Numerical modelling of the behaviour of flush end-plate bare-steel connections at elevated temperature

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Abstract

A simplified component-based model has been used to investigate the behaviour of bare-steel flush end-plate connections at elevated temperatures. The model has the capability of allocating individual temperatures to each element at a given bolt row, allowing the modelling of any form of temperature distribution based on test data or simulations of the temperature profile across the depth of the connection. Only those parameters such as elastic modulus, yield and ultimate tensile strength which represent the stiffness and strength of the connection are assumed to degrade with increasing temperatures.

Comparison of the bare-steel component model with existing test data generated good results especially in the elastic zone, and accurately predicted failure modes. Also the predicted rate of degradation of the connection stiffness and capacity compares well with the experimental results.

1 Introduction

Component-based models for representing connection behaviour are attractive because of their relative simplicity and their capability of providing a reasonable representation of the full range of connection response. They are based on a consideration of individual components representing the principal parts of the connection as a set of rigid and deformable elements. The response of the connection is obtained by superimposing the stiffnesses of individual components in the compression and tension zones. Due to their simplicity EC3: Annex J [1] proposed a procedure for the design of connections using the
component model. A series of component-based models has been proposed by Madas [2] for various forms of both bare-steel and composite connection types. Flexible end-plate, double web-angle, top- and seat-angle connections were considered. A number of components, such as column and bolt deformation, remain transferable between different connection types. In order to account for non-uniform deformations through the thickness of the slab, the concrete slab was sub-divided into a finite number of layers with an effective width. The influence of both shear connectors and reinforcement was included. Comparison with test data demonstrated close agreement in terms of both the observed failure mechanisms and overall form of response.

However, elevated temperature component-based models are rare probably due to the lack of experimental data that describes the connection behaviour. It is well known that connection fire tests are prohibitive and time consuming for preparation, carrying out such tests and interpretation of the results. If such simplified models are developed which has the capability of representing the connection response to an acceptable degree of accuracy, this of course will lead to better understanding of the high performance of steel structures in fire with fraction of testing costs and time. Consequently this will be beneficial in improving the current design codes in which the behaviour of steel structures in fire is inadequately addressed.

Leston-Jones [3] proposed a component model for bare-steel and composite flush end-plate connections at elevated temperatures. The bare-steel model compared well with experimental data for both major and minor axes flush end-plate connections. However, the composite model showed a significant difference in the rate of degradation compared with experimental results for elevated temperatures. It was suggested that this was due to neglecting the movement of the axis of rotation in the composite model in the context of the increased load applied to the column web. The model is modified in the present work to account for connections with more bolt rows and dimensions and used to predict the behaviour of two flush end-plate bare-steel connections. The results obtained are presented in this paper. Comparison of the bare-steel component model with existing test data is made along with predicted failure modes. Also the predicted rate of degradation of the connection stiffness and capacity is compared with the experimental results.

2 The component-based model

The model developed by Leston-Jones [3] was used to model the bare-steel flush end-plate connections tested at elevated temperature. It was originally developed to model connections with only two bolt rows in tension and it is modified in the present work to account for more bolt rows and larger connection details.

In the model, the connection components are treated as springs with known stiffnesses. By assembling the contributions of individual components which represent the connection as a set of rigid and deformable elements, it is possible to model connection behaviour throughout the entire moment-rotation relationship. The connection is divided into tension and compression zones.
The response of the connection as whole may be obtained by superimposing the stiffnesses of individual components in the tension and compression zones.

The connection is modelled as a two dimensional problem with the rotation of the connection assumed to occur about the centre-line of the beam bottom flange, as is typical of bare-steel connection models. The model assumes that the 'connection' includes the column web panel in the compression zone and the end-plate, column flange and bolts in the tension zone. Individual springs are used to simulate the stiffnesses of the individual components. In order to simplify the solution process the stiffness of all components acting in the tension zone are grouped and considered as a single spring of equivalent stiffness. The idealized representation of the connection is shown in Fig. 1.

The global rotational stiffness of the connection may be calculated for any given moment and temperature based on the stiffness of the elements in the compression zone and the collective stiffness of elements at each bolt row acting in tension. This may be expressed mathematically as:

\[
S_{jt}^{-1} = \left( K_{eqt} \cdot z^2 \right)^{-1} + \left( K_{cwt} \cdot z^2 \right)^{-1}
\]

Figure 1: Component-based model for flush end-plate connections

where, \( S_{jt} \) is the rotational stiffness of the bare-steel connection as a whole for a given temperature;
- \( K_{eqt} \) is the stiffness of the equivalent tension spring;
- \( K_{cwt} \) is the stiffness of the column web (in the compression zone);
- \( Z \) is the lever arm to the centre of the tension zone (location of equivalent tension spring).
Once the global stiffness of the connection is known the rotation of the connection may be determined at any value of moments with increasing temperature.

The model is capable of allocating individual temperatures to each element at a given bolt row, allowing the modelling of any form of temperature distribution based on test data or simulations of the temperature profile across the depth of the connection. Only those parameters such as elastic modulus, yield and ultimate tensile strength which represent the stiffness and strength of the connection are assumed to degrade with increasing temperatures.

The following properties are adopted in the model:
1. Geometrical properties are nominal values;
2. Material properties for the beam and column sections used are based on results from the tensile coupon tests [4], whilst nominal values are adopted
3. The temperature profile across the connection depth is based on experimental observations [5];
4. The degradation of structural steel is based on EC3: Part 1.2 [6] recommendations, with a strain level of 0.5% for strength. The degradation of bolt stiffness and capacity is based on recommendations presented by Kirby [7].

2 Experimental connection tests at elevated temperature

The connections modelled are two flush end-plate bare-steel connections selected from experimental tests conducted by Al-Jabri [5]. Series of elevated temperature connection tests were conducted to study the influence of parameters such as member size, end-plate type and thickness, and composite slab on the connection response in fire. Five different configurations were considered. A cruciform test arrangement was used and the tests were performed in a portable junction furnace specially designed for testing connections. The connection types included two flush end-plate and one flexible end-plate bare-steel connections and two flexible end-plate composite connections. For each configuration a series of tests was conducted, each at a different load level. Each test was performed at constant load and different temperatures. Details of the connections tested are shown in Fig. 2.

2.1 Group 1

This group consists of two 254x102UB22 beams connected to a 152x152UC23 column by 8mm thick flush end-plates as shown in Fig. 2(a). All of these were in Grade 43 steel. Six M16 grade 8.8 bolts in 18mm diameter clearance holes were used. Four tests were conducted at constant load levels of 4 kN.m, 8 kN.m, 13 kN.m and 17 kN.m and different temperatures.
2.2 Group 2

A pair of 356x171UB51 beams in grade 50 steel were connected to 254x254UC89, also grade 50 steel, by 10mm thick flush end-plates. Eight M20 grade 8.8 bolts in 22mm diameter clearance holes were used. Four tests were carried out at 27 kN.m, 56 kN.m, 82 kN.m and 110 kN.m load levels.

3 Comparison between experimental results and numerical modelling

The ambient and elevated temperature response of the connections obtained from the experimental tests is compared with the results predicted by the model. The rate of degradation of the connection’s stiffness and strength for the two groups is also compared with the numerical predictions.

3.1 Overall connections response at ambient temperature

Comparison of predicted ambient temperature response with experimental results for Group 1 and Group 2 tests are shown in Figs. 3(a) and 3(b) respectively. It can be seen from Fig. 3(a) that there is a close agreement between the predicted ambient temperature response of Group 1 connection and the experimental one. In order to assess the model capability in predicting the connection response over the entire moment-rotation relationship, the experimental connection response conducted by Leston-Jones [3] on a similar connection with thicker end-plate (i.e. 12mm) is compared with the predicted response. As can be seen that the model has the ability to predict the entire connection response although plastic response of the connection is underestimated due to the use of thin end-plate (i.e. 8mm) in the modelling. The model predicted connection deformation controlled by end-plate and column flange deformation in the tension zone, and column web crushing in the compression zone, corresponding with the experimental observations.
Similarly, it may be seen from Fig. 3(b) that the component model provides a close prediction of the initial stiffness of the connection at ambient-temperature. The model, however, somewhat overestimates the yield capacity of the connection, but the observed discrepancy is relatively small and may be attributable to variations in material properties. Unfortunately, test data describing the strain hardening and ultimate connection response is not available, due to the levels of loading adopted in the elevated-temperature tests. Failure mode of the connection was predicted as being governed by end-plate deformation in the tension zone corresponding with experimental observations, with the actual failure of the connection occurring as a result of end-plate deformation and slipping of top bolt rows in the tension zone.

Figure 3: Comparison of predicted ambient temperature response with experimental results for groups 1 and 2 connections

3.2 Degradation of connection stiffness and strength

The experimental rates of degradation of the connection characteristics are compared with those predicted for Groups 1 and 2 connections in the form of stiffness/capacity retention factors plots in Figs. 4 and 5 respectively. It may be seen that for both connections the predicted degradation of stiffness with temperature compared closely with that measured. Predicted degradation of Group 1 connection capacity compared well with experimental results, although the model slightly underestimates the actual rate of degradation. However, for
Group 2 connection, the model underestimates to some extent the recorded rate of degradation of connection capacity especially for temperatures between 450°C and 600°C. For both connections the model prediction of the degradation rate of the connection capacity remained in the conservative side. Due to lack of experimental data for temperatures below 500°C and 450°C for Groups 1 and 2 connections respectively, the model was not used for this range of temperature. This is mainly due to the levels of loading adopted in testing.

Figure 4: Predicted degradation of connection characteristics with temperature for Group 1 connection

Figure 5: Predicted degradation of connection characteristics with temperature for Group 2 connection
3.3 Overall connections response at elevated temperature

Three tests in each group were modelled by incorporating a constant moment and generating the temperature-rotation characteristics of the connection. The predicted elevated-temperature response of the connections is compared with experimental results as shown in Fig. 6(a) for Group 1 tests and Fig. 6(b) for Group 2 tests. It may be seen that there is a reasonable agreement between the predicted and the experimental response at low levels of loading. The initial and yielding responses of the connection are well predicted by the model whereas the model seems to underestimate slightly the connection response in the strain-hardening zone.

![Graph showing connection response at elevated temperature](image)

Figure 6: Comparison of predicted elevated temperature response with experimental data for groups 1 and 2 tests.

However, at high levels of loading of 17 kN.m and 110 kN.m for Groups 1 and 2 respectively, the model greatly underestimates the connection behaviour (comparison is not shown here). This resulted in lower failure temperature being predicted by the model than the ones actually observed from tests with temperature difference of approximately 200 °C. The difference was more pronounced in the plastic region. The probable reason for the variation in the behaviour may be due to lack of information that can describe the strain-
hardening response of the connection components. In the model the strain-hardening stiffness of the connection components was assigned a reduced value based on the connection initial stiffness. Generally, it is apparent that the component model is capable of predicting the connection response at both ambient and elevated temperatures to a reasonable accuracy specially in the elastic zone.

4 Conclusion

Whilst experimental tests remain the most reliable form of generating connection characteristics, due to the large quantity of arrangements which may exist, and the expense of testing, it is desirable that the moment-rotation response of connections may be accurately predicted. The modelling of connection response of connections becomes yet more significant at elevated temperatures due to the increased number of tests required to define the response of each arrangement. Thus component-based models offer an alternative solution to minimise the reliance on experimentation to investigate the connection response and reduce expense and time as well as easing the numerical complexities associated with modelling.

A simplified component-based model has been used to model the behaviour of two flush end-plate bare-steel connections at elevated temperatures. In the model the connection components were treated as springs with known stiffnesses. The entire connection response may be predicted by assembling the contributions of individual components which represent the connection as a set of rigid and deformable elements which are assumed to degrade with increasing temperatures. The predicted response of the connections was compared with the response observed from experimental tests. Results showed that there a good agreement between the predicted and the experimental response at low levels of loading. This agreement was more noticeable in the elastic zone. However, at high levels of loading and in the plastic region the model underestimates to some extent the connection response. This is may be attributed to the lack of experimental data that describes the connection behaviour in the strain hardening region. The rate of degradation of stiffness and strength was closely predicted by the model for both connections. In general the component model is capable of predicting the connection response at both ambient and elevated temperatures to a reasonable accuracy specially in the elastic zone.

It is apparent that the use of component-based models can provide a reasonable prediction of the connection response at both ambient and elevated temperatures similar to the results obtained from other forms of modelling based on an understanding of the behaviour of the components.

References


