Aalto University
School of Engineering

COE-C2004 - Materials Science and Engineering

Exercise 3

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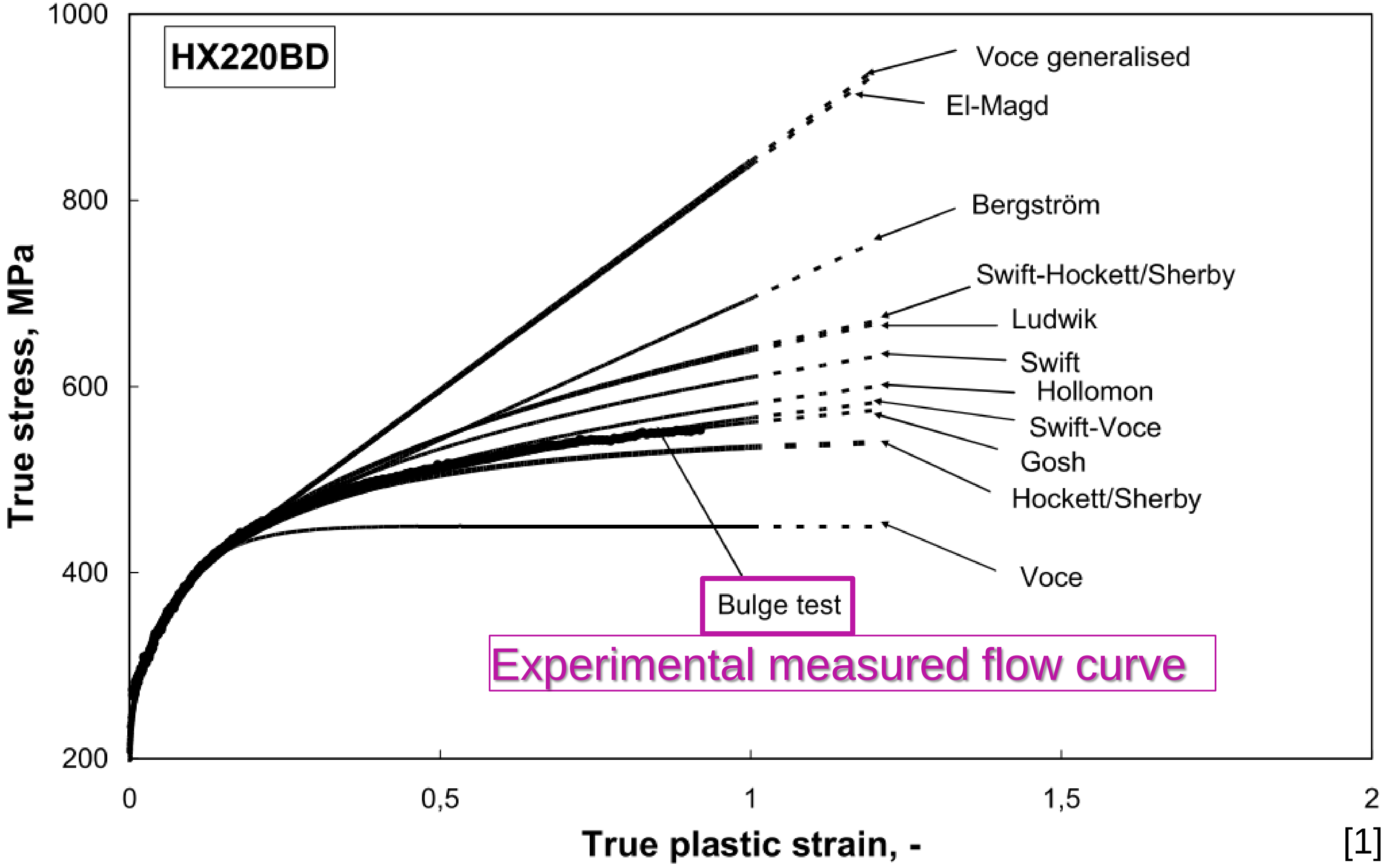
Outline

- Software introduction
  - Materials hardening law
  - ABAQUS

Materials hardening law - Flow curve derivation

Materials hardening law



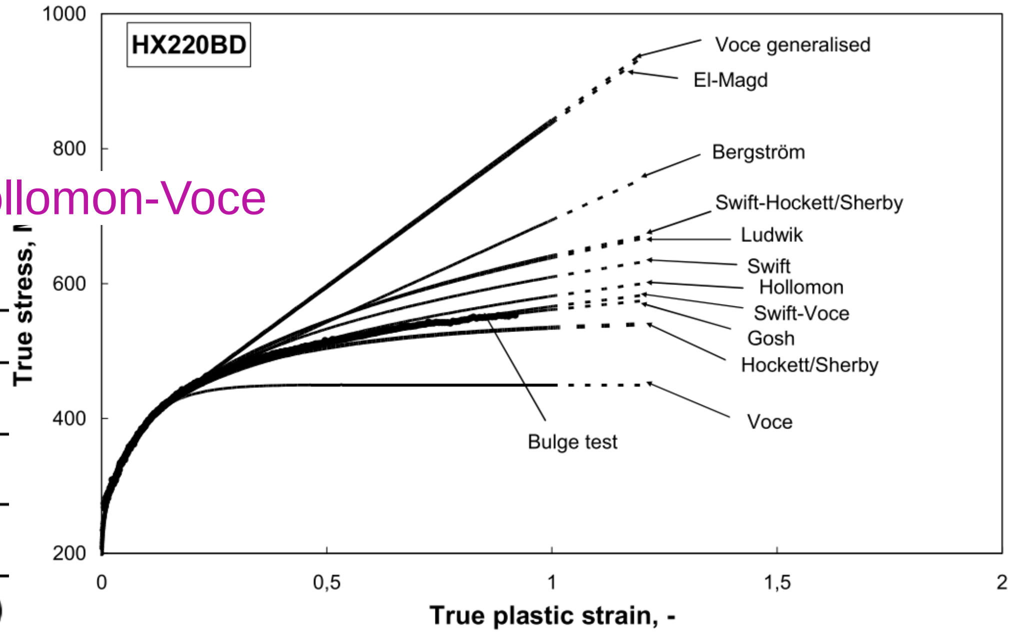
[1]

- In numerical simulation, a smooth and extended flow curve is necessary.
- waved exp. data
- in Abaqus, the strain value shall be always in increasing order
- measured true strain limitation ~<1
- local true strain could >2~3 during deformation

⇨ Flow curve derivation based on mathematic functions, i.e. hardening laws.

Materials hardening law

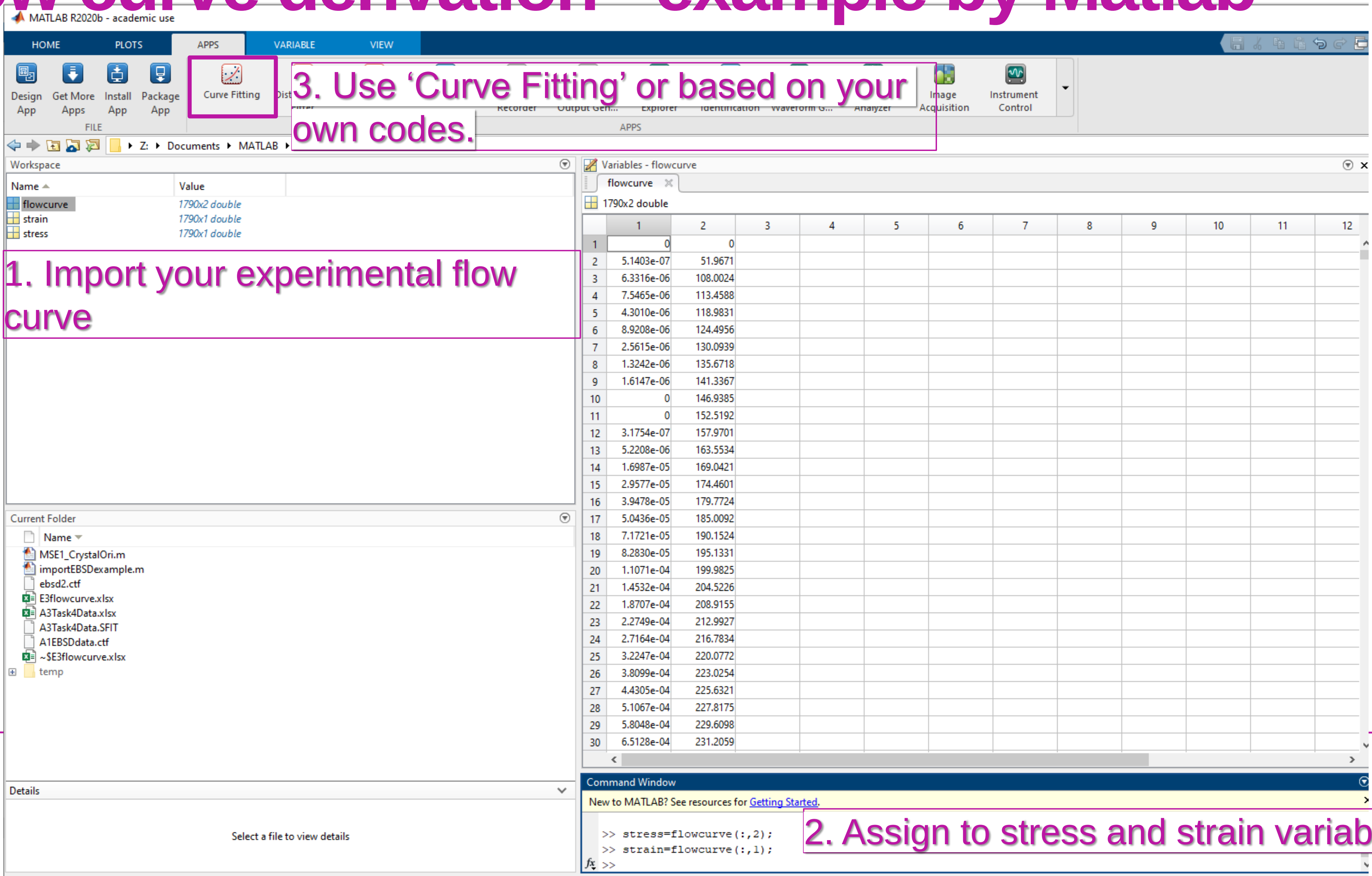
- Individual or combined format, e.g. combined Swift-Voce or Hollomon-Voce



Model	equation
Hollomon [25]	$\sigma(\varepsilon)=C_1.\varepsilon^{C_2}$
Ludwik [26]	$\sigma(\varepsilon)=C_1+C_2.\varepsilon^{C_3}$
Swift [27]	$\sigma(\varepsilon)=C_1.(C_2+\varepsilon)^{C_3}$
Voce [28]	$\sigma(\varepsilon)=C_1+(C_2-C_1).\exp(-C_3.\varepsilon)$
Hockett/Sherby [29]	$\sigma(\varepsilon)=C_2-(C_2-C_1).\exp(-C_3.\varepsilon^{C_4})$
Gosh [30]	$\sigma(\varepsilon)=C_1+C_2.(C_3+\varepsilon)^{C_4}$
Swift-Voce [31]	$\sigma(\varepsilon)=C_1.\sigma_{Swift}(\varepsilon)+(1-C_2).\sigma_{Voce}(\varepsilon)$
Swift-Hockett/Sherby [32]	$\sigma(\varepsilon)=C_1.(C_2+\varepsilon)^{C_3}+C_4.\exp(-C_5.\varepsilon^{C_6})$
El-Magd [33]	$\sigma(\varepsilon)=C_1+C_2.\varepsilon+C_3.[1-\exp(-C_4.\varepsilon)]$
Voce generalised [34]	$\sigma(\varepsilon)=C_1+(C_2+C_3.\varepsilon).[1-\exp(-C_4.\varepsilon)]$
Bergström [35], [36]	$\sigma(\varepsilon)=C_1+C_2.\left(C_3.(C_4+\varepsilon)+\{1-\exp[-C_5.(C_4+\varepsilon)]\}^{C_6}\right)$

[1]

Flow curve derivation - example by Matlab

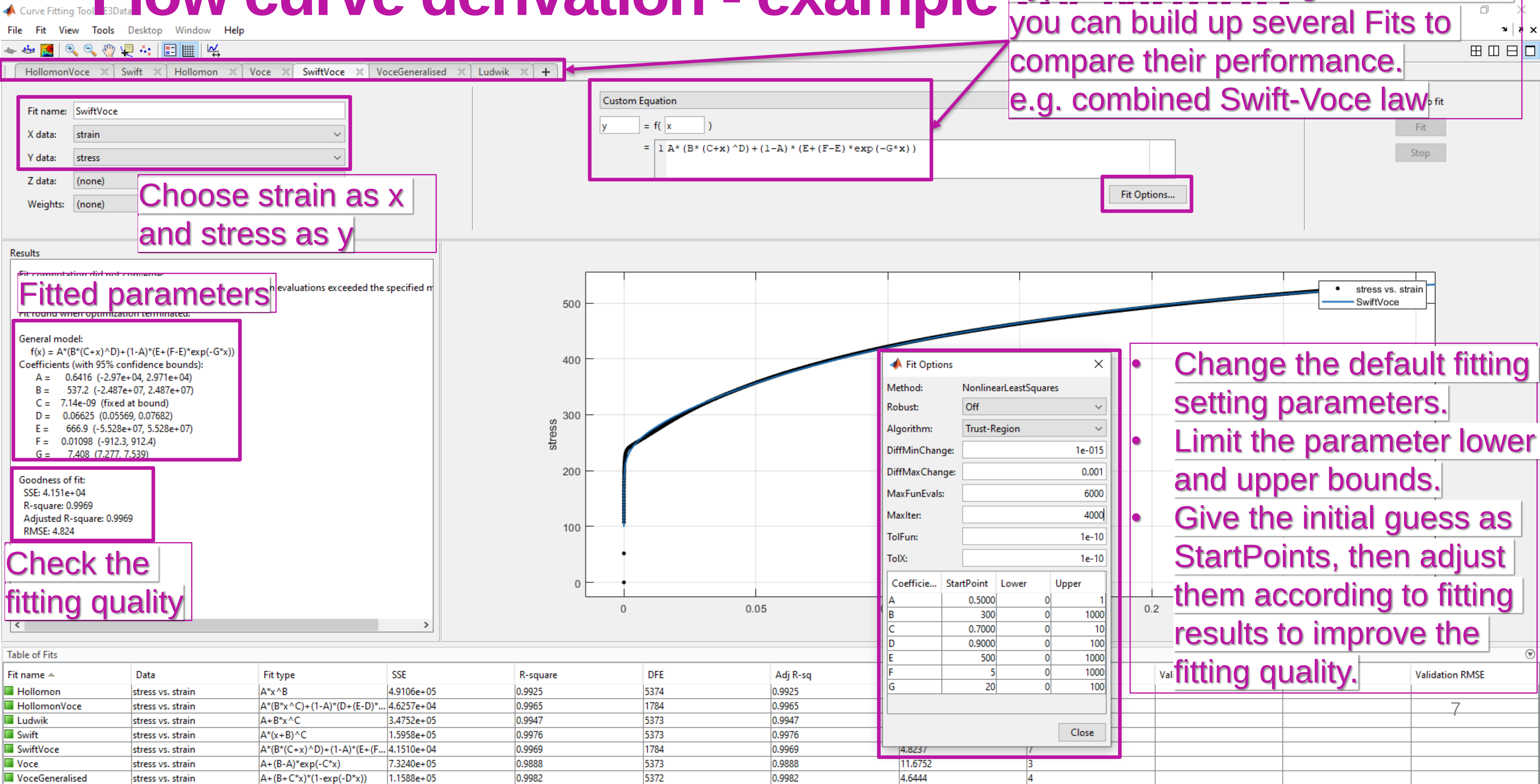


3. Use 'Curve Fitting' or based on your own codes.

1. Import your experimental flow curve

2. Assign to stress and strain variables

Flow curve derivation - example



Type in the hardening law function, you can build up several Fits to compare their performance. e.g. combined Swift-Voce law

Choose strain as x and stress as y

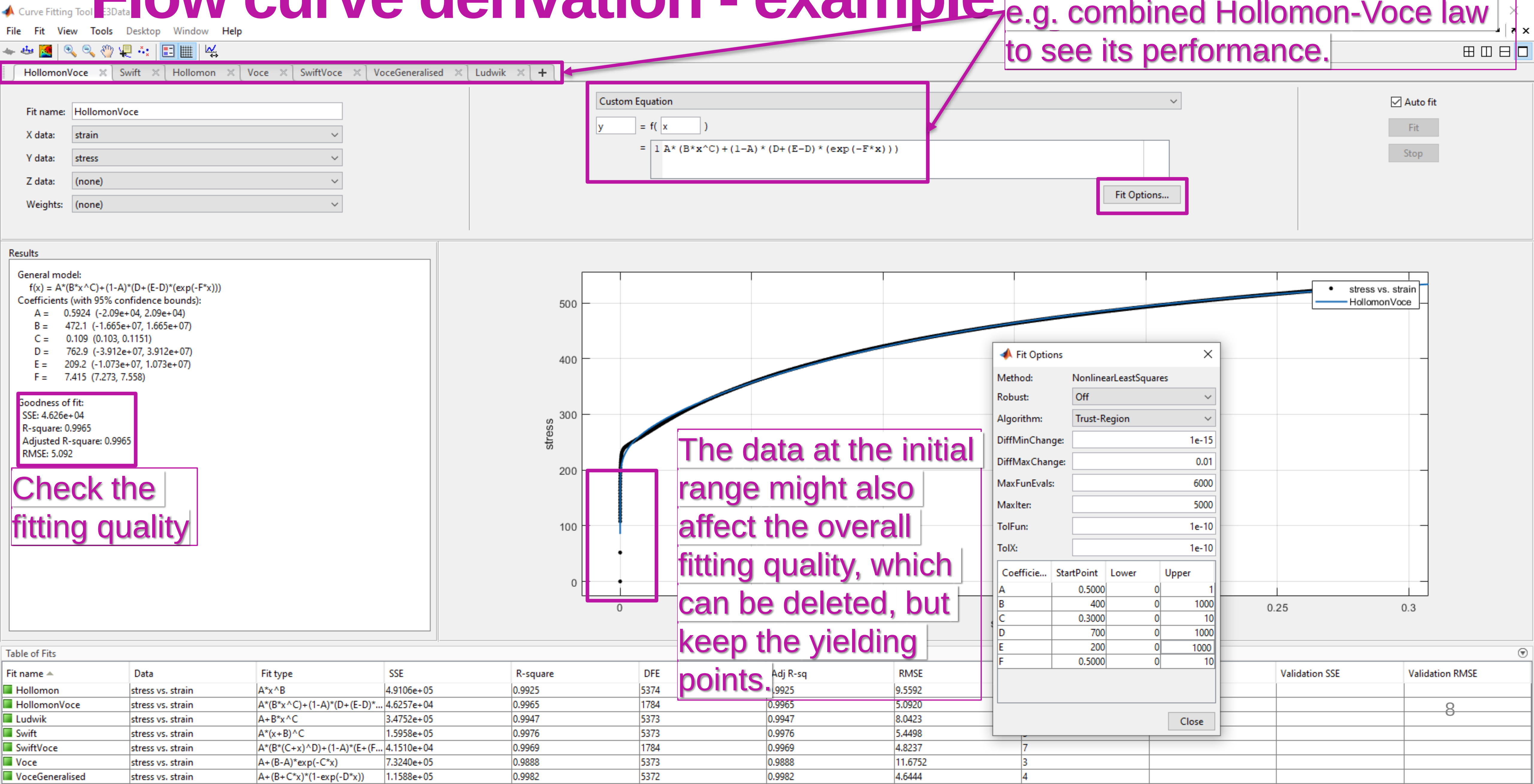
Fitted parameters

Check the fitting quality

- Change the default fitting setting parameters.
- Limit the parameter lower and upper bounds.
- Give the initial guess as StartPoints, then adjust them according to fitting results to improve the fitting quality.

Flow curve derivation - example

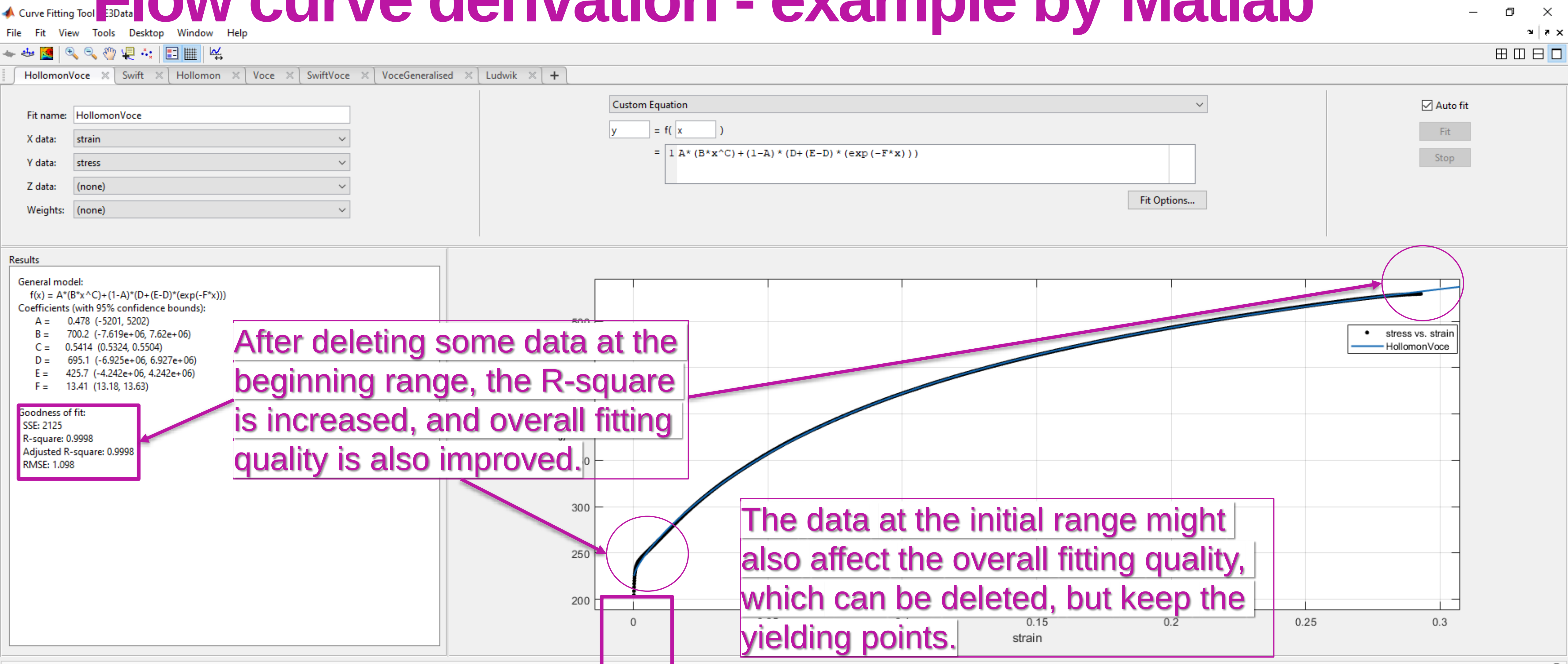
Change to another hardening law, e.g. combined Hollomon-Voce law to see its performance.



Check the fitting quality

The data at the initial range might also affect the overall fitting quality, which can be deleted, but keep the yielding points.

Flow curve derivation - example by Matlab



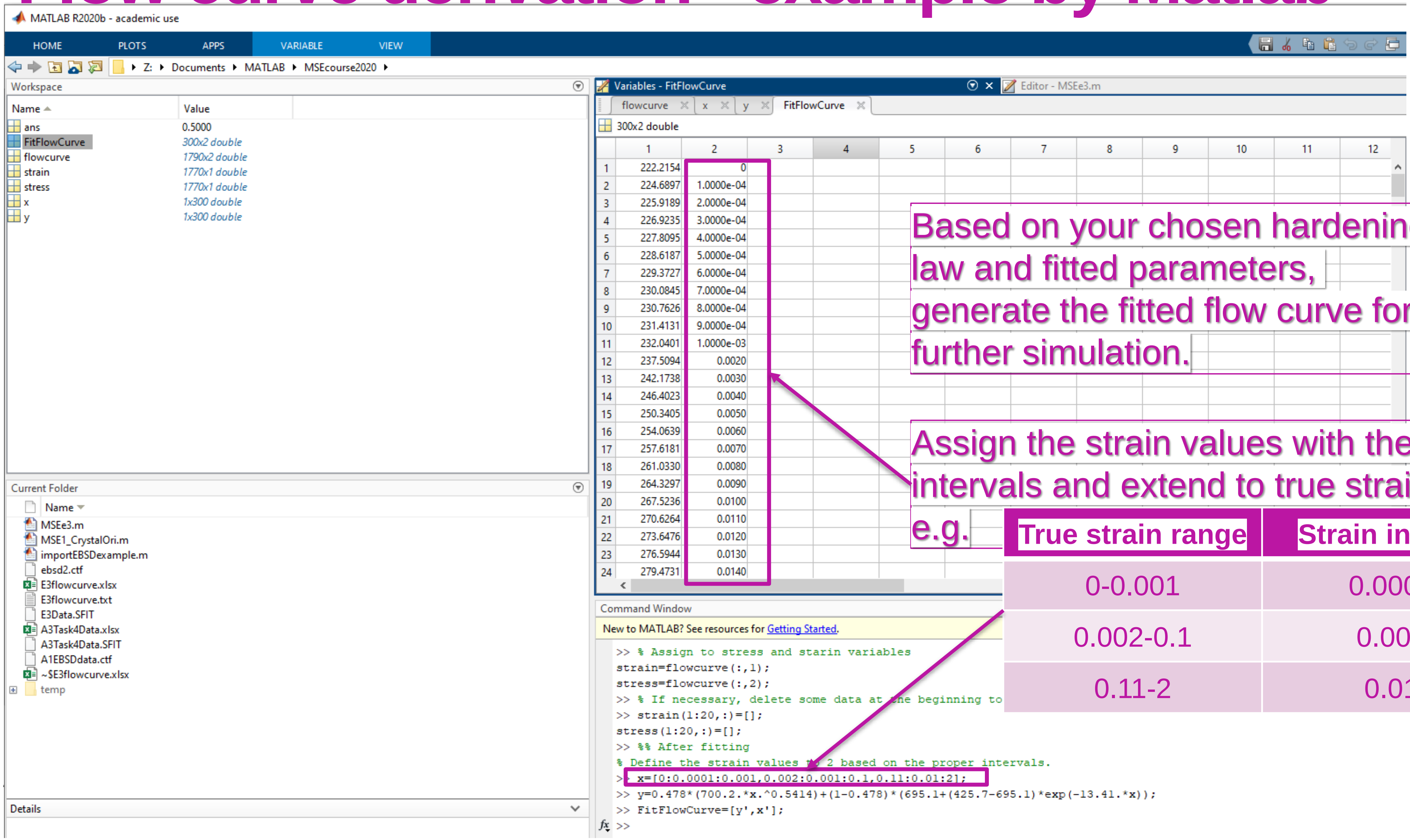
After deleting some data at the beginning range, the R-square is increased, and overall fitting quality is also improved.

The data at the initial range might also affect the overall fitting quality, which can be deleted, but keep the yielding points.

Table of Fits

Fit name	Data	Fit type	SSE	R-square	DFE	Adj R-sq	RMSE	# Coeff	Validation Data	Validation SSE	Validation RMSE
Hollomon	stress vs. strain	A*x^B	4.9106e+05	0.9925	537[illegible]	0.9925	9.5592	2			
HollomonVoce	stress vs. strain	A*(B*x^C)+(1-A)*(D+(E-D)*...	2.1251e+03	0.9998	176[illegible]	0.9998	1.0976	6			
Ludwik	stress vs. strain	A+B*x^C	3.4752e+05	0.9947	5373	0.9947	8.0423	3			
Swift	stress vs. strain	A*(x+B)^C	1.5958e+05	0.9976	5373	0.9976	5.4498	3			
SwiftVoce	stress vs. strain	A*(B*(C+x)^D)+(1-A)*(E+(F...	4.1510e+04	0.9969	1784	0.9969	4.8237	7			
Voce	stress vs. strain	A+(B-A)*exp(-C*x)	7.3240e+05	0.9888	5373	0.9888	11.6752	3			
VoceGeneralised	stress vs. strain	A+(B+C*x)*(1-exp(-D*x))	1.1588e+05	0.9982	5372	0.9982	4.6444	4			

Flow curve derivation - example by Matlab



Based on your chosen hardening law and fitted parameters, generate the fitted flow curve for further simulation.

Assign the strain values with the proper intervals and extend to true strain of 2, e.g.

True strain range	Strain interval
0-0.001	0.0001
0.002-0.1	0.001
0.11-2	0.01

Flow curve derivation - example by Matlab

- Summary

```
%% Import the exp. data
% Assign to stress and starin variables
strain=flowcurve(:,1);
stress=flowcurve(:,2);

%% Fit the exp. flow curve by 'Curve Fitting' or your own codes.

%% To improve the fitting quality, you can delete some data at the beginning range.
strain(1:20,:)=[];
stress(1:20,:)=[];

%% After fitting
% Define the strain values to 2 based on the proper intervals.
x=[0:0.0001:0.001,0.002:0.001:0.1,0.11:0.01:2];
% Calculate the stress according to the fitted harndening law.
% e.g. the combined Hollomon-Voce law.
y=0.478*(700.2.*x.^0.5414)+(1-0.478)*(695.1+(425.7-695.1)*exp(-13.41.*x));
% Obtain your fitted flow curve for Abaqus simulation.
FitFlowCurve=[y',x'];
```

Tip: The flow curve fitting and extension can also be achieved by Origin, Excel, Python, etc.