>
<tr>
<td>7</td>
<td>SHS 300 x 35</td>
<td>Na/Np x Ma/Mp = 0.5</td>
<td>2500</td>
<td>10,500</td>
<td>268.8</td>
<td>900</td>
<td>Yes</td>
<td>Lower column heated up to 500 °C</td>
</tr>
</tbody>
</table>

Na: applied axial load in column.
Ma = bending moment in the column caused by catenary action force in the beam.
Np = column axial compression resistance at ambient temperature.
Mp = column bending moment resistance at ambient temperature.
Because all connection components experienced failure when the applied load ratio was 0.7, using FR bolt (BFR) alone was not sufficient to increase the beam survival temperature greatly. More substantial increase in the beam survival temperature may be obtained by using FR steel for the connection components (CFR), as shown in Fig. 21 where the structural failure moved from the connection to the beam. Fig. 22 shows that in this case, the beam’s survival temperature was 853 °C, compared to 754 °C if only FR bolts were used.

4.9. Effect of CFT unloaded column temperatures

The assumption of column temperature distribution was based on the authors’ modelling of the tests of Ding and Wang [1]. In realistic structures, the columns would be heated throughout the height. However, since the focus of this parametric study was on the beam and the joints with the columns having only minor influences, the assumed column temperature distribution was considered acceptable. To confirm this, Fig. 23 compares the beam axial force and mid-span deflection–temperature curves for both column temperature distributions for Simulation 9 using extended endplate which had the most prolonged stage of catenary action. The effects of using the two different temperature distributions were minimal.

4.10. Implication on loaded column behaviour

In the above simulations, all the columns were unloaded and sufficiently strong to resist the axial loads from the beam. However in reality the column will be loaded. Should catenary action be used in structural robustness design under fire, it is important that the catenary force in the beam does not cause early failure of the columns. A number of additional simulations were carried out to investigate the effects of changing the column loading and temperature distributions. The additional column temperature distributions were either heating the entire lower columns or heating all the columns (to simulate fire spread). Two additional column loading conditions were investigated: under pure axial load to give an axial load ratio of 0.5 (applied axial load = 2500 kN), under combined axial load (applied axial load = 2500 kN) and maximum beam catenary force (=134.4 kN) to give a combined load ratio of about 0.5. Table 5 lists the different column loads, dimensions and basis of calculating the column load ratio and Fig. 24 compares the results for these different cases, Case 1 being the base case (Simulation 9 in Table 4). In all cases, there was no column failure due to compression load in the beam during the beam expansion stage. However, the behaviour of the beam was completely different when comparing unloaded columns with loaded columns. With unloaded columns (Case 1), the beam’s catenary action development was substantial and the beam’s survival temperature was very high. However, with load in the column but uncontrolled column temperature increase (Cases 2–5), it was not possible for the beam to develop much catenary action and the beam’s survival temperature was no more than 110 °C above the beam’s limiting temperature, even when the beam’s catenary action effect was taken into consideration in calculating the column load ratio (Cases 4 and 5). If the beam’s catenary action constraint was not included in designing the column (Cases 2 and 3), the increase in the beam’s survival temperature above the beam’s limiting temperature is very low (30 °C). This was because the columns were not able to survive temperatures above their own limiting temperatures due to a lack of alternative load carrying mechanism to the columns. For comparison, the limiting temperatures of the two columns in Table 5 (Cases 2 and 4) were 560 and 556 °C, respectively, similar to the column temperatures at beam failure (523 and 572 °C, respectively). Column failure can be clearly seen in Fig. 24c by the accelerating horizontal deformation of the beams.

Fig. 24. Effects of columns on beam behaviour using extended endplate connection.

If the column temperatures were controlled to be below their own limiting temperatures regardless of the increase in beam temperature, then the beam would be able to develop prolonged catenary action. This is shown in Fig. 24 by Cases 6 and 7, for which the column temperature was capped at 500 °C.

5. Conclusions

This paper has presented the results of a numerical study using ABAQUS, to improve understanding on how different design parameters may be used to enhance the survival temperatures of steel beams connected to concrete filled tubular (CFT) columns using reverse channel connections. The design parameters investigated include the connection details (connection types, endplate/reverse channel thicknesses, bolt size/grade), connection materials (ordinary bolt and carbon steel, FR bolt, FR connection components), connection temperature regime and the beam’s steel strain limit. The investigations were carried out for beams and columns...
with different levels of load. The following main conclusions may be drawn.

(1) Among the five connection types investigated, using the extended or hybrid extended/flexible endplate connections gave the best fire resistant performance for the beam. Using a flush endplate (or hybrid flush/flexible endplate) connection was not effective.

(2) Failure in the reverse channel and the endplate can be delayed by increasing their thickness.

(3) On the other hand, using bigger or higher grade bolts would not be an effective solution. To prolong the beam’s catenary action development when the failure mode is in the bolts, using fire resistant (FR) bolts can be an effective solution. The main benefit comes from the FR bolt’s enhanced strength and strain limits at high temperatures.

(4) Limiting the connection region temperature to be below 600 °C can also have the desired effect of giving the beam very high survival temperatures.

(5) Ductile materials (both the steel and bolts) are the key to achieving high beam survival temperatures. There is high uncertainty in the current steel mechanical property model which is based on experimental studies of many years ago when there was no requirement for understanding steel structural robustness in fire. Updating these mechanical property models is required.

(6) The method of using catenary action to achieve high beam survival temperature is most effective when the applied load ratio in the beam is low to moderate (less than 0.5). When the applied load ratio is higher, it becomes much more difficult to devise methods to substantially increase the beam’s survival temperature above the limiting temperature. Using extended endplate connection and FR steel for all connection components offers a possible solution.

(7) If using catenary action, the effect of beam axial force on the surrounding columns should be included in the column design. Very high beam’s survival temperature can be achieved in this case by limiting the column temperature below the column’s limiting temperature in combination with taking into consideration the additional bending moment in the column generated by the beam’s catenary action force.

Acknowledgements

The first author of this paper would like to thank the Egyptian Ministry of Higher Education for providing a scholarship to enable him to pursue PhD study at the University of Manchester.

References


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