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FRACTURE SIMULATION IN A STEEL CONNECTION IN FIRE

Simulation of a flush endplate connection at ambient and elevated temperatures including different methods for fracture simulation

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INTRODUCTION

Actual developments in numerical simulations of the structural behaviour in fire situation are focussed on taking into consideration the interaction of all structural members in a global numerical approach. Therefore it is necessary to model the load bearing behaviour of connections in detail.

In this paper a detailed 3D numerical model of a bolted steel endplate connection taking into account nonlinearities, e.g. temperature dependent material, is presented. The simulation is validated by experimental tests conducted at the University of Sheffield in 2008. During some of the experimental tests, large deformations and fractures occurred. These phenomena are simulated with the numerical model as well.

1 STATE OF THE ART

Since the first study of connection behaviour (Wilson et al, 1917), investigations in joints were traditionally based on experiments. The finite element method was used to simulate connection behaviour since 1974, when Krishnamurthy developed a two-dimensional FE-Model to simulate an endplate connection (Krishnamurthy, 1974). While experimental and numerical investigations at ambient temperatures have been conducted in a large number, tests at elevated temperatures are rather seldom. The reason for this might be that studying connection behaviour at elevated temperatures is costly because a number of tests at different temperatures are needed to develop a moment-rotation-temperature curve. However, elevated temperature tests on beam-to-column-connections have been carried out by (Kruppa, 1976), (Wang et al, 2007) and (Schaumann et al, 2008) for example. Further high temperature tests on different connections in fire, taking into account tensional forces caused by catenary action of adjacent beams, have been performed by Yu and will be used for this investigation. Results have been published for different connection types in (Yu et al, 2007), (Yu et al, 2008a), and (Yu et al, 2009), to mention but a few.

In addition, numerical investigations have been conducted for some elevated temperature tests. For example in (Sarraj et al, 2007) a numerical model of fin plate connections has been developed. In (Yu et al, 2008b) a simulation of a steel connection using explicit analysis was presented. The explicit equation solver algorithm was found to be an alternative to the standard algorithm especially if large deformations occur. In (Hu et al, 2008) a flexible endplate connection in fire using an explicit dynamic analysis was presented. To simulate a tensile fracture of the beam web, cohesive elements were included to the analysis.

2 METHODS

In this paper, a numerical simulation of a joint at ambient and elevated temperatures is presented. The numerical calculation has been conducted using the FE-software Abaqus. Both, the implicit (Abaqus/Standard) and the explicit solver algorithm (Abaqus/Explicit) have been applied to the analysis.

A shear fracture in the endplate, which occurred during some of the tests, was simulated using two different methods. The first method was the use of cohesive elements located where shear failure occurred in the test. The second method was a fracture strain criterion for ductile materials. This algorithm is able to reduce the stiffness of elements and delete them during the analysis.

3 PARAMETER OF EXPERIMENTS AND NUMERICAL SIMULATION

3.1 Test Setup and Geometry of the Connection

During 2007 and 2008 the University of Sheffield carried out a wide range of experimental tests within different steel connections, different temperatures and a different load angle α (c.f. Fig. 1). The test setup, geometrical details and material properties of this test have been published in (Yu et al, 2008a) in detail and will be described shortly. The general test assembly is shown in Fig. 1.

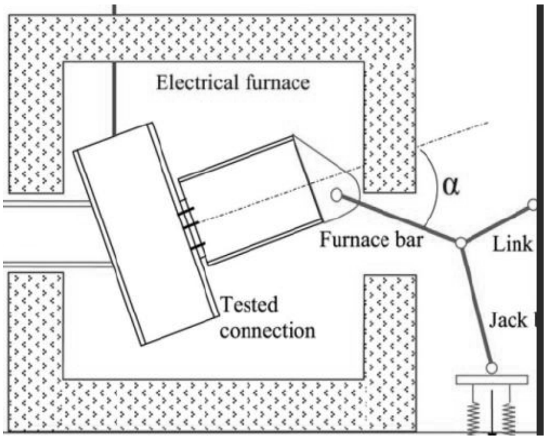

Fig. 1 Scheme of test setup (Yu et al, 2008a)

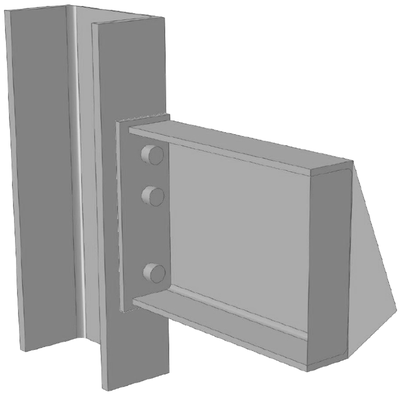

Fig. 2 Numerical model of flush endplate connection (including symmetry)

The distance controlled load is induced by a jack through a construction of three steel struts, which are connected by hinges. Due to this construction, the load angle α (c.f. Fig 1) is variable. For the numerical simulation, tests with an initial load angle of $\alpha=55°$ have been used. It has to be taken into account that the load angle is changing during the test for the reason of the jack movement and the joint rotation.

The investigated connection consists of a flush endplate of dimensions 325x200x10 and is connected to the column by six M20 grade 8.8 bolts. The connection detail can be found in Fig. 2. The beam cross section is UB 305x165x40 and the column cross section is UC 254x89. The numerical model has been created as half-geometry taking into account the connection symmetry to reduce computing time.

3.2 Material Properties

The beam and the endplate are made of S275 grade steel. As described in (Yu et al, 2009) for one of the tests, a standard tensile test specimen has been cut from the beam flange to determine the material properties at ambient temperatures. The Young's Modulus is $E=176{,}350\ \text{N/mm}^2$, the yield stress is $f_y=356\ \text{N/mm}^2$ and the ultimate tensile stress is $f_u=502\ \text{N/mm}^2$. As there were no tests available for the endplate and the column, the material parameters have been adopted.

There were no tests to gain material properties at elevated temperatures. For this reason investigations of (Renner, 2005), which have been conducted with tensile specimen at different steady-state temperatures and different strain rates, were used to extrapolate the data. Material properties according to the Eurocodes have not been used as those properties are developed for transient temperatures. The material properties used in the numerical model are shown in Fig. 3.

According to bolt behaviour, three bolts have been tested at ambient temperatures. An average tensile force of 224 kN and a Young's Modulus of 206,009 N/mm^2 were determined (c.f. (Yu et al, 2009)). There is no data available to determine the stress strain relationship for bolts at steady-state elevated temperatures. For this reason the relationship has been determined by equations from (Eurocode 3, 2010). Reduction factors for yield stress according to (Hu et al, 2007) have been used. The stress-strain-relationship used for the bolts is shown in Fig. 4.

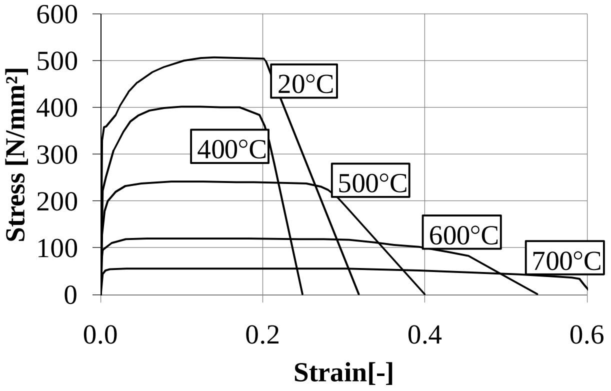

Fig. 3 Stress-strain-relationship for structural steel in numerical model

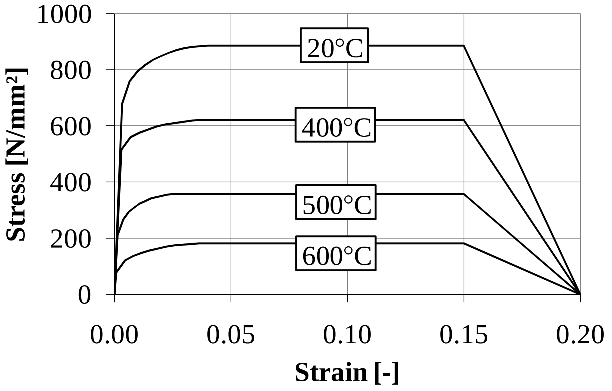

Fig. 4 Stress-strain-relationship for bolts in numerical model

4 RESULTS WITHOUT FRACTURE SIMULATION

The implicit equation solver algorithm (Abaqus/Standard) was used to simulate the connection behaviour first. Up to a rotation of 2°, the calculated behaviour was very close to the test results. The simulation at higher rotations was not possible because of convergence problems due to large deformations.

The load-rotation behaviour of the tested connection, calculated by an explicit equation solver, is shown in Fig. 5 for ambient and elevated temperatures. It can be seen that test results and calculated load-rotation behaviour are correlating very well for rotations up to 5°. At higher rotations, the load capacity of the connection is overestimated by the numerical model. This can be seen at the test at 450°C.

To verify the calculation internal and external energies have been investigated. To avoid singular modes (c.f. hourglass control), artificial energies are added during the simulation. To ensure realistic results, the amount of this energy should be negligible compared to “real” energies. A value of 10% of internal energies was determined to be the maximum allowable fraction. This value has been reached for most calculations at a rotation of about 8°. As the calculation is quasi-static, the kinetic energy fraction should be marginal as well. The kinetic energy was found to be less than 1% of internal energies.

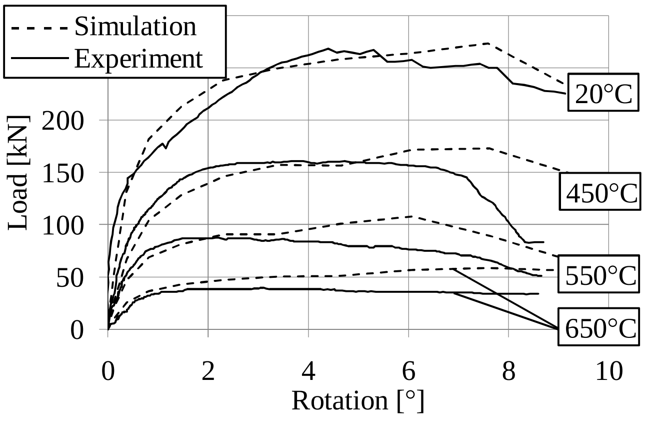

Fig. 5 Load-rotation behaviour at different temperatures (numerical and test results)

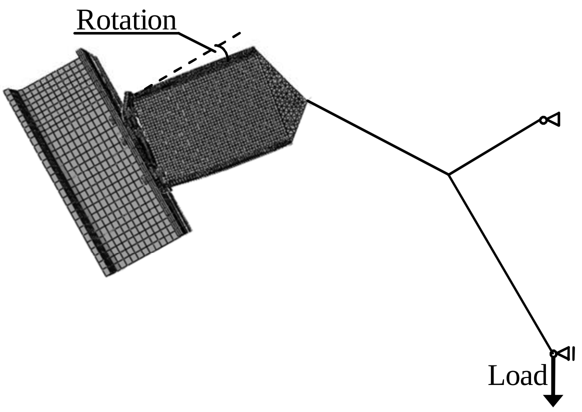

Fig. 6 Definition of load and rotation in Fig. 5, Fig. 8 and Fig. 11

5 COHESIVE ELEMENTS

As described in (Yu et al, 2008a), the test specimen showed two different failure modes. While at higher temperatures of 550°C and 650°C the bolts failed in tension, at 20°C and 450°C a shear fracture occurred very close to the beam web in the endplate.

A thin layer of cohesive elements has been implemented in the endplate next to beam web and flange to simulate this shear fracture. Failure of the cohesive layer has been simulated using material properties based on a fracture strain. As can be seen in Fig. 7, the stress strain relationship of the cohesive elements has been defined as linear elastic until a damage initiation criterion is reached. The damage initiation stress is defined as ultimate stress of the material. The Young's modulus has been defined as ultimate stress divided by the strain at the beginning of failure (c.f. Fig. 3). The failure strain, as defined in Fig. 7, has been determined to $\varepsilon_{fail}=3$. For the reason of a very thin layer of cohesive elements, the influence of failure strain is negligible to the results, while the simulation is more stable using a higher strain.

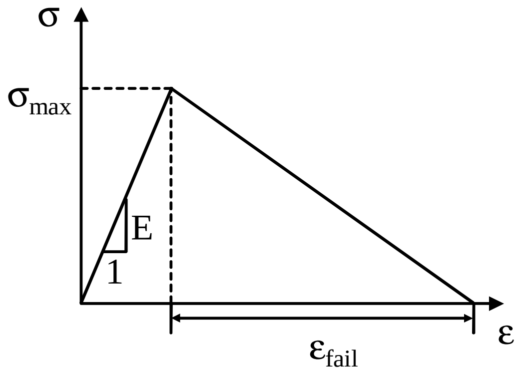

Fig. 7 Scheme of material behaviour of cohesive elements

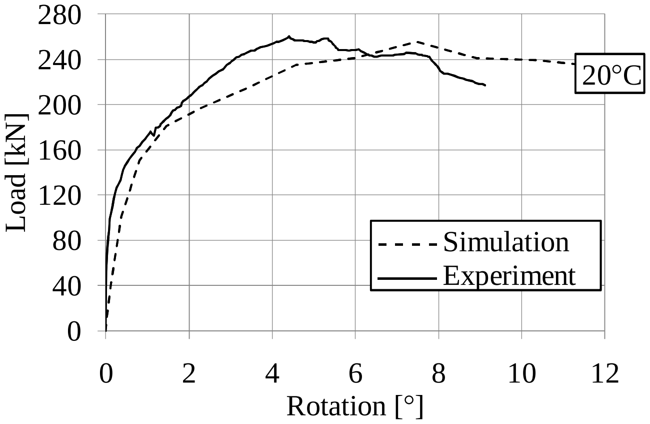

Fig. 8 Load-rotation relationship of connection at 20°C (numerical and test results)

In Fig. 8 the load rotation relationship for the test at ambient temperatures is compared to the calculation including cohesive elements. As can be seen, the curves are correlating very well and the decrease of load capacity can be simulated. The main benefit of the simulation including cohesive elements is the ability to visualise fractures. As can be seen in Fig. 9 and Fig. 10, it is possible to simulate the fracture which occurred in the test at ambient temperature.

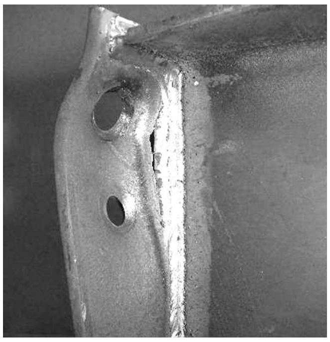

Fig. 9 Fracture of endplate in test specimen after test at 20°C

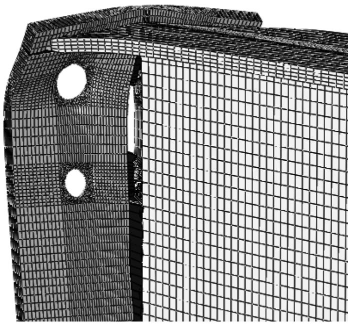

Fig. 10 Fracture of endplate in numerical simulation at rotation of 9°

6 GENERAL IMPLEMENTATION OF DAMAGE

Main problem of the use of cohesive elements in a fracture simulation is the need to know, where a fracture may occur. Otherwise, it is possible to implement a failure criterion to the general material properties.

The failure depends on a damage initiation strain, at which the stress reduction begins and failure strain at which the damage reaches 100%. The damage initiation strain can be described as strain-rate- and shear-stress-ratio-dependent. As there is no available data, the criterion has been set as constant for each temperature. The damage initiation strains have been determined to the strain at the beginning of stress reduction in the stress-strain-relationship (c.f. Fig. 3). Damage initiation strain and failure strain can be found in Tab 1.

Tab. 1 Temperature dependent strains for damage definition

Temperature [°C]	Damage initiation strain $\bar{\varepsilon}_S^{pl}$ [-]	Failure strain $\bar{\varepsilon}_f^{pl}$ [-]
20	0.200	0.5
400	0.200	0.5
500	0.275	0.5
600	0.400	0.5
700	0.575	0.5

The results of the simulation using a damage criterion for structural steel are shown in Fig. 11. It can be seen that the load-rotation-relationship is correlating very well for each temperature. While the results for tests at 550°C and 650°C are comparable to the calculation without a damage criterion, the results at 450°C are much closer to the test results especially at higher rotations and a decreasing load.

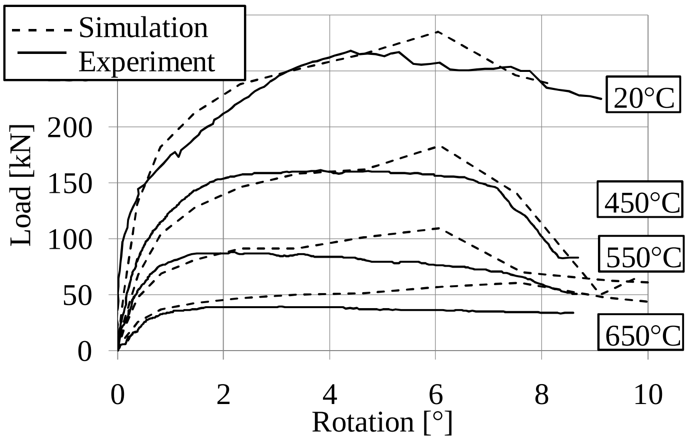

Fig. 11 Load-rotation behaviour of connection for different temperatures including a damage criterion for numerical results (for definition of load and rotation see Fig. 6)

As described in (Yu et al, 2008b), the failure at 20°C and 450°C was due to a shear fracture in the endplate at the beam web, while bolts failed due to tension at higher temperatures. This has been observed in the numerical simulation as well. In Fig. 12 the stress related to the ultimate stress at the specific temperature in the upper left bolt at a rotation of 7.5° is shown for the simulation at 20°C and 550°C. As can be seen by the low stress values in the bolt shaft at 550°C, the bolt has failed. For the reason of this failure, the load inside the endplate is reduced and the fracture at the beam web does not occur. As the bolt at 20°C is still functional, a fracture occurs in the endplate. In contrast to the experiments, the fracture in the simulation occurred as a tensional fracture. The reason for this slightly different behaviour may be found in the weld geometry or in the influence of the welding process in the heat affected zone.

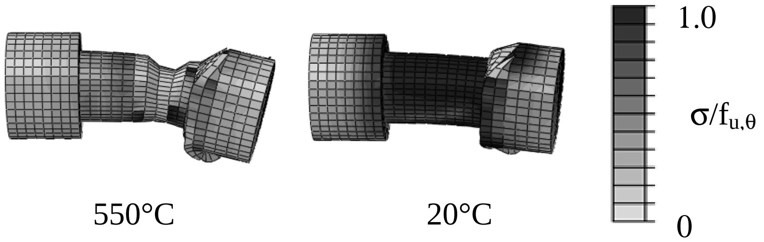

Fig. 12 Upper left bolt at rotation of 7.5° in numerical simulation at different temperatures

7 SUMMARY AND ACKNOWLEDGEMENT

In this paper, an experimental investigation in the load-rotation behaviour of flush endplate connections at ambient and elevated temperatures has been simulated. The simulation was conducted using a 3D finite element model including nonlinear material properties and large deformations. As in some of the tests a shear fracture occurred in the endplate, different methods to simulate this failure mode were tested.

It was found that an implicit equation solver algorithm was not able to compensate large deformations. Thus an explicit algorithm was preferred and showed good correlations with the test results.

To simulate shear fracture, cohesive elements have been found to be a useful tool. Main disadvantage is the need to know, where the fracture may occur. If this is not known, the implementation of a general failure criterion is possible. This opportunity was investigated and comparisons to the test results showed very good correlation for the load-rotation-relationship. Additionally, the different failure modes at ambient and elevated temperatures were simulated correctly.

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