Verification of the accuracy of OpenSees calculations under fire temperatures

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1 Introduction

To verify the precision of OpenSees in calculating the mechanical behavior of steel at high temperatures, two key indicators, namely Young's modulus (E) and the yield strength (f_y), are selected for testing.

Reference values are taken from carbon steel reduction factors at elevated temperatures as specified in the *EN 1993-1-2:2005* standards, along with experimental data on material stress-strain variations.

By analyzing changes in E and f_y under increasing temperature loading in OpenSees, our objective is to assess whether the results obtained comply with standard requirements.

2 Reduction Factors for Steel at High Temperatures

EN 1993-1-2 specifies that when steel is exposed to elevated temperatures (θ), its effective yield strength ($f_{y,\theta}$), proportional limit ($f_{p,\theta}$), and Young's modulus ($E_{a,\theta}$) undergo certain reductions due to thermal effects and microstructural changes. These reduction factors are defined as follows:

- **Effective yield strength**, relative to yield strength at 20°C: $k_{y,\theta} = \frac{f_{y,\theta}}{f_y}$
- **Proportional limit**, relative to yield strength at 20°C: $k_{p,\theta} = \frac{f_{p,\theta}}{f_y}$
- **Slope of linear elastic range**, relative to slope at 20°C: $k_{E,\theta} = \frac{E_{a,\theta}}{E_a}$

Table 1: Reduction factors for stress-strain relationship of carbon steel at elevated temperatures

Steel Temperature θ	$k_{y,\theta} = \frac{f_{y,\theta}}{f_y}$	$k_{p,\theta} = \frac{f_{p,\theta}}{f_y}$	$k_{E,\theta} = \frac{E_{a,\theta}}{E_a}$
20°C	1.000	1.000	1.000
100°C	1.000	1.000	1.000
200°C	1.000	0.807	0.900
300°C	1.000	0.613	0.800
400°C	1.000	0.420	0.700
500°C	0.780	0.360	0.600
600°C	0.470	0.180	0.310
700°C	0.230	0.075	0.130
800°C	0.110	0.050	0.090
900°C	0.060	0.0375	0.0675
1000°C	0.040	0.0250	0.0450
1100°C	0.020	0.0125	0.0225
1200°C	0.000	0.0000	0.0000

NOTE: For intermediate values of the steel temperature, linear interpolation may be used.

3 OpenSees Model

3.1 Model Assumptions

3.1.1 Material Properties

The selected material model is `Steel01Thermal`, which includes the temperature-dependent properties of carbon steel at elevated temperatures according to EN 1993-1-2. The material parameters are defined as follows:

- Initial Young's modulus: $E_s = 210,000$ MPa
- Initial yield strength: $F_y = 250$ MPa
- Strain-hardening ratio: 0.001

3.1.2 Section Fiber Discretization

A fiber discretization of 15×15 is adopted, with an error range of $\frac{1}{N^2}$=$\frac{1}{15^2}$ =0.44%. This selection ensures a balance between computational efficiency and accuracy.

3.2 Loading Conditions

The model consists of a steel beam with a length of 1000 mm and a cross-section of 100 mm $\times$ 100 mm. One end is fixed, while the other remains free. The fire loading is applied as a linear temperature increase up to T_{end} to simulate fire exposure. The simulations are performed for $T_{\text{end}} = 100, 200, 300, \ldots, 1000$ °C.

4 Computation Results and Analysis

4.1 Stress-Strain Curves

As shown in Figure 1 (OpenSees simulation) and Figures 2 (experimental results), the stress-strain curves of steel at different temperatures exhibit a similar trend. As the temperature increases, the stress decreases significantly, reflecting a reduction in yield strength.

Regarding the discrepancies in the data, as observed in the paper by Ju Chen[1], there exist considerable differences between the experimental data and the design codes. The reduction factors derived from actual experiments may not necessarily align with those specified in the codes. OpenSees strictly follows the EN 1993 standard for calculations, as indicated in its source code at line 593. [2] Therefore, the deviation between the OpenSees estimated curves and the experimental curves is possible.

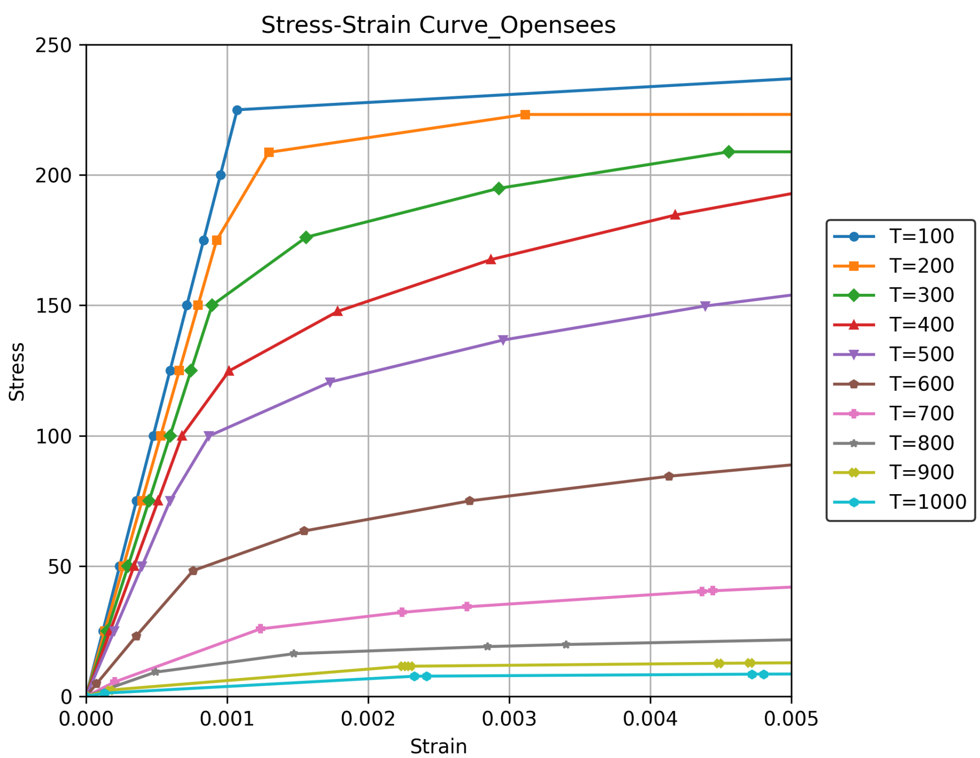
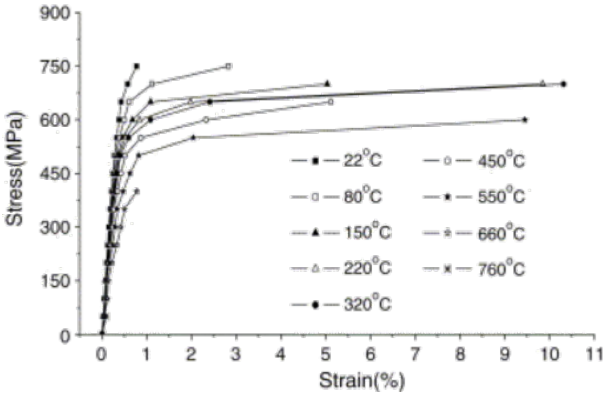
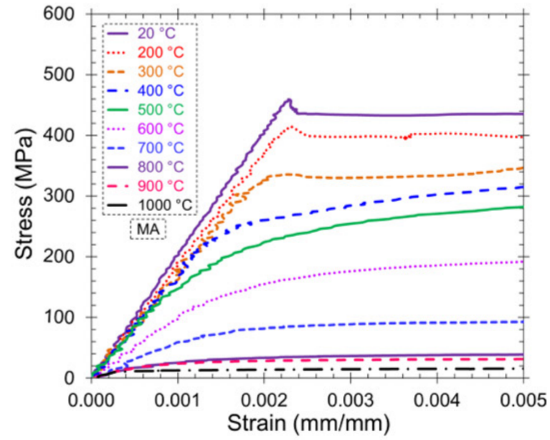


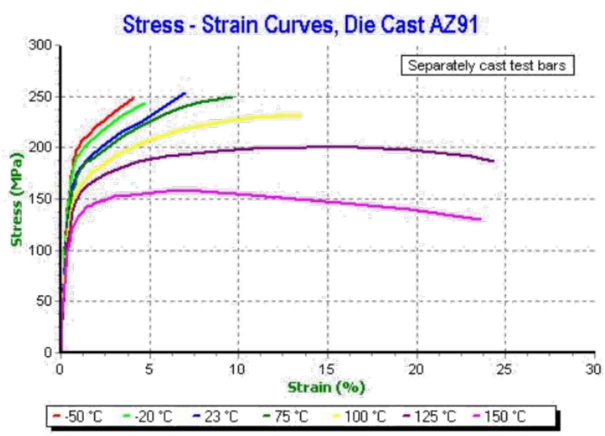
Figure 1: Stress-Strain Curve from OpenSees Simulation



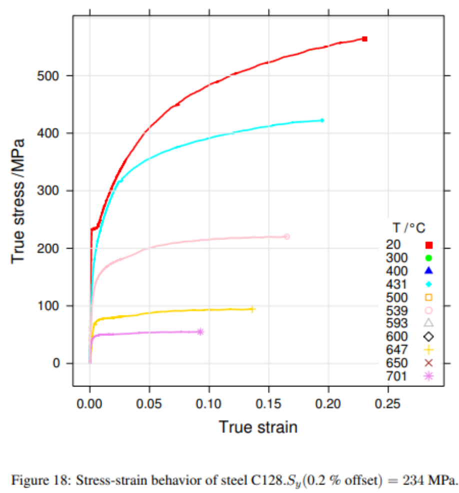
(a) Material: Steel EN 1.4462[1]



(b) Material: Steel A992[3]



(c) Material: **AZ91**[4]



(d) Material: **C128**[5]

Figure 2: Stress-Strain Curves from Experimental Data

Table 2: Material Properties: Young's Modulus (E) and Yield Strength (f_y)

Material	E (GPa)	f_y (MPa)
Steel EN 1.4462	870	227
Steel A992	455	200
AZ91	160	45
C128	585	200

4.2 Yield Strength

According to the EN 1993-1-2:2005 standard, the effective yield strength $f_{y,\theta}$ is taken as the stress value corresponding to the plateau region(Figure 3).The last point of the plateau segment in the OpenSees simulation results is extracted as the effective yield strength, and the corresponding $k_{y,\theta}$ is calculated.

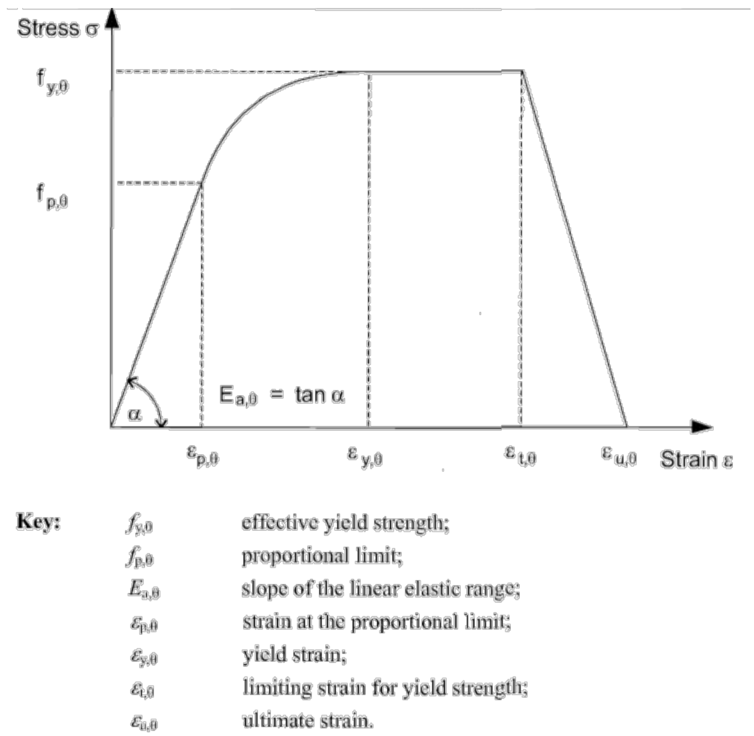


Figure 3: Definition of Effective Yield Strength in Steel

As shown in the Table3, the yield strength reduction factors of steel under tensile loading in a linear heating environment, as simulated by OpenSees, are consistent with the values specified in the standard.

Table 3: Comparison of Reduction Factor and OpenSees Results

Standard		**OpenSees**			
Temperature	$k_{y,\theta}$	Temperature	Stress	Strain	Stress/250
20	1				
100	1				
200	1	200	250	23.4339	1
300	1	300	250	24.4323	1
400	1	400	250	24.6373	1
500	0.78	500	195	30.1472	0.78
600	0.47	600	117.5	35.6463	0.47
700	0.23	700	57.5	39.8201	0.23
800	0.11	800	27.5	42.2911	0.11
900	0.06	900	15	43.257	0.06
1000	0.04	1000	10	43.5256	0.04
1100	0.02				
1200	0				

5 Conclusion

The effective yield strength calculated by OpenSees is consistent with the EN 1993-1-2 standard. The stress-strain curves exhibit a similar trend to the experimental results, showing a decrease in yield strength and an increase in plastic deformation capacity with rising temperature. However, full conformity with specific experimental data has not been verified.

6 Potential Improvements

1. No experimental material with properties similar to the Steel01Thermal model used in OpenSees was found, making it impossible to accurately verify the data points.

2. The reduction factors of yield strength match the standard because OpenSees inherently adopts the reduction coefficients from the EN 1993 table in its core computations for E and f_y[2]. It is difficult to prove that every point in the linear heating simulation matches the actual conditions perfectly.

References

[1] J. Chen and B. Young, "Stress–strain curves for stainless steel at elevated temperatures," *Engineering Structures*, vol. 28, no. 2, pp. 229–239, 2006. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0141029605002762

[2] OpenSees Development Team, "Steel01Thermal Source Code," 2024. [Online]. Available: https://github.com/OpenSees/OpenSees/blob/fe578a5b51333e5489097f327f89d16de0797f56/SRC/material/uniaxial/Steel01Thermal.cpp

[3] W. Cai, M. A. Morovat, and M. D. Engelhardt, "True stress-strain curves for astm a992 steel for fracture simulation at elevated temperatures," *Journal of Constructional Steel Research*, vol. 139, pp. 272–279, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0143974X17302626

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[5] W. Luecke, S. Banovic, and J. McColskey, "High-temperature tensile constitutive data and models for structural steels in fire," 2011-11-30 2011.