Fracture simulation of structural steel at elevated temperature using XFEM technique

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Abstract. Modeling fracture is important for predicting the actual behavior of structural steel in fire, where fracture of steel members is often the failure mode that affects the overall strength and deformation capacity of steel members. Therefore, in this paper, recent research on modeling steel fracture at elevated temperature is presented. Extended Finite Element (XFEM) together with fracture criterion of principle logarithmic strain is used to simulate the fracture behavior of three different types of tensile test specimens named MA, MB and MC made from American structural steel ASTM A992 at elevated temperature up to 1000°C. The simulation results are then compared with test results to validate the accuracy of simulations. In addition, study is conducted to evaluate how sensitive the predicted engineering stress-strain curves and fracture initiation point on the curves to the selected value of principle logarithmic strain at fracture. Finally, the generalized principle logarithmic strains at each temperature case are proposed for fracture simulation of ASTM A992 steel specimens.

1. Introduction
Fracture behavior of steel at elevated temperature is of great interest because it can significantly influence the response of steel structure in fire. One example of collapse of steel building mainly due to connection fracture is WTC building collapse in US in fire event after severe attacks. It was also observed that steel fracture in tension was a common failure mode during heating or cooling stage in fire events. However, to accurately predict fracture behavior of steel in fire is still difficult due to lack of enough test data and studies. Therefore, in order to propose an approach to predict fracture behavior of steel in fires with reasonable accuracy, standard steel specimens under unaxial tension at room temperature and elevated temperature up to 1000°C with 100°C intervals are investigated and simulated using advanced computational method such as finite element method. The obtained engineering stress-strain curves and failure mechanism of structural steel are compared with several tests data to verify the proposed approach.

1.1. Theoretical background for fracture
In general, fracture can be directly defined as the separations of materials into several pieces as shown in Figure 1. Normally, two categories of fracture modes including brittle fracture and ductile fracture are observed in building materials. Based on several experimental observations, for brittle fracture modes, materials usually undergoes quite little plastic deformation before onset of fracture and cracks will propagate rapidly after fracture initiates; for ductile fracture modes, before the formation of fracture materials developed quite significant plastic deformation and cracks will propagate relatively slowly after onset of fracture. As for structural steel in tension at elevated temperature, it demonstrates ductile fracture modes since it develops quite significant plastic deformation before onset of fracture. Therefore, the research described herein will focus on predicting the ductile fracture behavior of steel.
Ductile fracture initiation in steel can be usually recognized from engineering stress-strain curves as illustrated in Figure 2. Fracture usually initiates once the stiffness of the material begins to degrade significantly.

**Figure 1.** Fracture captured in simulated beam section.

**Figure 2.** Fracture initiation point captured from engineering stress-strain curve of structural steel.

### 1.2. Possible approaches to simulate fracture of steel under uniaxial tension

Several fracture initiation models have been proposed in the literatures to simulate fracture behavior of ductile metals. This includes models proposed by McClintock (1968), Rice and Tracey (1969), Hancock and Mackenzie (1976), Johnson and Cook (1985), Hooputra (2004) and Gurson (1977) model [1]-[6] etc. In computational finite element analysis programs, several of these fracture initiation models have been implemented. Fracture simulation of structural steels can be performed using these fracture models together with fracture propagation rules. Nevertheless, accurate fracture model parameters depending on material properties are always required in order to generate accurate prediction results. Calibration of the fracture models parameters still needs lots of efforts and significant numbers of tests and simulations.

Another approach to simulate fracture behavior of ductile metals is using extended finite element method which is designated as XFEM. XFEM technique has been used for fracture prediction of ductile metals by several scholars and reported in literatures. Schiavone et al [7] used both Gurson model and XFEM to capture fracture behavior in Aluminium specimens with different notched shapes and observed that the crack shapes were predicted correctly using two approaches, with the exception of the square-notch case using XFEM. Hosseini-Toudeshky and Jamalian [8] performed fracture modeling for bulk Aluminium Al5083 using XFEM and predicted the ductile fracture behavior of Al5083 very well by demonstrating the comparison of stress-strain behavior results between simulations and tests. Vajragupta et al [9] employed XFEM technique to capture fracture behavior of dual phases steel (DP steel), where both ductile fracture and brittle fracture were observed, and demonstrated the capability of XFEM for predicting both ductile and brittle fracture in the same specimen. Ramazani et al [10] investigated the fracture behavior of DP600 steel with various chemical contents and demonstrated that XFEM captured fracture behavior of different types of DP600 steel quite well. It should be noted that the above-mentioned researches using XFEM were all under ambient temperature. According to the knowledge of author, there are very limited studies reported in literatures on fracture simulations of steel at elevated temperatures using XFEM. In this study, XFEM will be investigated and implemented to capture fracture behavior of structural steels at both ambient and elevated temperatures.

### 1.3. Background of extended finite element method

The extended finite element method (XFEM), although not a new technique for simulation, can be used for fracture simulation for both brittle and ductile failures. XFEM is based on the concept of partition of an element and allows the presence of discontinuities in an element by enriching degrees of freedom with special displacement functions as shown in Equation (1) [11]. In Equation (1), the
The first term in brackets represents the basic nodal function of all the nodes in element. The second term considers the node whose shape function is cut by an interior crack, and the third term takes account of nodes whose shape function is cut by crack tips. In XFEM, initial representation of a crack location is not required and arbitrary crack path can be generated between different nodes.

\[ u^h(x) = \sum_{i \in N} N_i(x)[u_i + H(x) a_i + \sum_{a=1}^{d} F_a(x)b_i^a] \]  

- \( u_i \): Nodal DOF for conventional shape function \( N_i \)
- Heaviside enrichment term
  - \( H(x) \): Heaviside distribution
  - \( a_i \): Nodal enriched DOF (jump discontinuity)
  - \( N_i \): Nodes belonging to elements cut by crack
- Crack tip enrichment term
  - \( F_a(x) \): Crack tip asymptotic functions
  - \( b_i^a \): Nodal DOF (crack tip enrichment)
  - \( N_A \): Nodes belonging to elements containing crack tip

Two distinct types of fracture modelling can be used in XFEM techniques. The first one is called cohesive segments approach using traction-separation laws based on the maximum principle stress, normal stress, maximum principle strain or normal strain [11]. For this type of fracture simulation, once the principle strain or stress in element reaches critical values defined in material properties, the crack initiates and propagates until the entire member fractures. The other is linear elastic fracture mechanics approach based on the traditional brittle fracture mechanics [11]. In general, cohesive segments approach is applicable for both brittle and ductile fracture, but linear elastic fracture mechanics approach is only applicable for brittle fracture mechanics [11]. Several experimental results suggest that structural steel demonstrates ductile fracture behaviour at elevated temperature. Therefore, XFEM together with cohesive segments approach are employed in this study to predict fracture behaviour of American structural steel ASTM A992 at elevated temperature up to 1000°C. The process of simulation will be elaborated in the following section.

2. Procedure for simulating fracture behaviour of structural steel

2.1. Steel specimens from tests
The tensile test steel specimens made from American structural steel ASTM A992 used for fracture simulations were reported by Lee et al [12]. These were among the limited test of structural steel in tension at elevated temperature providing adequate data from the beginning of load up to fracture. The ASTM A992 materials used for the steel specimens were defined as MA, MB and MC which were cut from the flange and web of wide-flange sections of ASTM A992 steel. The dimensions of three different specimens are shown in Figure 3. The tension tests were conducted as steady-state temperature tests. The obtained engineering stress-strain data of three specimens were recorded from 20°C up to 1000°C.

![Figure 3. Steel specimens from Lee et al's tests [12].](image)

2.2. Simulation of steel specimens in ABAQUS
Detailed models of above tested specimens were developed in finite element program ABAQUS in version 6.12. In order to obtain the simulation results with reasonable accuracy, material properties of steel should be defined correctly and these include true stress and strain response together with material fracture criterion. It should be noted that true stress represented by loading divided by actual cross sectional area of specimen and true strain represented by instantaneous increment of elongation, cannot be directly measured from tests results due to the change of cross sectional areas in the loading process as well as the complicated stress state after onset of necking. However, accurate true stress and true strain data can be obtained from engineering stress and strain data through calibrating detailed finite element models of tension coupons to match measured engineering stress-strain data.

Once the true stress and strain data are ready for input to material properties, the next part is fracture modelling using XFEM procedure. The detailed specimen model was generated in ABAQUS program with three-dimensional solid brick element (C3D8R). Similar to the boundary conditions in test, one end of the specimen was fixed in each direction, and the other end was free along the axial direction but fixed in other directions. The loading was applied as target displacement with the value of approximately 25mm. The mesh size of the model was defined as approximately 2 mm based on the mesh sensitivity study.

At the beginning of the stage, fracture was not defined in the program; therefore, the simulated engineering stress-strain curves were extended beyond the point at fracture (Figure 4). The aim of this beginning stage is to capture fracture point from engineering stress-strain curves so that the principle logarithmic strain also defined as principle true strain along the loading direction at this point can be calibrated from ABAQUS outputs and further used as the fracture criterion of traction-separation laws. Taking MA specimens at 300°C as example shown in Figure 4, simulation without fracture was compared with test data to locate the fracture point at which the stiffness of material degraded much more significantly than other regions. Then the principle logarithmic strain at this point can be obtained from simulation results and can be taken from the element at the centre of necked area of the model, since fracture initiates at the centre of necked area in specimen according to several experimental observations [13]. Therefore, obtained fracture principle logarithmic strain of necked region was 0.76 mm/mm for MA specimen at 300°C from ABAQUS (see Figure 5).

Figure 4. Engineering stress-strain curve of MA at 300°C from test and simulation without fracture.

Figure 5. Maximum logarithmic strain at centre of specimen.

Once the principle logarithmic strain at fracture was determined, the fracture simulation can be conducted subsequently. By defining material properties of “Damage for Traction Separation Laws” with maximum principle strain equal to 0.76, the fracture criterion was defined. The displacement at fracture can be determined using principle logarithmic strain multiplied by the mesh size in the necked area so that the mesh size effects on the results can be considered. For ductile fracture simulation, cohesive segment approach in XFEM would be appropriate; therefore, cohesive behaviour of the segment should be assigned in the interaction properties to capture material separation in the model. Possible fracture location should be assigned in the model by creating crack domain. The entire model can be assigned with crack domain so that any crack formation in the model can be captured. Further,
in order to make the crack formation and propagation visible, in addition to the force, stress and strain output, failure state of "PHILSM" representing fracture surface and "STATUSXFEM" indicating state of cracked elements should be selected as outputs as well. The formation and development of fracture are shown in Figure 6. The crack was first formed in the necked area in the middle of specimens and was further propagated throughout the cross section. Finally, the specimen was cut by the formed fracture surface and divided into two separate parts. The same phenomenon can be also observed in tests.

**Figure 6.** Fracture formation process in simulation.

The simulated engineering stress-strain curves were compared with tested curves as shown in Figure 7. The failure modes from simulation were compared with those from tests as illustrated in Figure 8. The results for MA specimen at 300°C from simulation agree with tests results quite well. The comparison suggests that the XFEM approach can capture the fracture behaviour of simulated specimen quite well.

**Figure 7.** Comparison of test and simulation results of engineering stress-strain curves for MA 300°C.

**Figure 8.** Failure mode of MA specimen at 300°C from test and simulation.

### 3. Observations from simulation results

#### 3.1. Comparison of simulation and test results at different temperature cases

In this research, three different types of ASTM A992 steel specimens MA, MB and MC were investigated under uniaxial tension and at elevated temperatures. The obtained results of each specimen for each temperature case were illustrated in Figure 9. These figures demonstrate the comparison of engineering stress-strain curves between tests and simulations. Some difference is still observed in the comparison, especially at higher temperatures such as 700°C or 800°C, however, in general, the simulated results match tested results quite well indicating the practicability of XFEM approach to simulating fracture behaviour of steel at elevated temperature.
Figure 9. Comparison of engineering stress-strain curves of three specimens between tests and simulations for each temperature case.
3.2. Sensitivity study of fracture simulation results to selected principle logarithmic strain

In this research, the principle logarithmic strain at fracture of the central element in the necked area was used as critical strain to initiate the fracture. The sensitivity of simulation results to the selected principle logarithmic strains is of interest since the sensitivity study will be useful for generalizing the principle logarithmic strain at fracture and predicting the fracture of other ASTM A992 steel specimens besides MA, MB and MC.

Taking MA specimen at 200°C as example, the sensitivity study of the fracture principle logarithmic strain is only mildly sensitive to small variation of selected logarithmic strain. Based on this limited sensitivity study, it is observed that prediction of fracture based on the principle logarithmic strain criterion is only mildly sensitive to small variation of selected logarithmic strain.

For MA, MB and MC specimen at other temperature cases, the similar observations can be reached. Sensitivity study for MC specimen at 500°C, with the variation of fracture principle logarithmic strain within this range has little effect on the predicted maximum engineering stress. However, results suggest that there is some variation in the predicted engineering stress and strain at fracture as fracture strain is varied.

The same sensitivity study was also performed for MB specimen. Taking MB specimen at 400°C as example, with the change of fracture principle logarithmic strain from 13% to 25%, the maximum predicted engineering stress demonstrates quite little change (See Figure 10(b)), but there is some variation in the predicted engineering stress and strain at fracture (see Figure 10(b) and Table 1).

As for sensitivity study for MC specimen at 500°C, with the variation of fracture principle logarithmic strain from 19% to 38%, the predicted maximum engineering stress is not varied, however, the predicted engineering stress and strain at fracture are changed with the variation of principle logarithmic strain (see Figure 10(c) and Table 1).

For MA, MB and MC specimen at other temperature cases, the similar observations can be reached when the selected principle logarithmic strain at fracture was varied within approximately 15% to 30%. Based on this limited sensitivity study, it is observed that prediction of fracture based on the principle logarithmic strain criterion is only mildly sensitive to small variation of selected logarithmic strain.

![Figure 10. Sensitivity study for selected fracture strain.](image-url)
Table 1. Example of sensitivity study of fracture strain.

| Specimens | Principle logarithmic strain at fracture | Variation of principle logarithmic strain in percentage | Predicted engineering strain at fracture | Variation of predicted engineering strain at fracture in percentage |
|-----------|-----------------------------------------|--------------------------------------------------------|----------------------------------------|---------------------------------------------------------------|
| MA at 200°C | 0.66                                   | 0%                                                     | 0.47                                   | 0%                                                           |
|           | 0.76                                   | 15%                                                    | 0.51                                   | 8%                                                           |
|           | 0.86                                   | 30%                                                    | 0.54                                   | 15%                                                          |
| MB at 400°C | 0.80                                   | 0%                                                     | 0.50                                   | 0%                                                           |
|           | 0.90                                   | 13%                                                    | 0.53                                   | 6%                                                           |
|           | 1.00                                   | 25%                                                    | 0.58                                   | 15%                                                          |
| MC at 500°C | 0.53                                   | 0%                                                     | 0.32                                   | 0%                                                           |
|           | 0.63                                   | 19%                                                    | 0.34                                   | 6%                                                           |
|           | 0.73                                   | 38%                                                    | 0.36                                   | 13%                                                          |

3.3 Generalized fracture strains for fracture simulation of structural steel at elevated temperature

According to the simulation results of MA, MB and MC specimens at room temperature and elevated temperature, the simulation results agree with tests results quite well in general. The principle logarithmic strain criterion in simulations is summarized and generalized as Figure 11. Below and inclusive 600°C, the fracture principle logarithmic strains are all lower than 1.0 mm/mm, but for 700°C and 800°C temperature cases, they are higher than 1.0 mm/mm, and then as for 900°C and 1000°C cases, they are dropped below 1.0 mm/mm again.

From Table 2, the critical logarithmic strains in simulations for MA, MB and MC were relatively consistent from 200°C to 600°C as well as 1000°C. The maximum difference of the fracture principle logarithmic strains between that for each specimen and average value for three specimens are no more than 8%. According to previous sensitivity study for selected principle logarithmic strain, the variation of the strain within approximately 15%, the variation of predicted results were approximately 6% to 8%. Therefore, using average value of critical strains may still predict the fracture behavior of those specimens with reasonable accuracy. But cautions should be made when average values of principle logarithmic strain at 20°C, 700°C, 800°C and 1000°C are used for fracture simulations, because large difference exists in principle logarithmic strains among MA, MB and MC indicative of inconsistence in fracture criterion for simulations at these temperature cases by using XFEM. More tests on different types of specimens are still needed at these temperatures to investigate this inconsistence.

Figure 11. Summary of critical logarithmic strain at fracture for different temperature cases.
Table 2. Summary of principle logarithmic strain at fracture for fracture simulation of ASTM A992 steel at elevated temperature.

| Temperature | Principle Logarithmic Strain at Fracture |            |            | Average |
|-------------|-----------------------------------------|------------|------------|---------|
|             | MA                                      | MB         | MC         |         |
| 20°C        | 0.93                                    | 0.60       | 0.83       | 0.79    |
| 200°C       | 0.66                                    | 0.63       | 0.57       | 0.62    |
| 300°C       | 0.76                                    | 0.78       | 0.81       | 0.78    |
| 400°C       | 0.75                                    | 0.80       | 0.70       | 0.75    |
| 500°C       | 0.70                                    | 0.66       | 0.60       | 0.65    |
| 600°C       | 0.94                                    | 0.95       | 0.90       | 0.93    |
| 700°C       | 1.37                                    | 1.20       | 1.10       | 1.22    |
| 800°C       | 1.80                                    | 1.20       | 1.10       | 1.37    |
| 900°C       | 0.90                                    | 0.94       | 0.90       | 0.91    |
| 1000°C      | 0.48                                    | 0.80       | 0.50       | 0.59    |

4. Conclusion and future research

Work presented in this study has demonstrated the feasibility of simulating fracture behaviour of ASTM A992 steel tension specimens at elevated temperatures using extended finite element method (XFEM). In addition, fracture principle logarithmic strain as fracture criterion for XFEM approach was also generalized for fracture simulations for structural steels. Several conclusions are reached as follows:

- Fracture behaviour of steel tension specimen can be simulated not only by using traditional fracture models but also by using extended finite element method. In general, the principle logarithmic strain or principle stress is needed to initiate the fracture in simulations.
- Based on study of different type of ASTM A992 steel specimens, the simulation results using XFEM approaches match test results quite well at the elevated temperatures above 200°C and below 1000°C.
- As for the fracture criterion described in this research, study suggests that the fracture principle logarithmic strains of three different specimens at same temperature case are quite consistent in general; prediction of fracture based on the principle logarithmic strain criterion is only mildly sensitive to small variation of selected logarithmic strain; and the maximum predicted engineering stress is not affected by the variation of fracture logarithmic strains if other material properties are not changed.

In general, this study has demonstrated the potential for reasonable computational prediction of fracture for ASTM A992 tensile test specimens under ambient and elevated temperatures. The proposed modelling procedure and generalized logarithmic fracture strain can be used as reference for fracture simulation of the same material. However, there are still some limitations existing in this study. Firstly, the work is mainly based on the limited experimental data from three different types of steel specimens made from ASTM A992; therefore, further research work is also needed on a sufficient number of samples of steel to quantify variability and uncertainty in fracture prediction. In addition, large difference observed in logarithmic strains at fracture at same temperature may be due to either the material variability or effects from modelling technique such as mesh size, element type, model geometry etc. Thus, modelling technique effects on fracture simulation accuracy should be investigated in the further research.

5. References

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