User Manual

Cyclic Plasticity Model of Structural Steels

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May 30, 2016

Outline

1. Install ABAQUS, VS & IVF
2. Configure ABAQUS to run user subroutines
3. Model calibration
4. Step-by-step procedure to use UMAT
5. Application

1. Install ABAQUS, VS & IVF

Available choices for compatibility

- **Abaqus 6.10/6.11/6.12**
  Visual Studio 2008/2010
  Intel Visual Fortran Composer XE 2011
- **Abaqus 6.13**
  Visual Studio 2012
  Intel Visual Fortran Composer XE 2013
- **Abaqus 6.14 (Recommended on Windows 10)**
  Visual Studio 2013
  Intel Visual Fortran Composer XE 2013
- **Abaqus 2016 ?** **VS should be installed before IVF**

2. Configure ABAQUS

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Edit with Notepad

C:\SIMULIA\Abaqus\Commands\abq6145.bat

```
@echo off
"C:\SIMULIA\Abaqus\6.14-5\code\bin\abq6145.exe" %*
```

```
@call "C:\Program Files (x86)\Microsoft Visual Studio 12.0\VC\vcvarsall.bat" x64
@call "C:\Program Files (x86)\Intel\Composer XE 2013 SP1\bin\ipsxe-comp-vars.bat" intel64 vs2013
@echo off
"C:\SIMULIA\Abaqus\6.14-5\code\bin\abq6145.exe" %*
```

Run Abaqus Verification

Abaqus …… with user subroutines
PASS

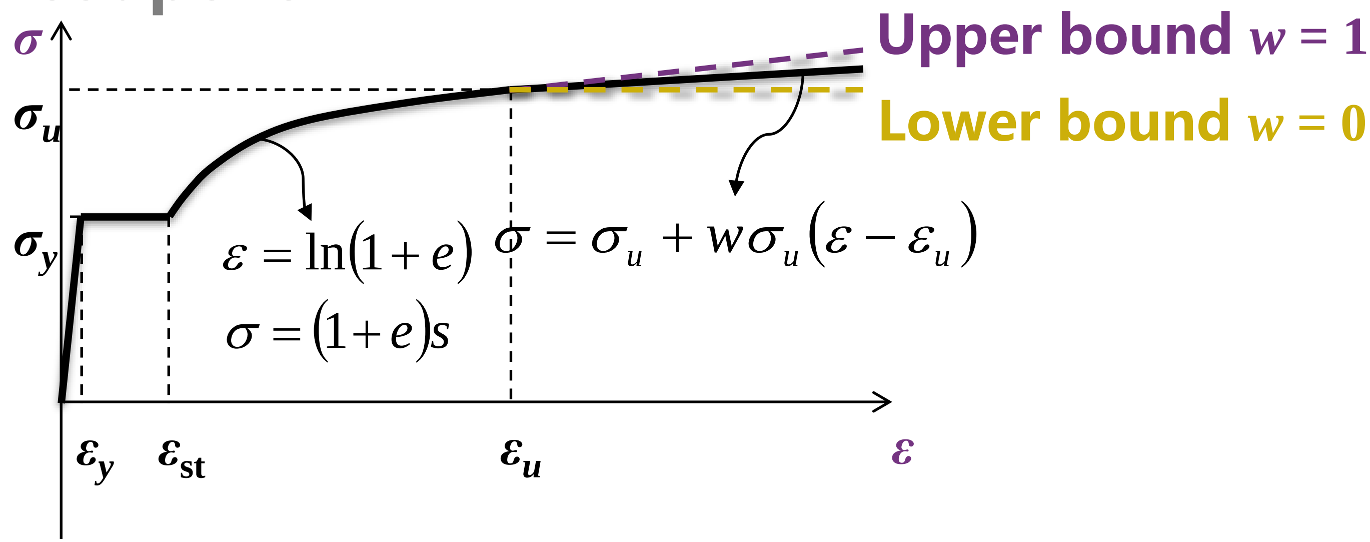
Write your subroutines now !

3. Model calibration

○ Structural steels with yield plateau

- **First, obtain the monotonic true stress – true strain curve using tension coupon test.**

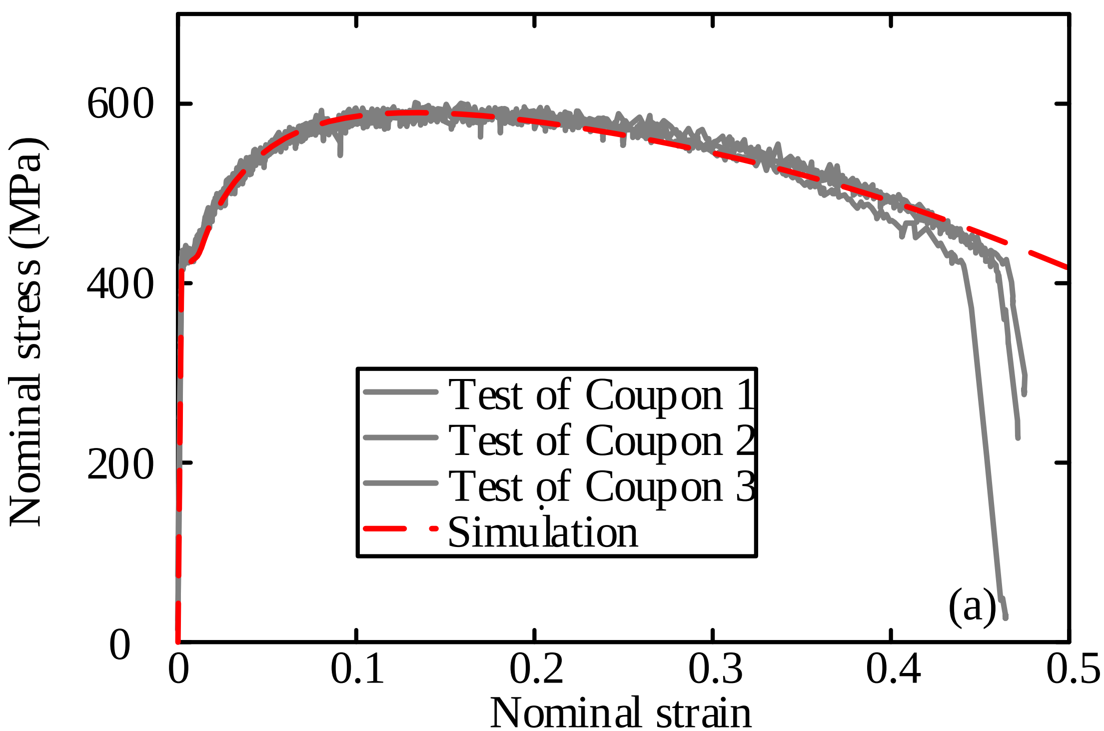
s, e	nominal stress and strain
ε, σ	true stress and strain
w	calibrated by numerical simulation of coupons

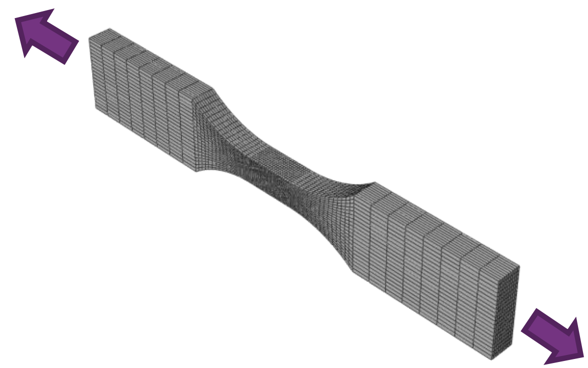


3. Model calibration

Structural steels with yield plateau

- **An example to calibrate w**





Q345 steel

Approximate best-fitting value
$w = 0.6$

3. Model calibration

Structural steels with yield plateau

- Second, evaluate all those parameters by using only the monotonic true stress – true strain curve.

monotonic

v	Possion's ratio
E	Elastic modulus
σ_y	yield stress
$\varepsilon_{\mathrm{st}}^{\mathrm{p}}$	plastic strain at the end of yield plateau

cyclic

plateau region

$\bar{\varepsilon}_{\mathrm{st}}^{\mathrm{p}}$	Threshold
c^s	Memory scalar
Q_1^s b_1^s	Isotropic softening
C_1^s γ_1^s C_2^s γ_2^s	Kinematic hardening

hardening region

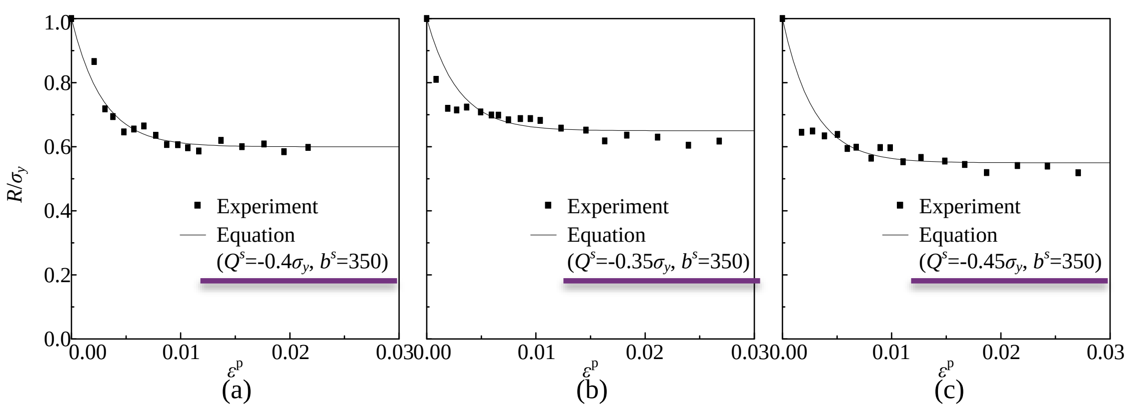
c^l	Memory scalar
Q_1^l b_1^l	Isotropic hardening
C_1^l γ_1^l C_2^l γ_2^l	Kinematic hardening

3. Model calibration

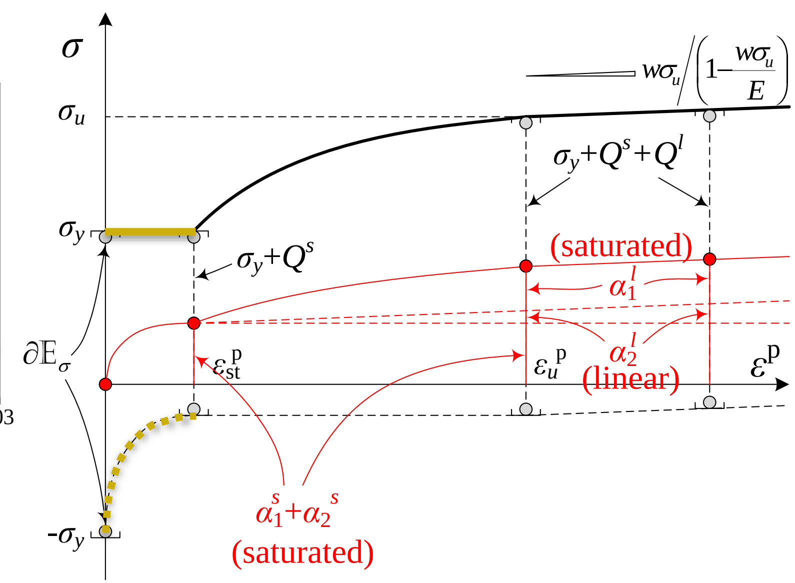
Structural steels with yield plateau

- Saturation of softening for the yield surface should be completed within the yield plateau in the case of monotonic loading.

$$\boxed{Q_1^s = -(0.3 \sim 0.5)\sigma_y \quad \text{and} \quad b_1^s = 300 \sim 400}$$



SS400 **SM570** **LYR60**



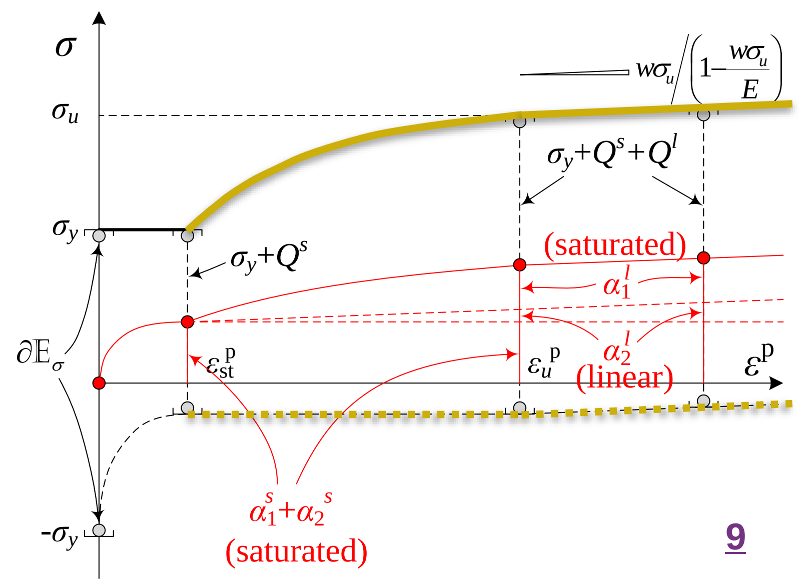
3. Model calibration

Structural steels with yield plateau

- The lower bound of elastic range remains unchanged after strain hardening initiates until the ultimate stress, and the expansion of the yield surface should be completed at the ultimate stress in the case of monotonic loading.

$$\boxed{Q_1^l = \frac{\sigma_u - \sigma_y}{2}}$$

The saturation rate $\boxed{b_1^l}$ is obtained by a best fitting of the monotonic loading curve.



3. Model calibration

○ Structural steels with yield plateau

- **Consistency condition**

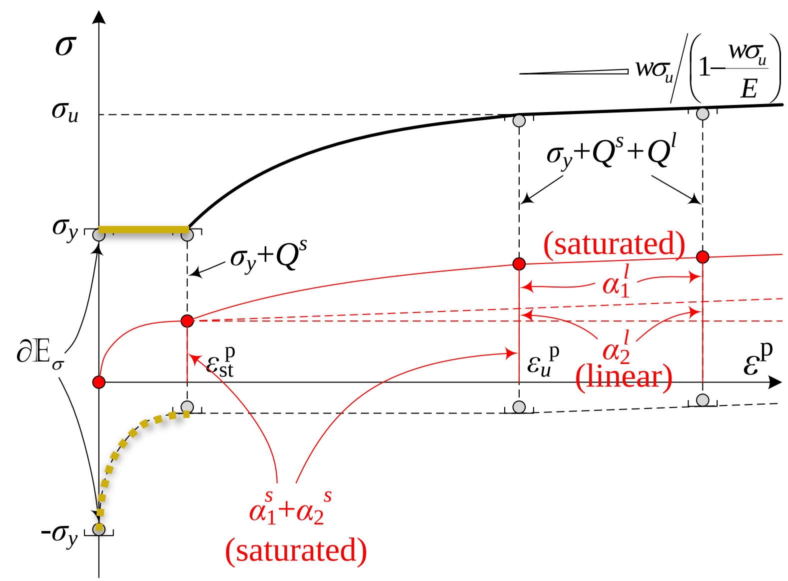
$$\sum_{j=1}^{2} \frac{C_j^s}{\gamma_j^s} = -Q_1^s \qquad \min_j \left(\gamma_j^s\right) \geq b_1^s$$

- **Empirical assumption**

$$\boxed{\gamma_1^s = 10\gamma_2^s \quad \text{and} \quad \gamma_2^s = b_1^s}$$

$$\boxed{\frac{C_1^s}{\gamma_1^s} = -\frac{1}{3} Q_1^s}$$

$$\boxed{\frac{C_2^s}{\gamma_2^s} = -\frac{2}{3} Q_1^s}$$



3. Model calibration

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Structural steels with yield plateau

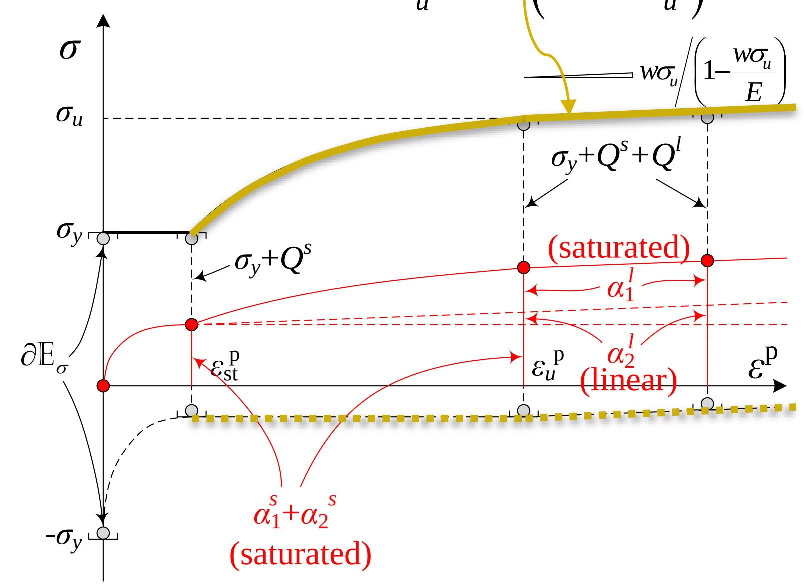
- It is natural to set one long-range backstress component as nonlinear and the other as linear.

$$H = \frac{w\sigma_u}{1-\frac{w\sigma_u}{E}}$$

$$\sigma = \sigma_u + H\left(\varepsilon^{\mathrm{p}} - \varepsilon_u^{\mathrm{p}}\right)$$

$$\boxed{C_2^l = H \quad \text{and} \quad \gamma_2^l = 0}$$

$$\boxed{\frac{C_1^l}{\gamma_1^l} = \frac{\sigma_u - \sigma_y}{2} - H\left(\varepsilon_u^{\mathrm{p}} - \varepsilon_{\mathrm{st}}^{\mathrm{p}}\right)}$$



The saturation rate $\boxed{\gamma_1^l}$ is obtained by a best fitting of the monotonic loading curve.

3. Model calibration

Structural steels <u>with</u> yield plateau

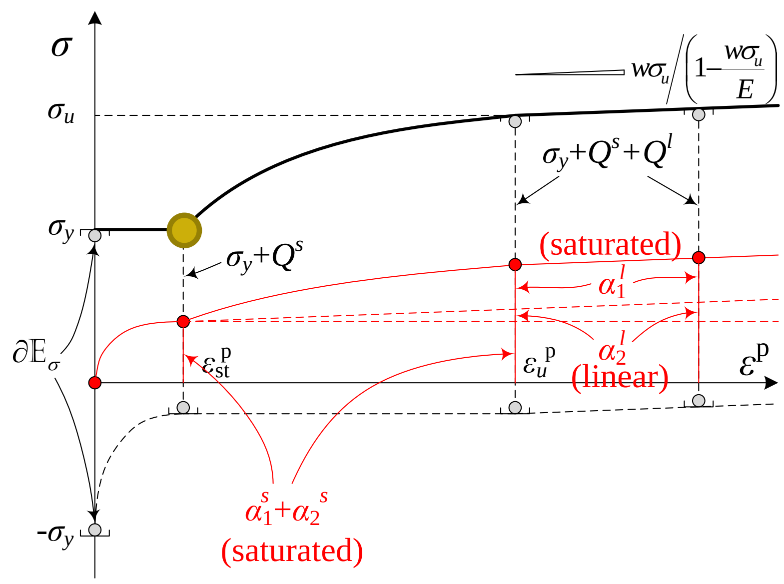
- Additional requirement to correctly capture the transition from the yield plateau to the hardening region for monotonic loading.

$$\boxed{\bar{\varepsilon}_{\mathrm{st}}^{\mathrm{p}} \leq c^{s} \varepsilon_{\mathrm{st}}^{\mathrm{p}}}$$

Empirical values:

$$\boxed{\bar{\varepsilon}_{\mathrm{st}}^{\mathrm{p}} = 0.4\% \sim 0.6\%}$$

$$\boxed{c^{s} = 0.5 \quad \text{and} \quad c^{l} = 0.2 \sim 0.4}$$

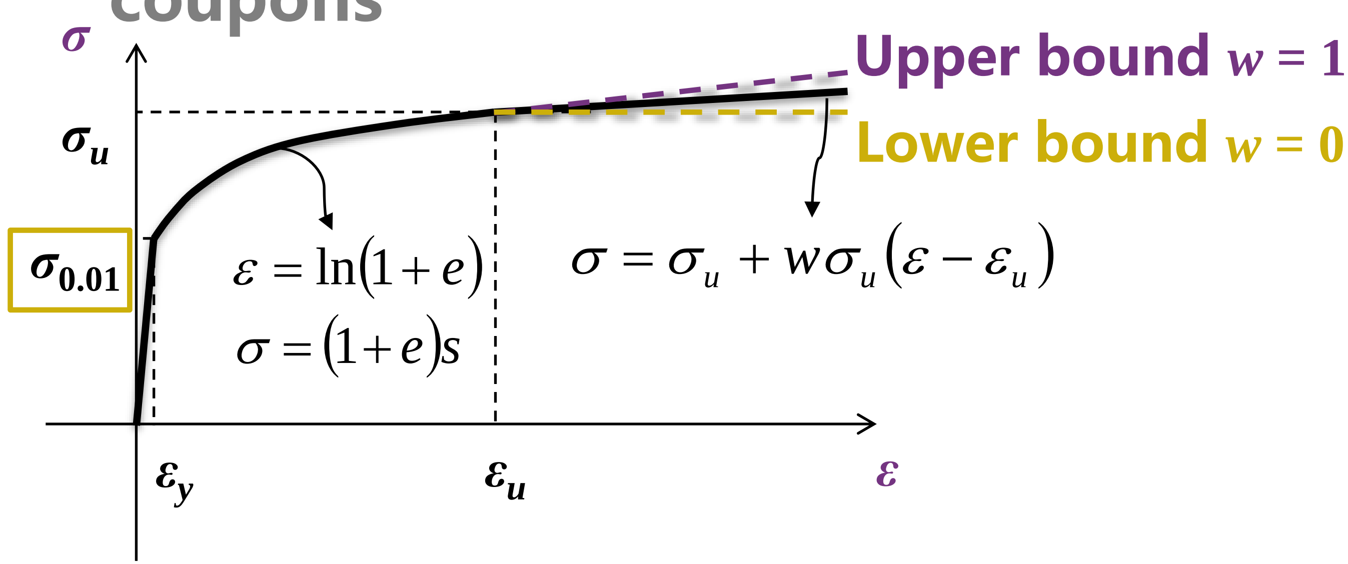


3. Model calibration

Structural steels <u>without</u> yield plateau

- **First, obtain the monotonic true stress – true strain curve using tension coupon test.**

$\sigma_{0.01}$	approximate yield stress in plasticity model
w	calibrated by numerical simulation of coupons



3. Model calibration

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Structural steels without yield plateau

- Second, evaluate all those parameters by using only the monotonic true stress – true strain curve.

monotonic

v	Possion's ratio
E	Elastic modulus
$\sigma_{0.01}$	yield stress

cyclic

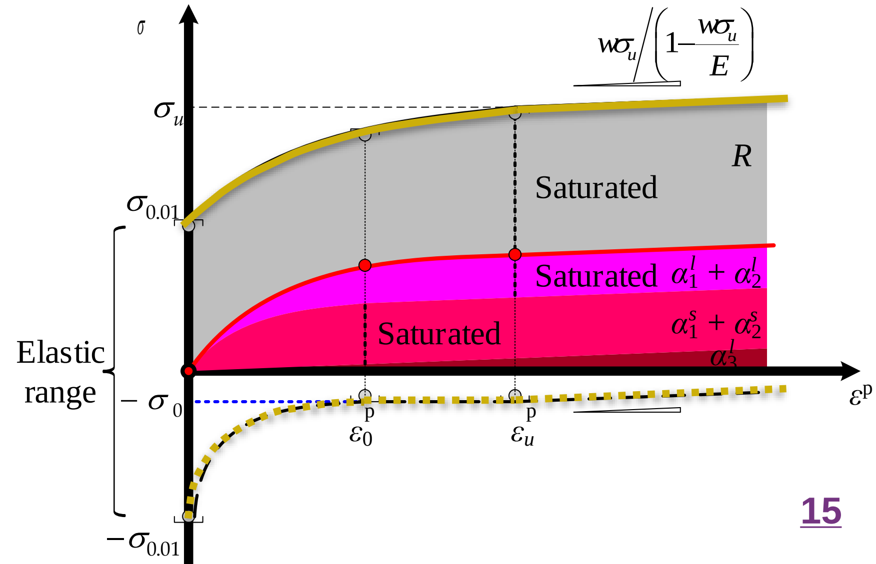
$Q_1^s\ b_1^s\ Q_2^s\ b_2^s$	Isotropic softening (short-range)
$C_1^s\ \gamma_1^s\ C_2^s\ \gamma_2^s$	Kinematic hardening (short-range)
$Q_1^l\ b_1^l\ Q_2^l\ b_2^l$	Isotropic hardening (long-range)
$C_1^l\ \gamma_1^l\ C_2^l\ \gamma_2^l\ C_3^l\ \gamma_3^l$	Kinematic hardening (long-range)
c^l	Memory scalar

3. Model calibration

○ Structural steels without yield plateau

- The lower bound of elastic range is assumed to experience a **three-stage evolution** under monotonic loading, and its stable value at moderate strain levels is empirically determined as follows:

$$\boxed{-\sigma_0 = -0.2\sigma_{0.01}}$$



3. Model calibration

Structural steels without yield plateau

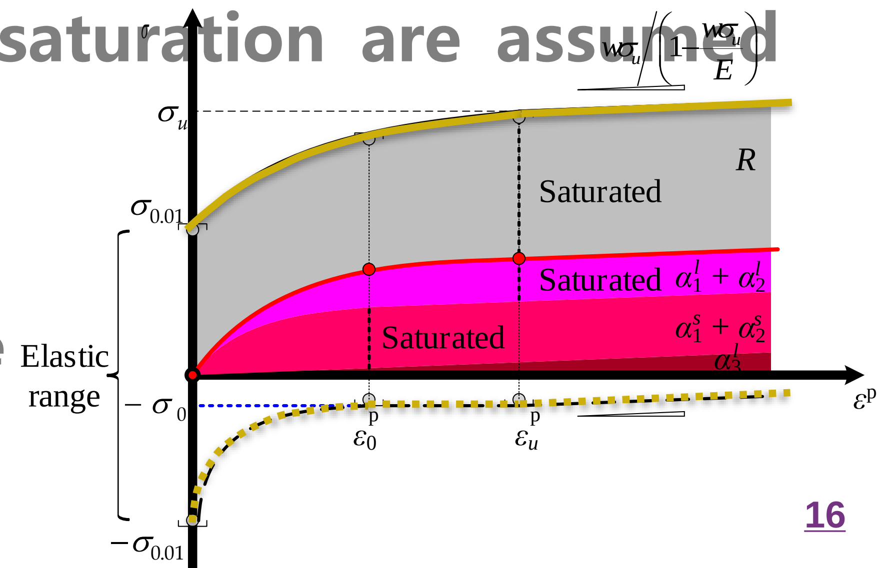
- Assume that there exist two short-range isotropic softening components and their saturation satisfies:

$$\boxed{\sum_{j=1}^{2} Q_j^s = -\frac{\sigma_{0.01} - \sigma_0}{2}}$$

- For convenience, their saturation are assumed to be equal:

$$\boxed{Q_1^s = Q_2^s}$$

The saturation rates $\boxed{b_1^s \;\; b_2^s}$ are empirically determined to fit cyclic test results.



3. Model calibration

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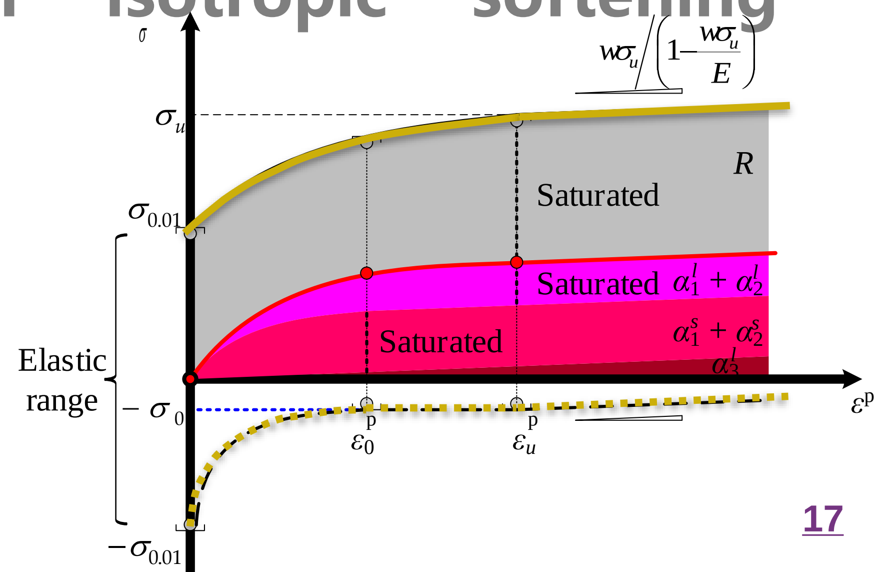
○ Structural steels without yield plateau

- To ensure the consistency of positive hardening modulus after initial yielding, a solution is that there should exist two short-range kinematic hardening components and their saturation and evolution rates are exactly the same in absolute value with those of isotropic softening components:

$$\boxed{\frac{C_j^s}{\gamma_j^s} = -Q_j^s} \quad \boxed{\gamma_j^s = b_j^s} \quad j = 1,2$$



3. Model calibration

Structural steels without yield plateau

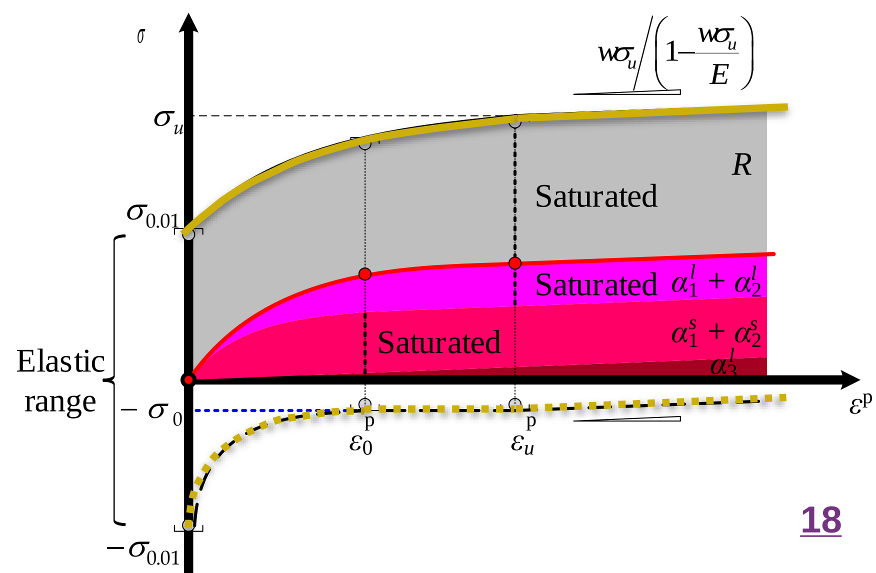
- Assume there are two long-range isotropic hardening components, and their saturation should satisfy at ultimate plastic strain:

$$\boxed{\sum_{j=1}^{2} Q_j^l = \frac{\sigma_u + \sigma_0}{2} - \sigma_{0.01} - \sum_{j=1}^{2} Q_j^s = \frac{\sigma_u - \sigma_{0.01}}{2}}$$

- Empirical assumption

$$\boxed{Q_1^l : Q_2^l = 2 : 1}$$

The saturation rates $\boxed{b_1^l \quad b_2^l}$ are obtained by a best fitting of the monotonic loading curve.



3. Model calibration

Structural steels without yield plateau

- It is natural to set one long-range backstress component as linear and the other two as nonlinear that should saturate at ultimate plastic strain. $C_3^l = H \quad \text{and} \quad \gamma_3^l = 0$

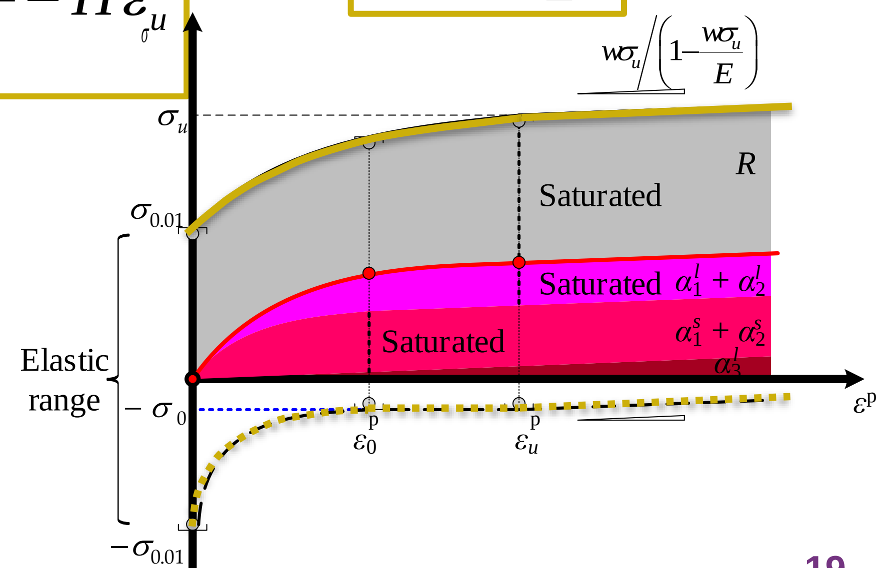
$$H = \frac{w\sigma_u}{1 - \frac{w\sigma_u}{E}}$$

$$\sum_{j=1}^{2} \frac{C_j^l}{\gamma_j^l} = \frac{\sigma_u - \sigma_0}{2} - \sum_{j=1}^{2} \frac{C_j^s}{\gamma_j^s} - H\varepsilon_u^{\mathrm{p}} = \frac{\sigma_u - \sigma_{0.01}}{2} - H\varepsilon_u^{\mathrm{p}}$$

- Empirical assumption

$$\frac{C_1^l}{\gamma_1^l} : \frac{C_2^l}{\gamma_2^l} = 2:1$$

The saturation rates $\gamma_1^l\ \gamma_2^l$ are obtained by a best fitting of the monotonic loading curve.

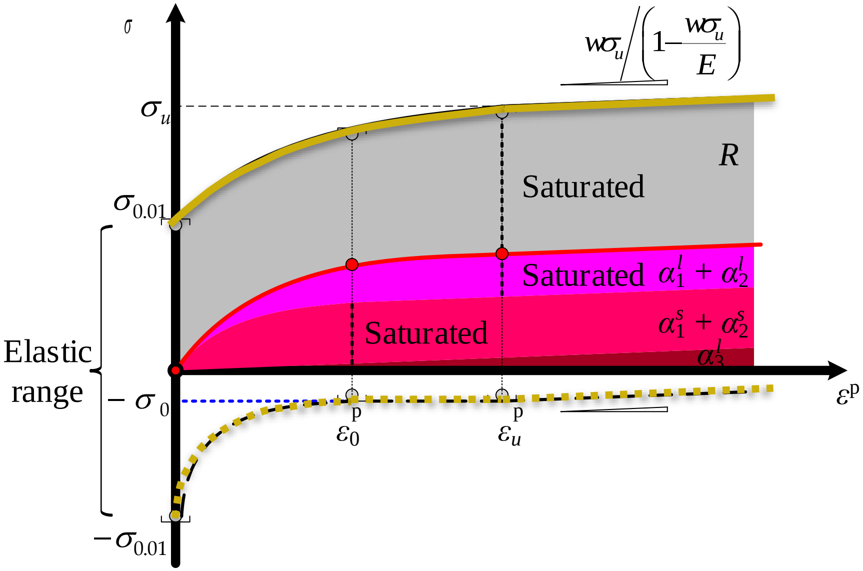


3. Model calibration

Structural steels <u>without</u> yield plateau

- Memory scalar generally ranges from 0 to 0.5 and is assumed to take the following empirical value:

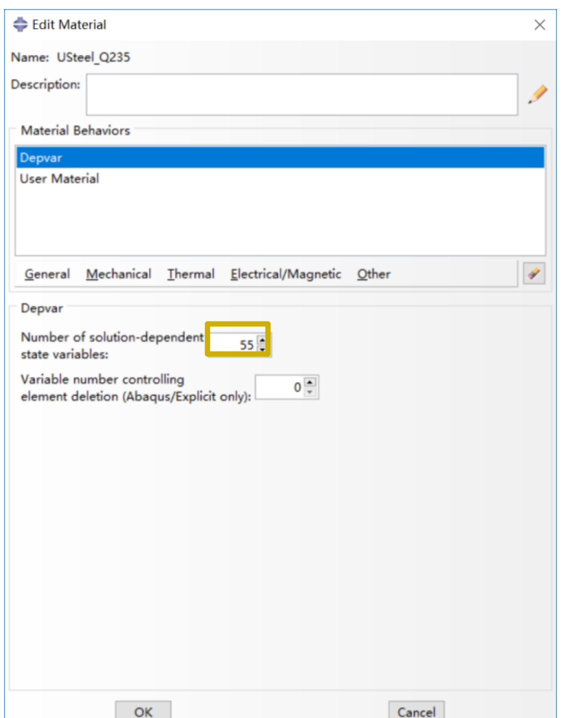
$$\boxed{c^l = 0.2}$$

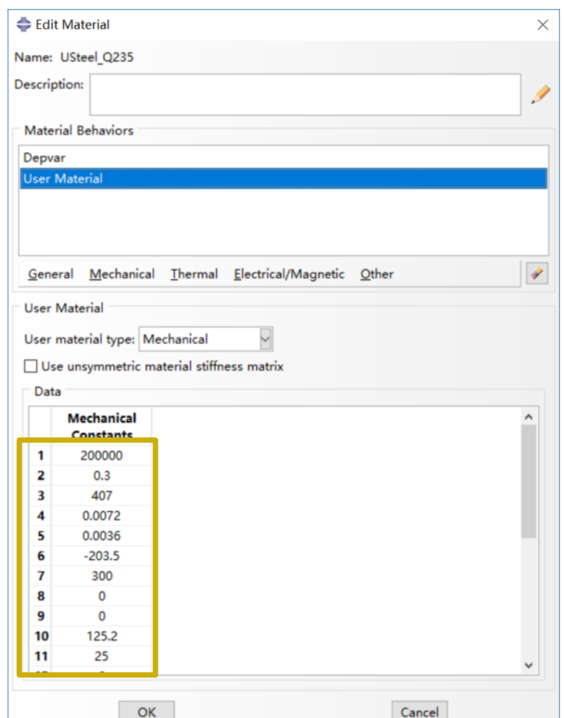


4. Step-by-step proc. using UMAT

Step 1: Property module, Edit Material

- Select General->Depvar: Define the Number of solution-dependent variables to be 55
- Select General->User Material: Define 25 Mechanical Constants





4. Step-by-step proc. using UMAT

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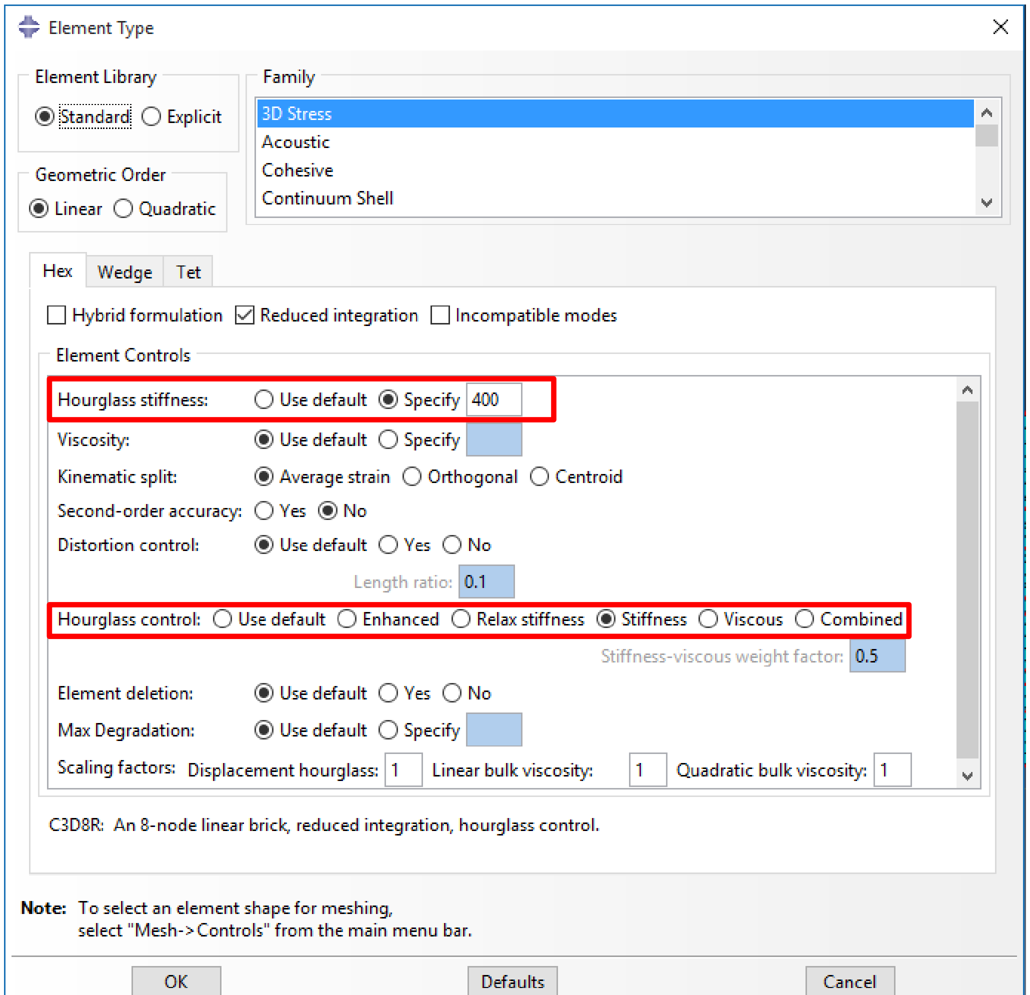
- Step 1: Property module, Edit Material
  - The order of 25 Mechanical Constants

1	E	14	C_1^s
2	v , 0.3 for steel	15	γ_1^s
3	σ_y	16	C_2^s
4	$\varepsilon_{\mathrm{st}}^{\mathrm{p}}$, 0 if w/o yield plateau	17	γ_2^s
5	$\bar{\varepsilon}_{\mathrm{st}}^{\mathrm{p}}$, 0 if w/o yield plateau	18	C_1^l
6	Q_1^s	19	γ_1^l
7	b_1^s	20	C_2^l
8	Q_2^s , 0 if with yield plateau	21	γ_2^l
9	b_2^s , 0 if with yield plateau	22	C_3^l , 0 if with yield plateau
10	Q_1^l	23	γ_3^l , 0 if with yield plateau
11	b_1^l	24	c^s , 0.5 if with yield plateau; 0 if without yield plateau
12	Q_2^l , 0 if with yield plateau		
13	b_2^l , 0 if with yield plateau	25	c^l

4. Step-by-step proc. using UMAT

Step 2: Mesh module, when using C3D8R

- **Define hourglass stiffness in Element Type**



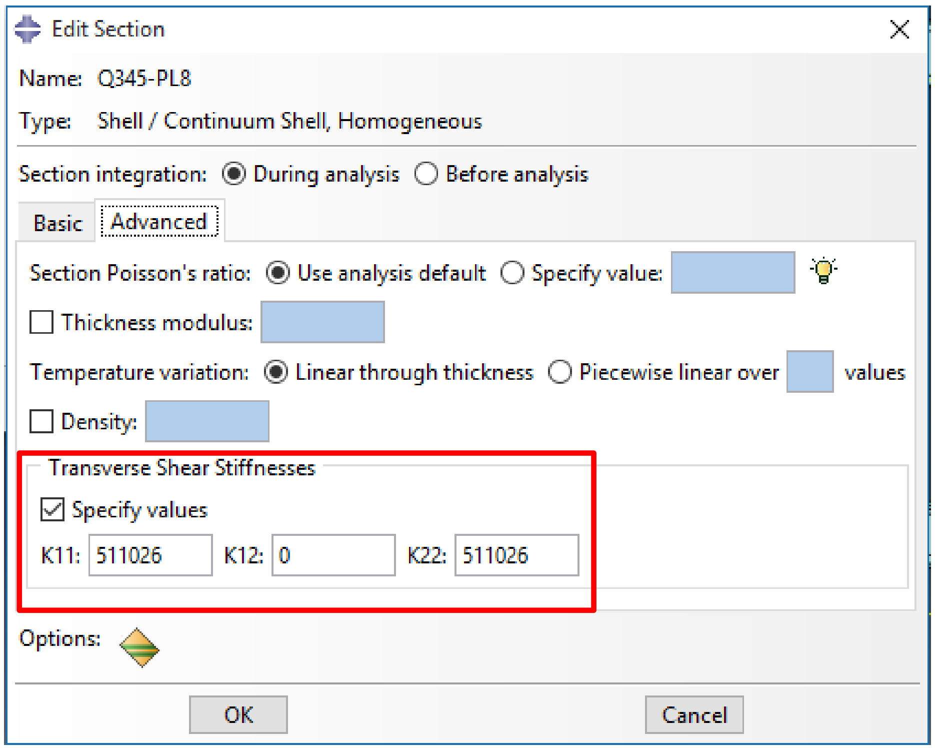
Calculate hourglass stiffness

$$\boxed{0.005 \cdot \frac{E}{2(1+v)}}$$

4. Step-by-step proc. using UMAT

Step 2: Property module, when using S4R

- **Define transverse shear stiffness in Edit Section ->Advanced**



Calculate transverse shear stiffness

$$K_{11} = K_{22} = \frac{5}{6} \cdot \frac{E}{2(1+v)} t$$

$$K_{12} = 0$$

t **is the shell thickness**

4. Step-by-step proc. using UMAT

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Step 3: Step module, Field Output (Optional)

- Select **solution-dependent state variables (SDV)** if you want to output:

  elastic strain

  plastic strain

  backstress

  equivalent plastic strain

  (The default PEEQ is useless in this case)

  yield index

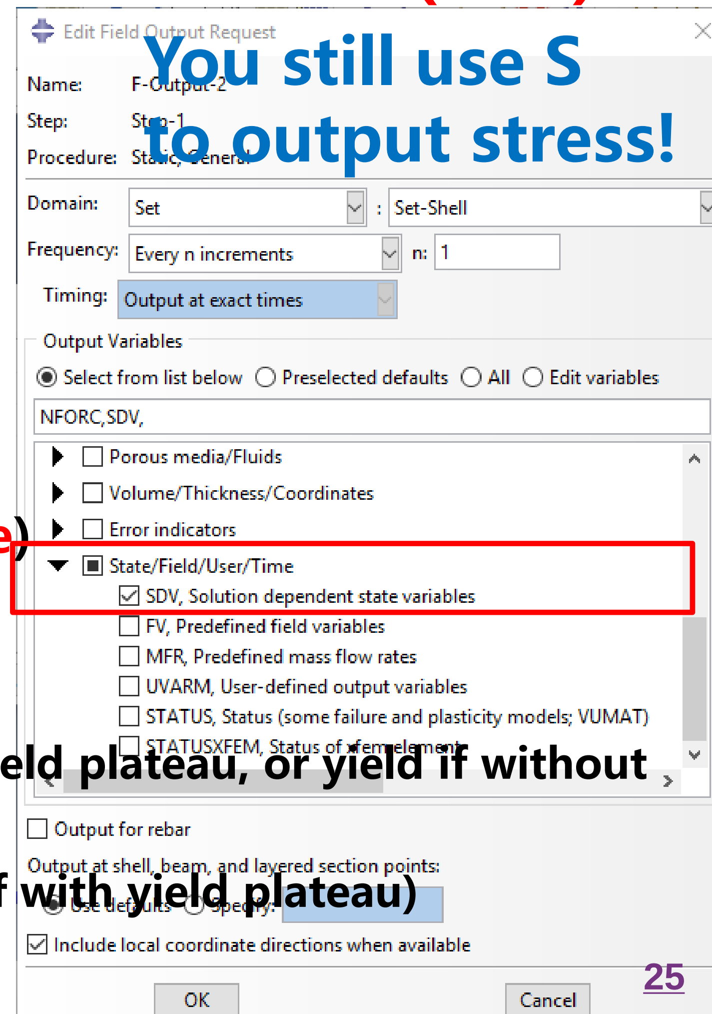
  (0 indicates initial elastic response)

  (1 indicates yield in plateau region if with yield plateau, or yield if without yield plateau)

  (2 indicates yield in hardening region only if with yield plateau)

  and other memory variables.

You still use S to output stress!



4. Step-by-step proc. using UMAT

Step 3: <u>Step</u> module, Field Output (Optional)

- **List of SDVs**

elastic strain	SDV1~SDV6
plastic strain	SDV7~SDV12
center of memory surface	SDV13~SDV18
1st short-range backstress	SDV19~SDV24
2nd short-range backstress	SDV25~SDV30
1st long-range backstress	SDV31~SDV36
2nd long-range backstress	SDV37~SDV42
3rd long-range backstress	SDV43~SDV48
1st short-range softening stress	SDV49
2nd short-range softening stress	SDV50
1st long-range hardening stress	SDV51
2nd long-range hardening stress	SDV52
radius of memory surface	SDV53
equivalent plastic strain	SDV54
yield index	SDV55

4. Step-by-step proc. using UMAT

Step 3: Step module, Field Output (Optional)

- **Since output of all SDVs will be very expensive for storage when your are analyzing a large model, and if you want to output only variables you are interested, edit the Keywords (*.inp file).**

E.g. you want to output only equivalent plastic strain and yield index, as I usually do, just replace SDV with SDV54, SDV55 in *.inp file.

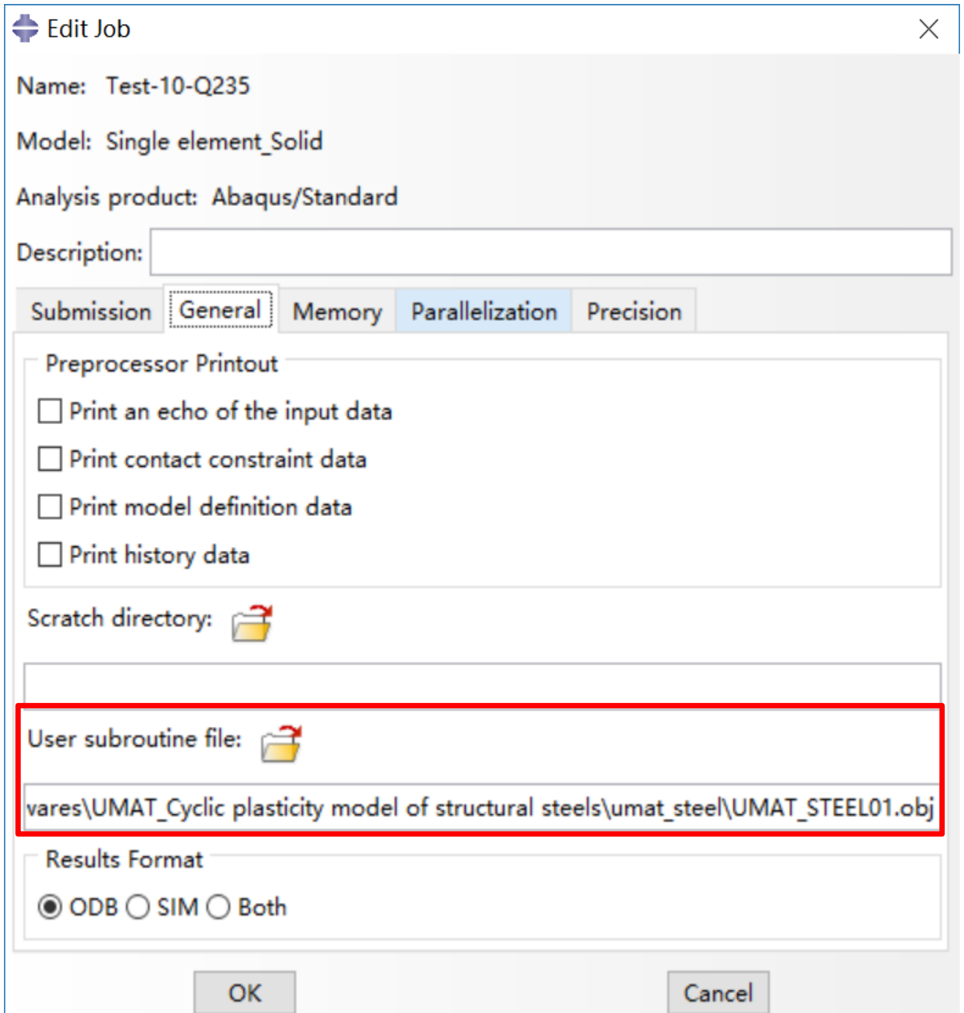
```
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, time interval=0.02
    *Node Output
    U,
    *Element Output, directions=YES
    LE, S, SDV54, SDV55
```

Note that instead of 6 components (11, 22, 33, 12, 13, 23) for stress and strain tensors in a solid element, there are only 3 valid components (11, 22, 12) for stress and strain tensors in a shell element. Therefore, the last 3 components for tensor SDVs will be always 0 in a shell element!

4. Step-by-step proc. using UMAT

Step 4: Job module, Edit Job

- **Use subroutine file under the General tab**



Subroutine file for structural steels with yield plateau

aba_param.inc
UMAT_STEEL01.obj or
UMAT_STEEL02.obj

Subroutine file for structural steels without yield plateau (high strength steels)

both files should be placed in the same directory

5. Application

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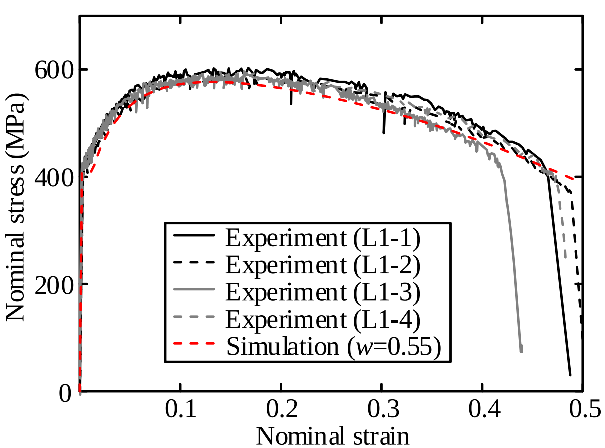
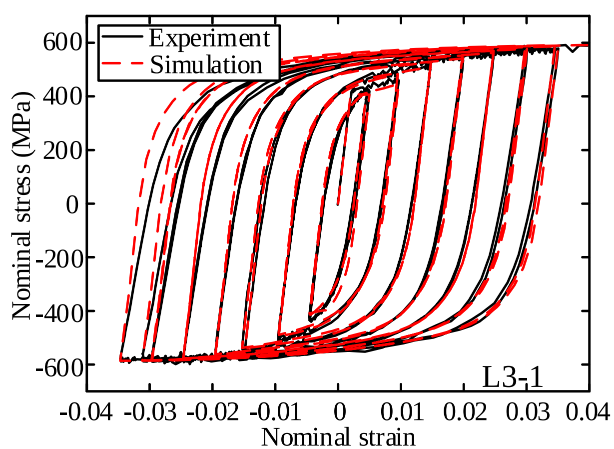
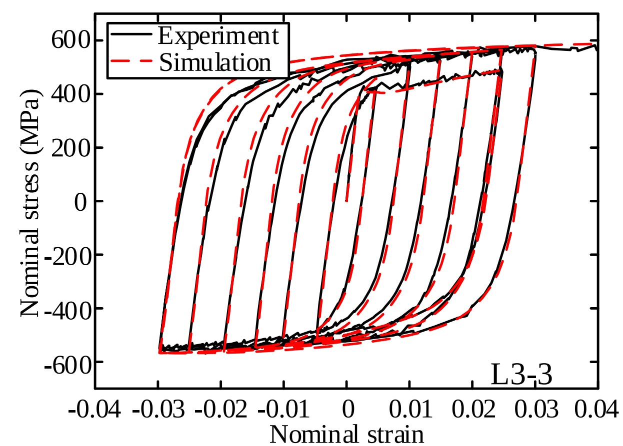
○ Coupon test of Q235 steel

- Shi YJ, Wang M, Wang YQ. Experimental and constitutive model study of structural steel under cyclic loading. Journal of Constructional Steel Research, 2011, 67: 1185–97.

E σ_y	ε^{p}_{st} $\bar{\varepsilon}^{p}_{st}$	Q_1^s b_1^s	Q_1^l b_1^l	C_1^s γ_1^s	C_2^s γ_2^s	C_1^l γ_1^l	C_2^l γ_2^l	c^s c^l
200000	0.0072	-203.5	125.2	203500.0	40700.0	2657.3	362.2	0.5
407.0	0.0036	300	25	3000	300	30	0	0.3

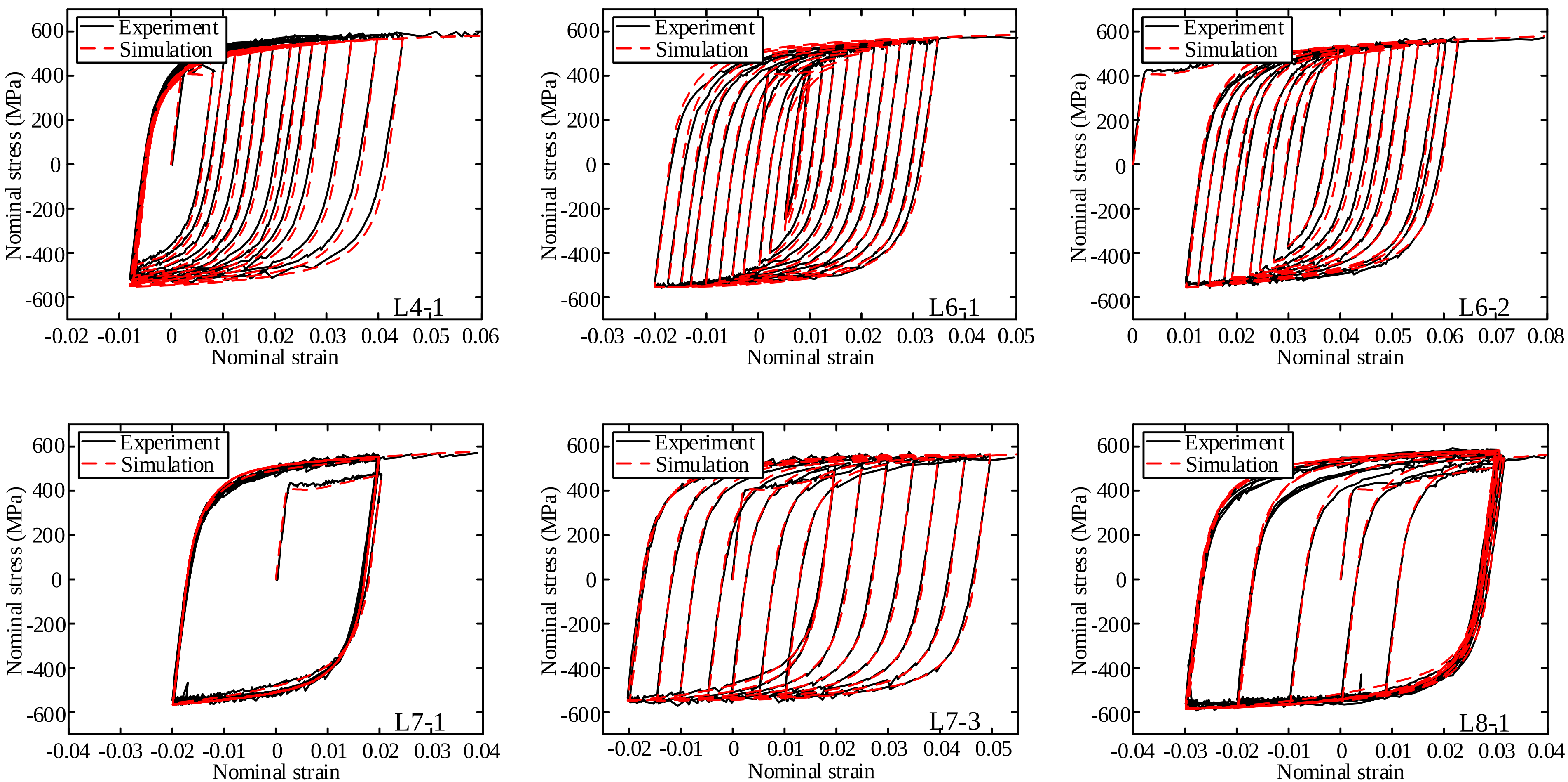






5. Application

Coupon test of Q235 steel

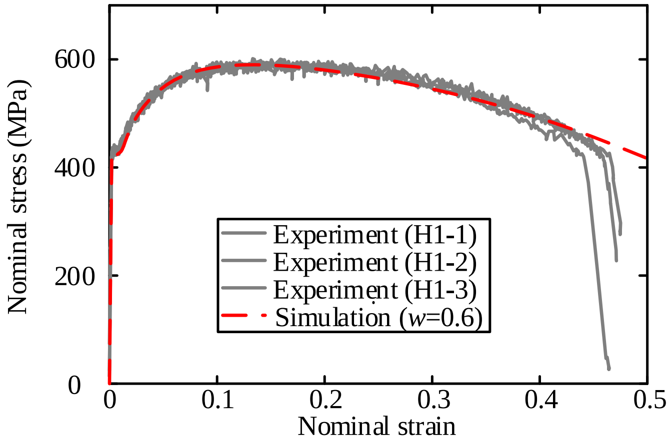


5. Application

Coupon test of Q355 steel

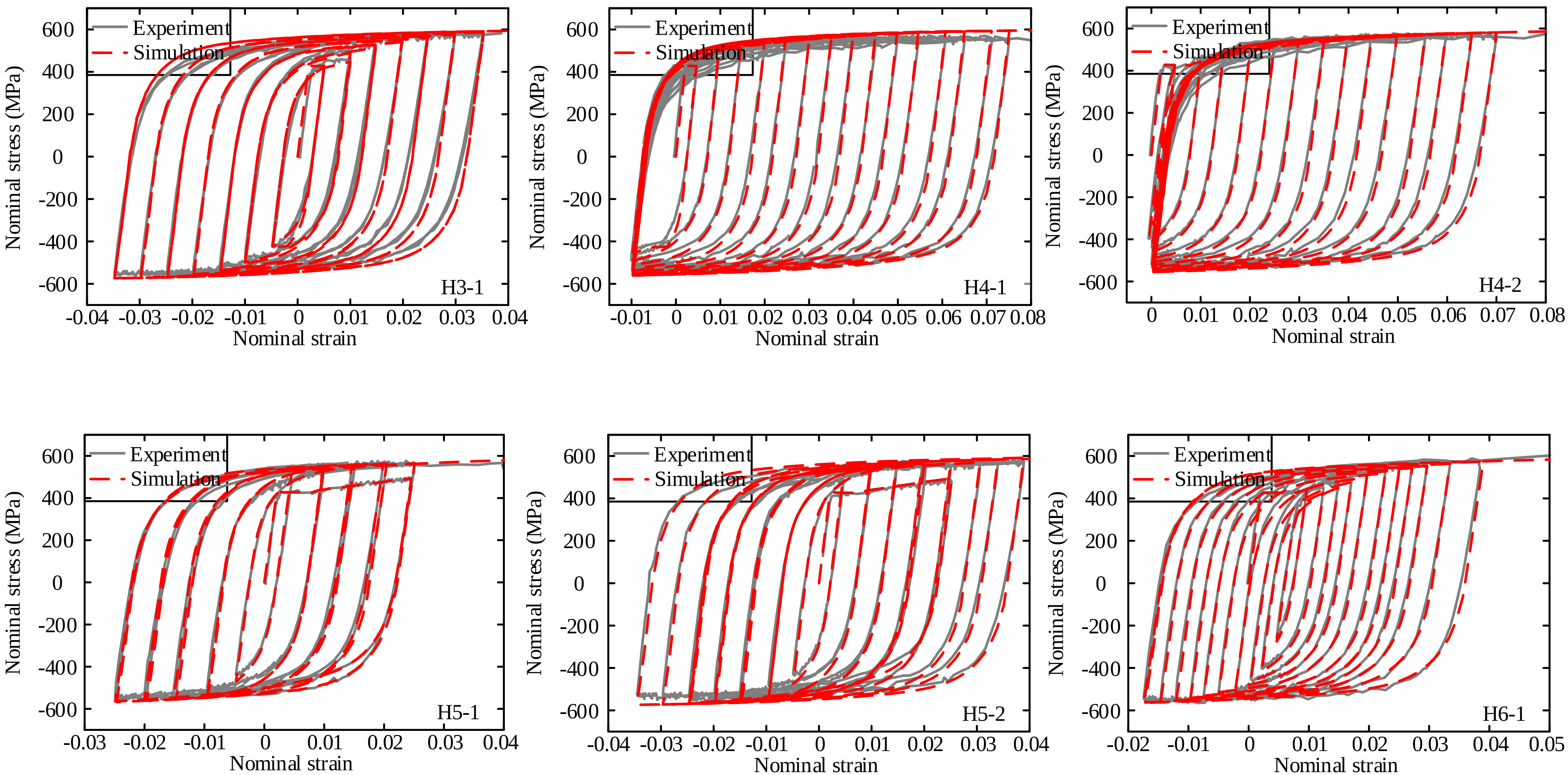
- Shi YJ, Wang M, Wang YQ. Experimental and constitutive model study of structural steel under cyclic loading. Journal of Constructional Steel Research, 2011, 67: 1185–97.

E σ_y	ε_{st}^{p} $\bar{\varepsilon}_{st}^{p}$	Q_1^s b_1^s	Q_1^l b_1^l	C_1^s γ_1^s	C_2^s γ_2^s	C_1^l γ_1^l	C_2^l γ_2^l	c^s c^l
205000 429.0	0.0060 0.0030	-214.5 300	125.1 25	214500.0 3000	42900.0 300	2245.0 30	408.3 0	0.5 0.3



5. Application

Coupon test of Q355 steel



5. Application

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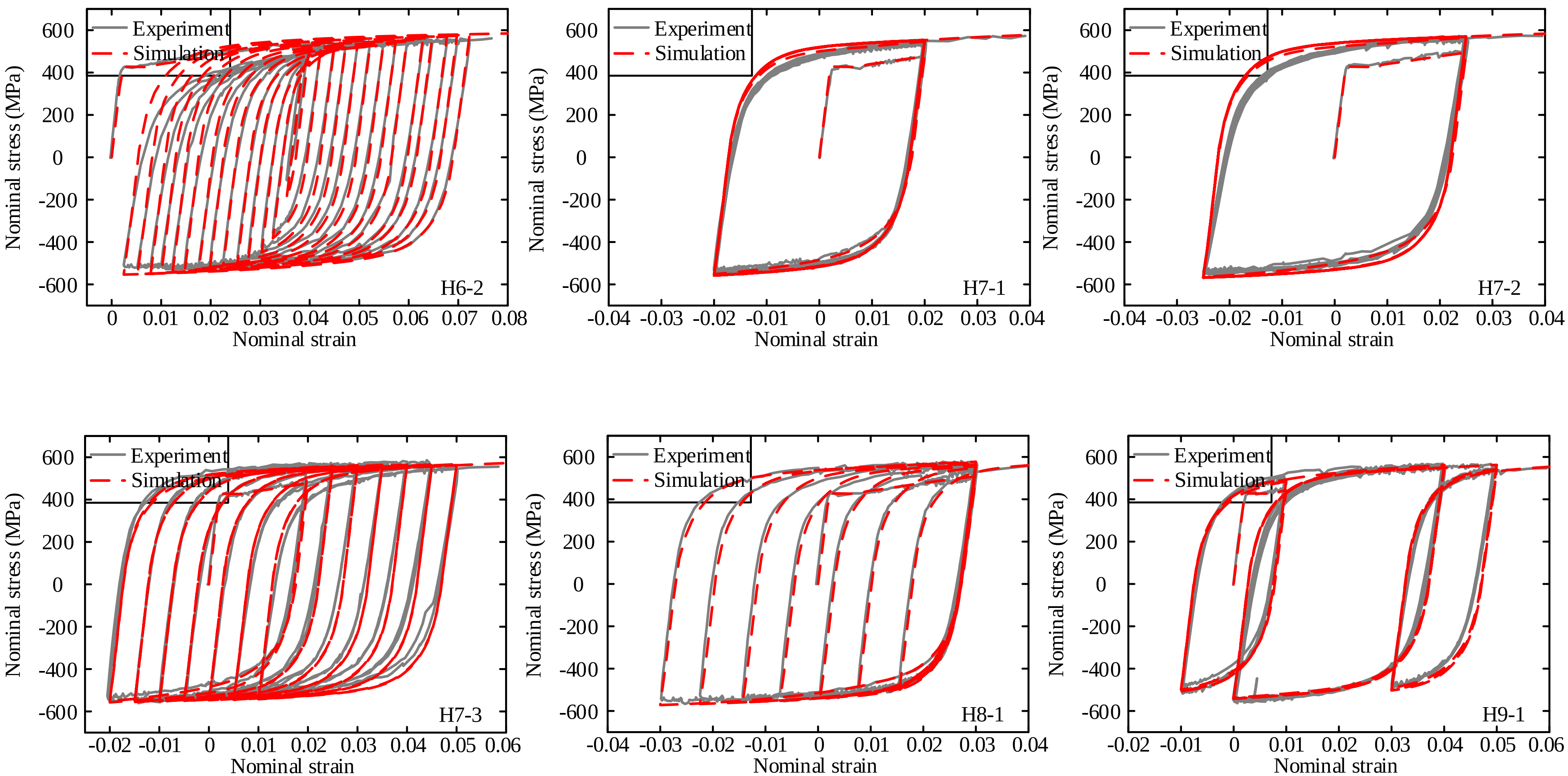
Coupon test of Q355 steel

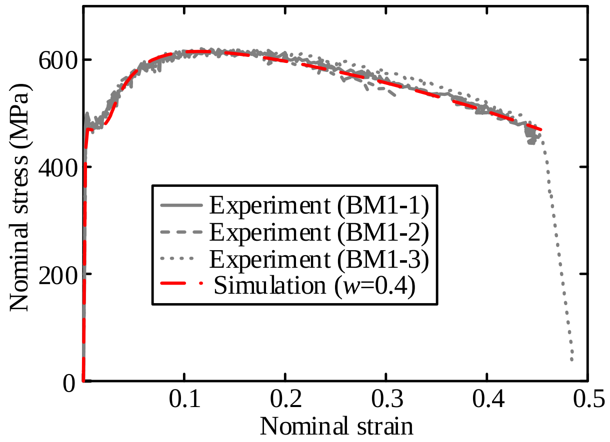


5. Application

Coupon test of Q460 steel

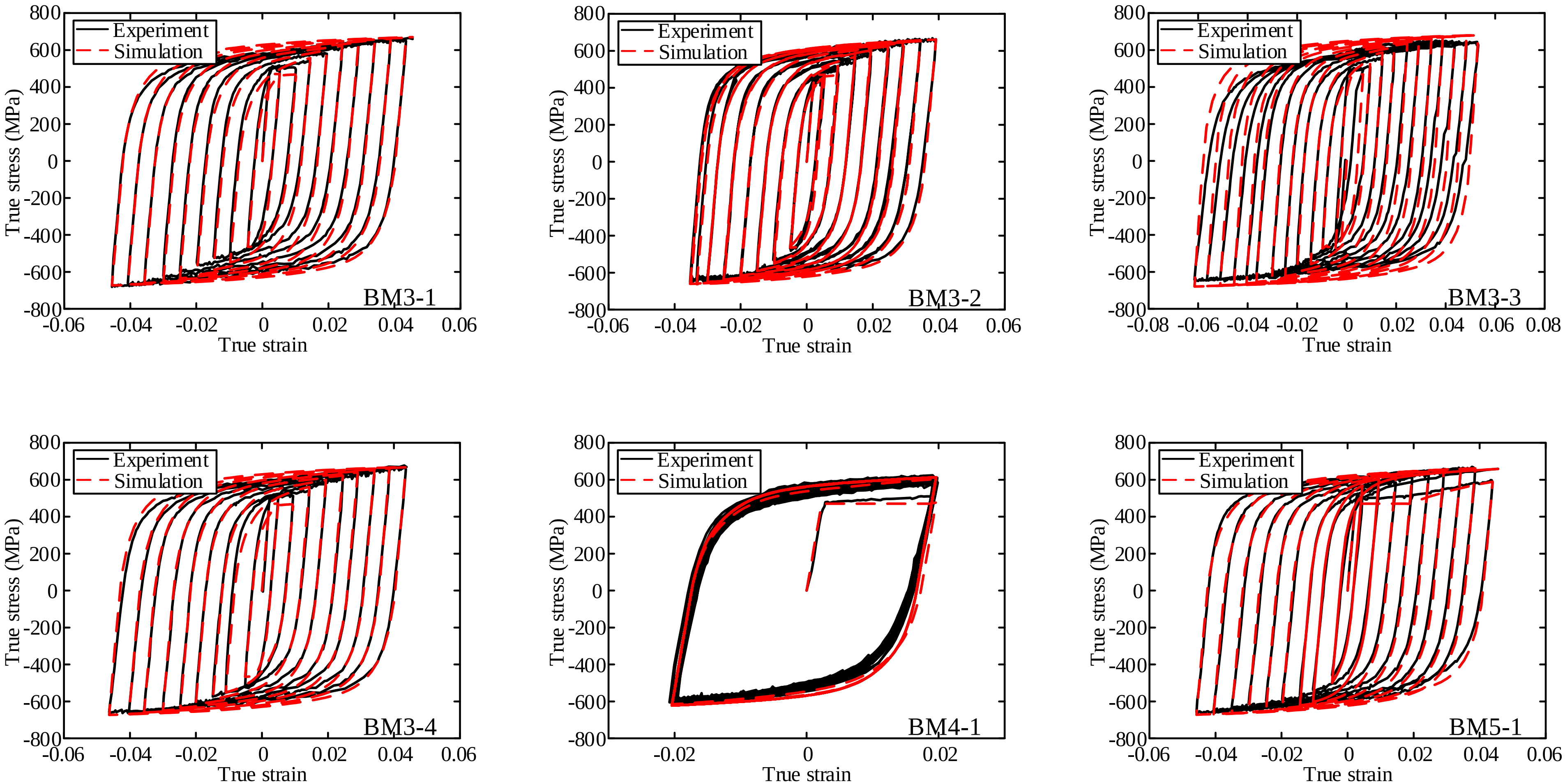
- Shi G, Wang M, Wang YQ, Wang F. Cyclic behavior of 460 MPa high strength structural steel and welded connection under earthquake loading. Advances in Structural Engineering, 2013, 16(3): 451–66.

E σ_y	ε_{st}^{p} $\bar{\varepsilon}_{st}^{p}$	Q_1^s b_1^s	Q_1^l b_1^l	C_1^s γ_1^s	C_2^s γ_2^s	C_1^l γ_1^l	C_2^l γ_2^l	c^s c^l
208000 470.0	0.0163 0.0050	-235.0 300	114.3 30	235000.0 3000	47000.0 300	3352.5 40	279.8 0	0.5 0.3



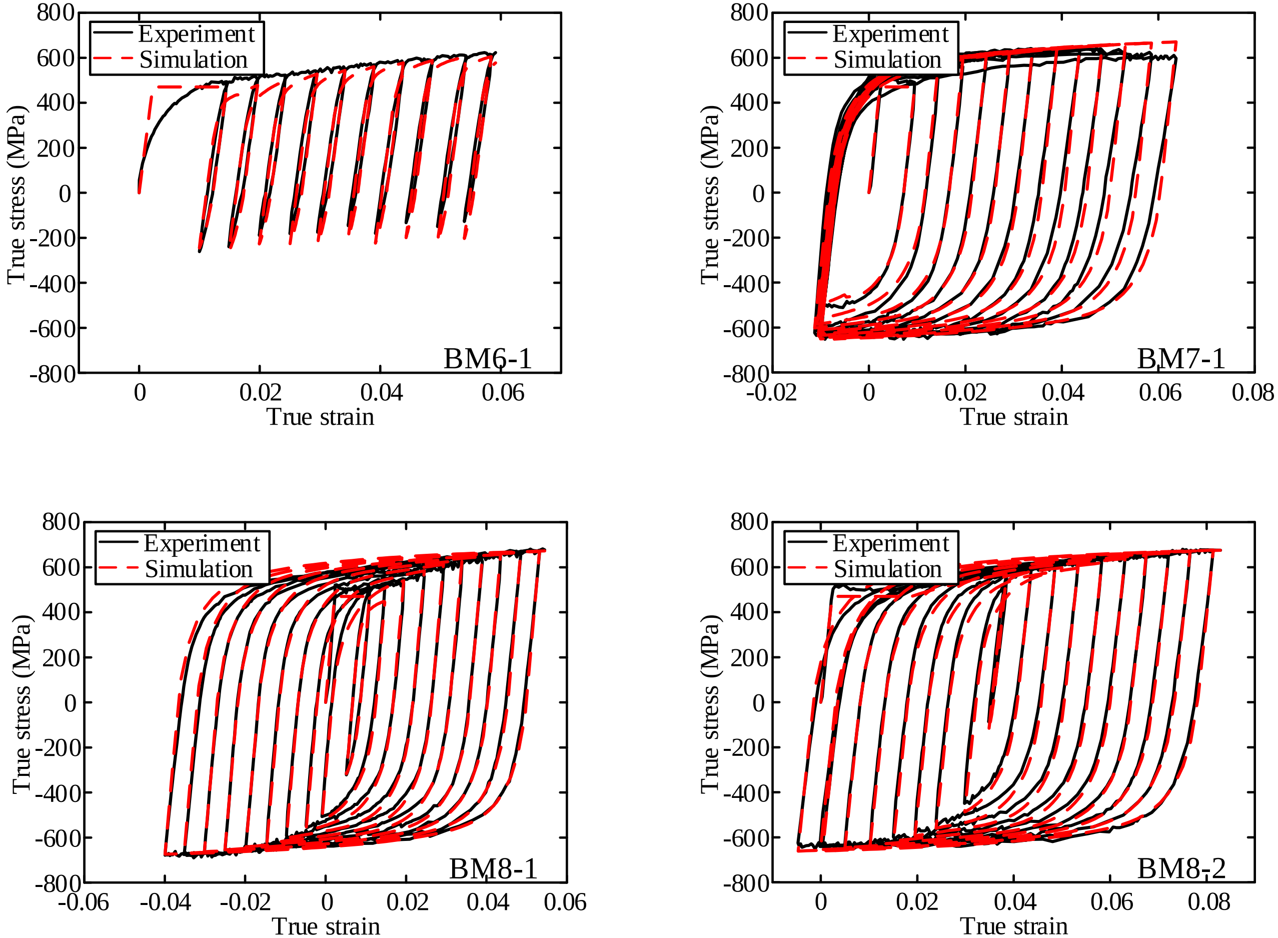
5. Application

Coupon test of Q460 steel



5. Application

Coupon test of Q460 steel

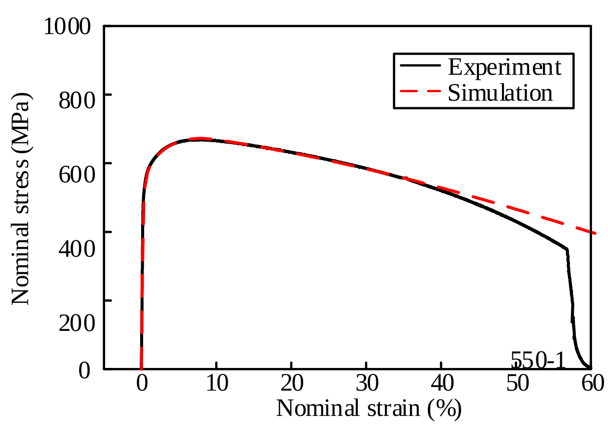


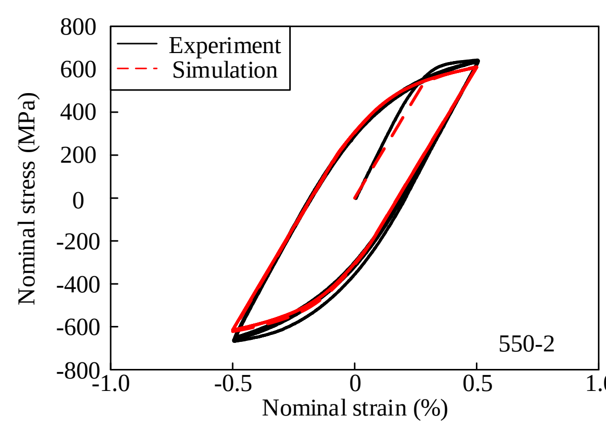
5. Application

Coupon test of Q550 steel

E $\sigma_{0.01}$	Q^s_1 b^s_1	Q^s_2 b^s_2	Q^l_1 b^l_1	Q^l_2 b^l_2
230330 468.0	-93.6 3000	-93.6 300	84.8 40	42.4 600

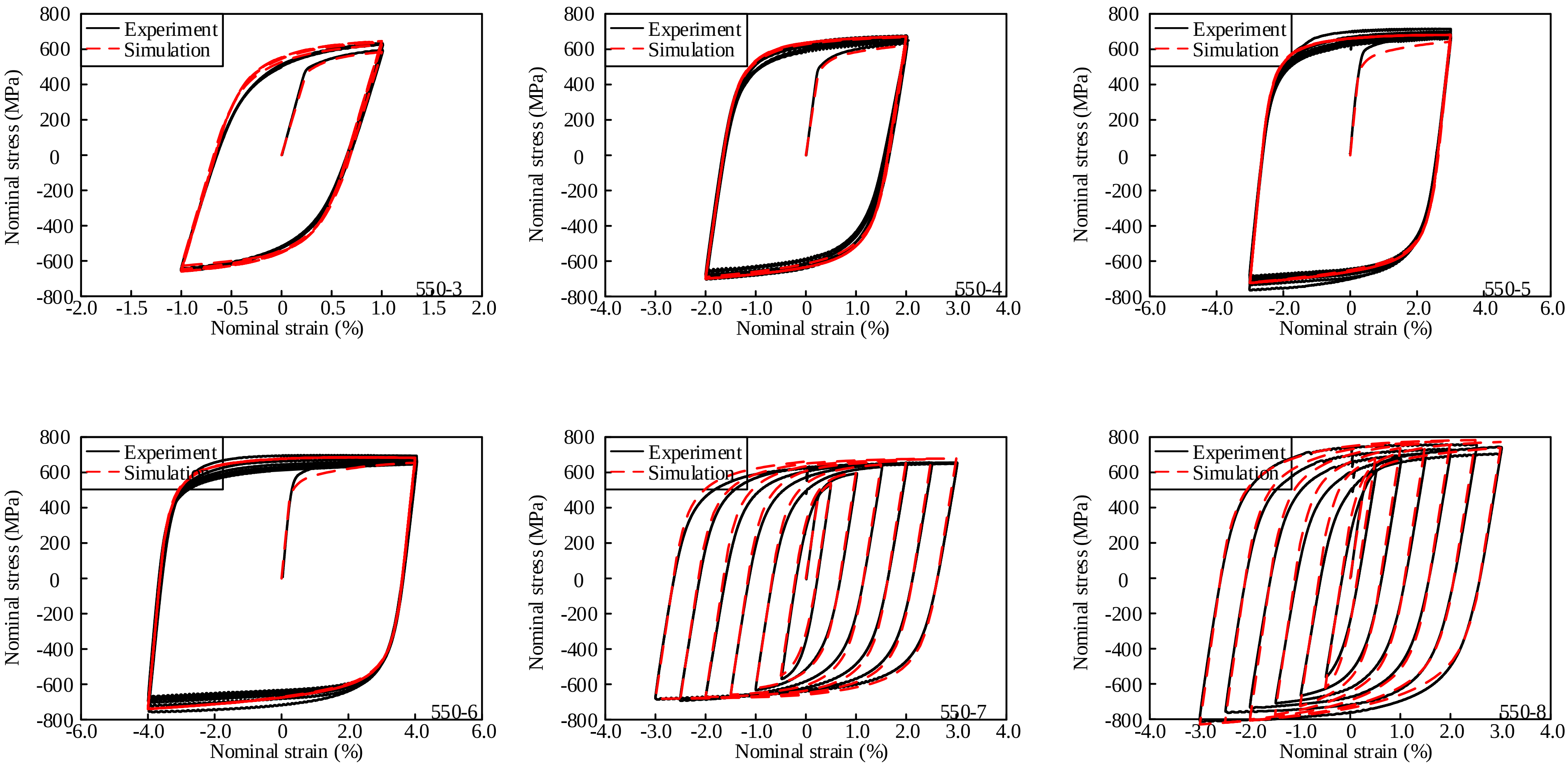
	C^s_1 γ^s_1	C^s_2 γ^s_2	C^l_1 γ^l_1	C^l_2 γ^l_2	C^l_3 γ^l_3	c^l
	280800 3000	28080 300	3708.2 50	25957.4 700	217 0	0.2





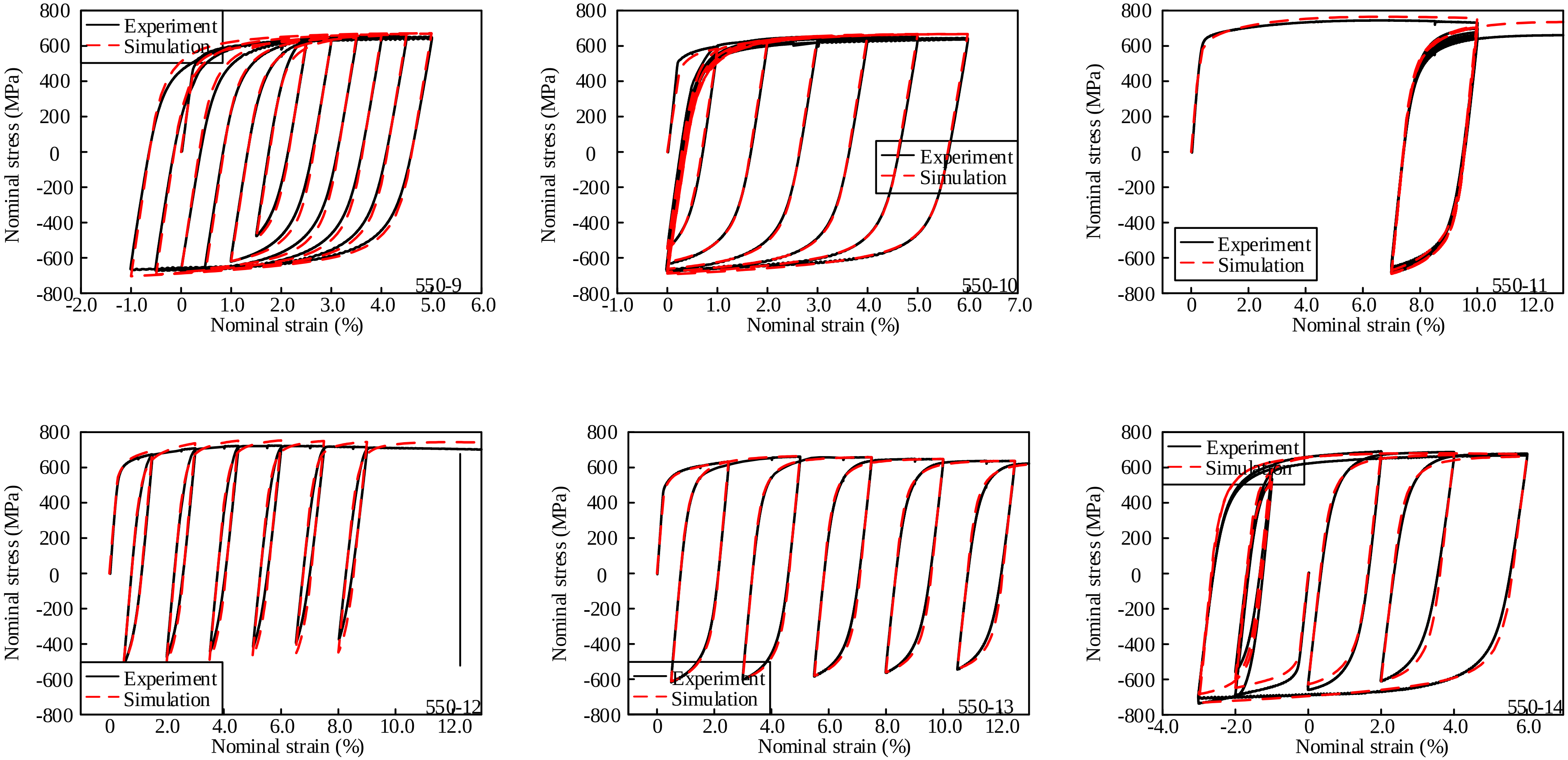
5. Application

Coupon test of Q550 steel



5. Application

Coupon test of Q550 steel

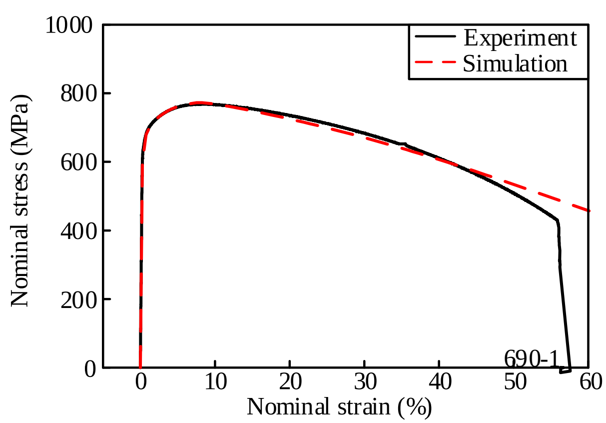


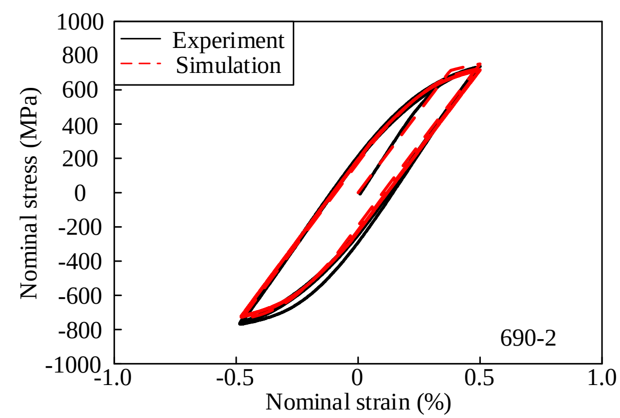
5. Application

Coupon test of Q690 steel

E $\sigma_{0.01}$	Q^s_1 b^s_1	Q^s_2 b^s_2	Q^l_1 b^l_1	Q^l_2 b^l_2
242800 584.8	-117 3000	-117 300	73.4 35	36.7 650

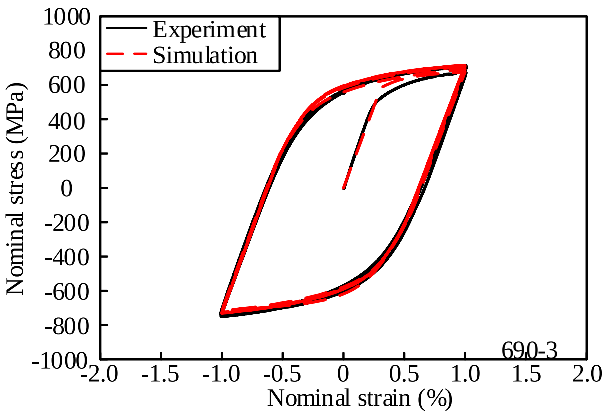
	C^s_1 γ^s_1	C^s_2 γ^s_2	C^l_1 γ^l_1	C^l_2 γ^l_2	C^l_3 γ^l_3	c^l
	350905.7 3000	35090.6 300	2765.2 45	26115.3 850	241.7 0	0.2

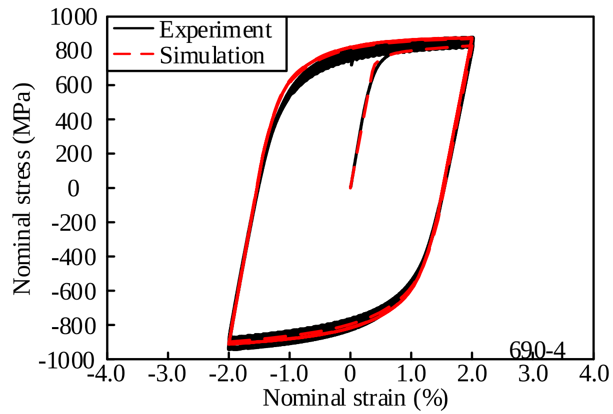


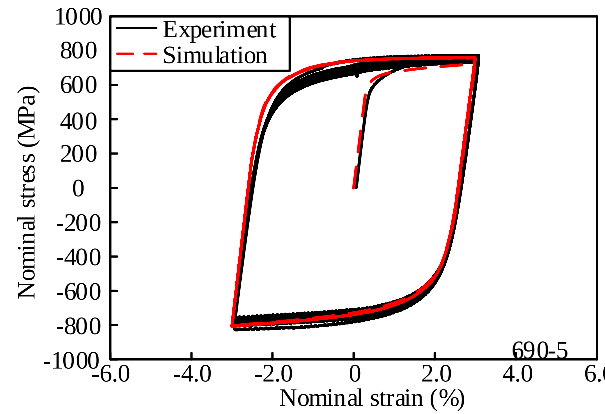


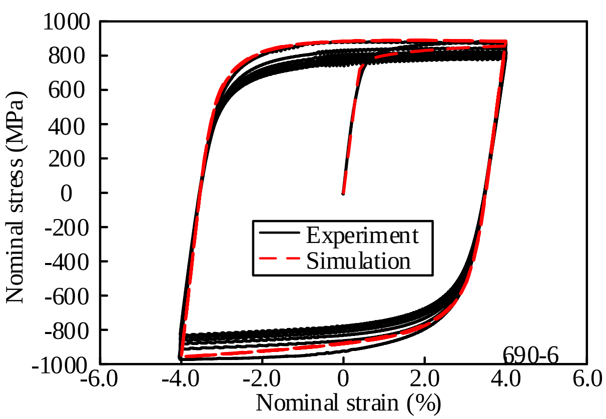
5. Application

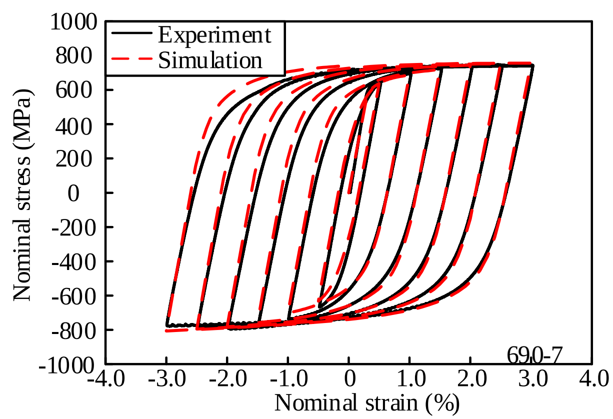
○ Coupon test of Q690 steel

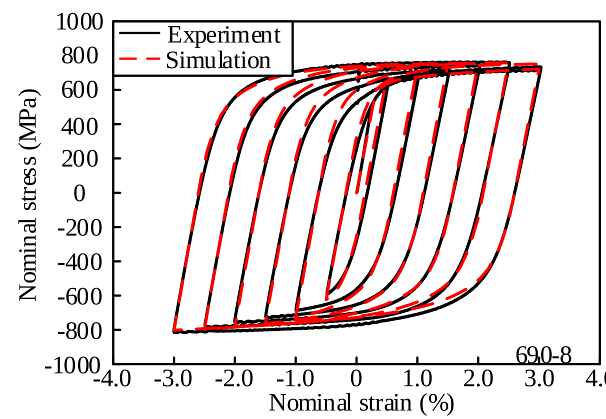






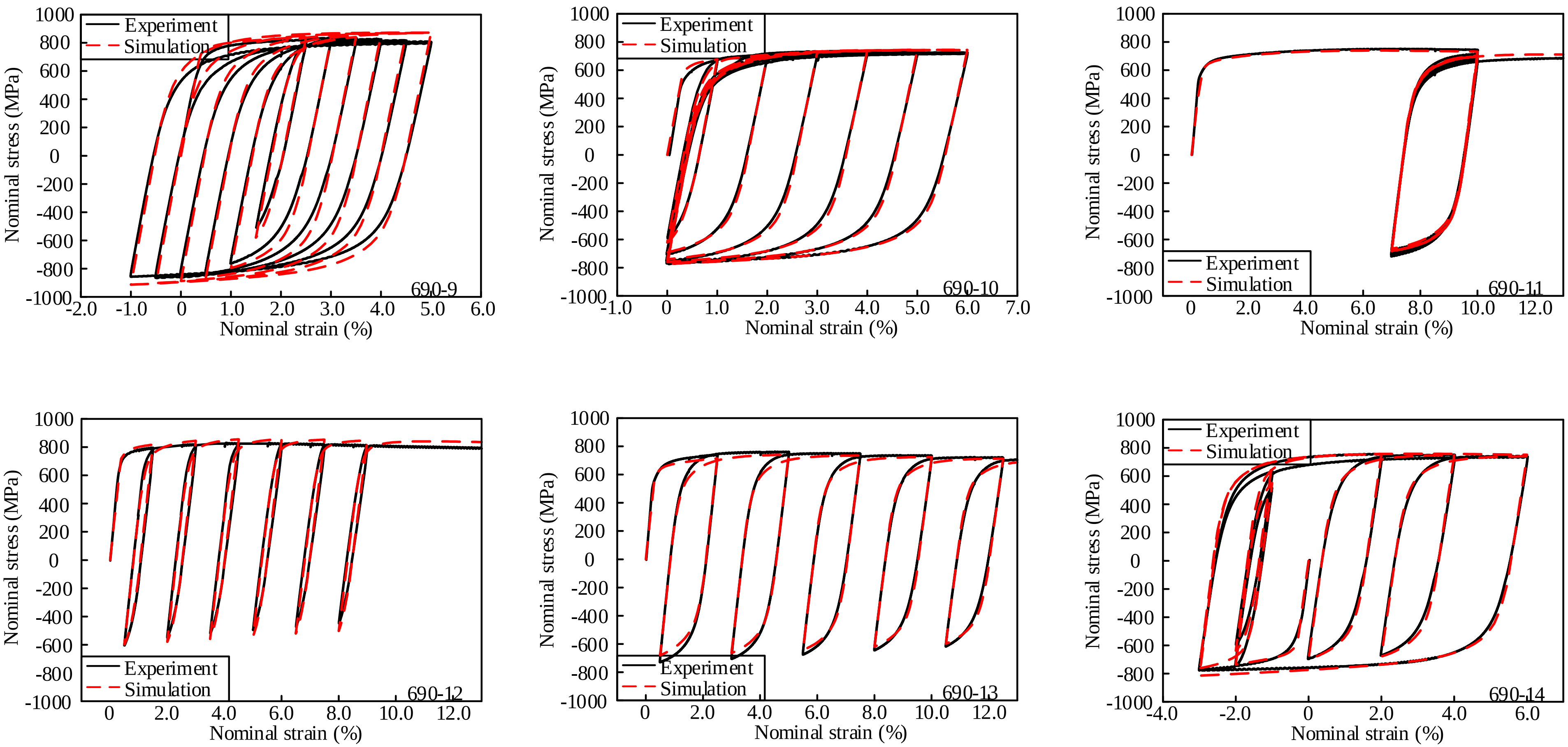






5. Application

Coupon test of Q690 steel



5. Application

- **Default parameters for calibration by a new tension coupon test**

E σ_y	ε^{p}_{st} $\bar{\varepsilon}^{p}_{st}$	Q^s_1 b^s_1	Q^l_1 b^l_1	C^s_1 γ^s_1	C^s_2 γ^s_2	C^l_1 γ^l_1	C^l_2 γ^l_2	c^s c^l
* *	* 0.005	$-0.5\sigma_y$ 300	$(\sigma_u-\sigma_y)/2$ *	$-Q^s_1\gamma^s_1/3$ 3000	$-2Q^s_1\gamma^s_2/3$ 300	Eq. (1) *	Eq. (2) 0	0.5 0.3

Q235 (b^l_1=25, γ^l_1=30)
Q355 (b^l_1=25, γ^l_1=30)
Q460 (b^l_1=30, γ^l_1=40)

Eq. (1) $C^l_1 = [Q^l_1 - C^l_2(\varepsilon_u - \sigma_u/E - \varepsilon^{p}_{st})]\gamma^l_1$

Eq. (2) $C^l_2 = w\sigma_u/(1-w\sigma_u/E)$

E $\sigma_{0.01}$	Q^s_1 b^s_1	Q^s_2 b^s_2	Q^l_1 b^l_1	Q^l_2 b^l_2	C^s_1 γ^s_1	C^s_2 γ^s_2	C^l_1 γ^l_1	C^l_2 γ^l_2	C^l_3 γ^l_3	c^l
* *	$-0.2\sigma_{0.01}$ 3000	$-0.2\sigma_{0.01}$ 300	$(\sigma_u-\sigma_{0.01})/3$ *	$(\sigma_u-\sigma_{0.01})/6$ *	$-Q^s_1\gamma^s_1$ 3000	$-Q^s_2\gamma^s_2$ 300	Eq. (3) *	Eq. (4) *	Eq. (5) 0	0.2

Q550 (b^l_1=40, b^l_2=600, γ^l_1=50, γ^l_2=700)
Q690 (b^l_1=35, b^l_2=650, γ^l_1=45, γ^l_2=850)
Q890 (b^l_1=35, b^l_2=650, γ^l_1=45, γ^l_2=850)
Q960 (b_1=35, b_2=650, γ_1=45, γ_2=850)

Eq. (3) $C^l_1 = 2[(\sigma_u-\sigma_{0.01})/2 - C^l_3(\varepsilon_u-\sigma_u/E)]\gamma^l_1/3$

Eq. (4) $C^l_2 = [(\sigma_u-\sigma_{0.01})/2 - C^l_3(\varepsilon_u-\sigma_u/E)]\gamma^l_2/3$

Eq. (5) $C^l_3 = w\sigma_u/(1-w\sigma_u/E)$

5. Application

Default parameters for benchmark properties

- Ban HY, Shi G, Shi YJ, Wang YQ. Research progress on the mechanical property of high strength structural steels. Advanced Materials Research, 2011, 250-253: 640-648.
- Shi G, Zhu X, Ban HY. Material properties and partial factors for resistance of high-strength steels in China. Journal of Constructional Steel Research, 2016, 121: 65-79.

	Elastic modulus	Nominal yield strength	Nominal offset strength	Nominal plateau strain	Nominal ultimate strength	Nominal ultimate strain	Weight factor
Steel Gr.	E	s_y or $s_{0.01}$	$s_{0.2}$	e_{st}	s_u	e_u	w
Q235	206000	235	-	0.025	370	0.2	0.6
Q355	206000	355		0.02	470	0.18	0.6
Q460	206000	460		0.02	550	0.12	0.4
Q550	206000	$0.9s_{0.2}$	550	-	670	0.085	0.3
Q690	206000		690		770	0.065	0.3
Q890	206000		890		940	0.055	0.3
Q960	206000		960		980	0.04	0.3

5. Application

Default parameters for benchmark properties

Steel Gr.	E σ_y	ε_{st}^{p} $\bar{\varepsilon}_{st}^{p}$	Q_1^s b_1^s	Q_1^l b_1^l	C_1^s γ_1^s	C_2^s γ_2^s	C_1^l γ_1^l	C_2^l γ_2^l	c^s c^l
Q235	206000 235	0.0235 0.005	-117.5 300	104.5 25	117500 3000	23500 300	1881.5 30	266.7 0	0.5 0.3
Q355	206000 355	0.0180 0.0050	-177.5 300	99.8 25	177500 3000	35500 300	1546.4 30	333.3 0	0.5 0.3
Q460	206000 460	0.0175 0.0050	-230.0 300	78.0 30	230000 3000	46000 300	2204.1 40	246.7 0	0.5 0.3

Steel Gr.	E $\sigma_{0.01}$	Q_1^s b_1^s	Q_2^s b_2^s	Q_1^l b_1^l	Q_2^l b_2^l	C_1^s γ_1^s	C_2^s γ_2^s	C_1^l γ_1^l	C_2^l γ_2^l	C_3^l γ_3^l	c^l
Q550	206000 495	-99 3000	-99 300	77.3 40	38.7 600	297000 3000	14850 300	3297.8 50	23084.9 700	218.3 0	0.2
Q690	206000 621	-124.2 3000	-124.2 300	66.4 35	33.2 650	372600 3000	18630 300	2549.8 45	24081.7 850	246.3 0	0.2
Q890	206000 801	-160.2 3000	-160.2 300	63.6 35	31.8 650	480600 3000	24030 300	2425.0 45	22902.5 850	297.9 0	0.2
Q960	206000 864	-172.8 3000	-172.8 300	51.7 35	25.9 650	518400 3000	25920 300	2013.2 45	19013.1 850	306.2 0	0.2

Summary

- User manual_Cyclic plasticity model of structural steels.pptx
  Instructions on how to use the UMAT model
- User manual_Cyclic plasticity model of structural steels.xlsx
  Instructions on how to quickly calibrate parameters
- aba_param.inc
- UMAT_STEEL01.obj, UMAT_STEEL02.obj
  UMATs for steels with and without yield plateau
- Single element_Shell.cae
- Single element_Solid.cae
  Simple examples using the UMAT

ABAQUS 6.14 model files

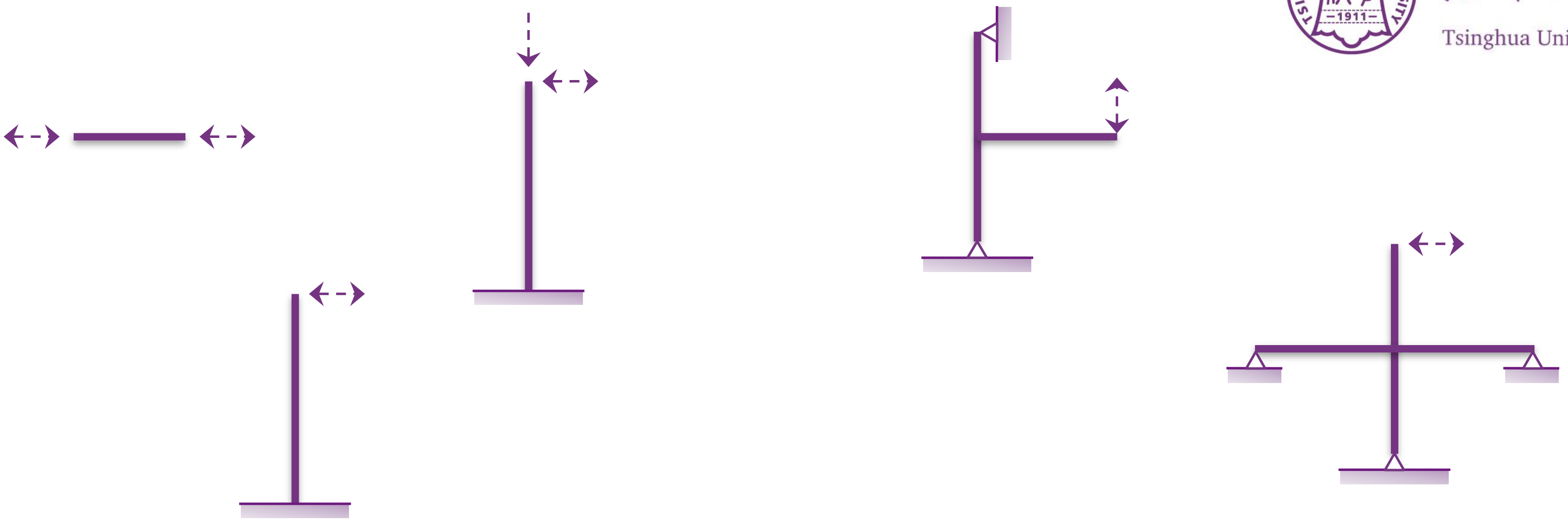
References

- Hu F X, Shi G, Shi Y J. Constitutive model for full-range elasto-plastic behavior of structural steels with yield plateau: Formulation and implementation. Engineering Structures, 2018, 171: 1059-1070.

- Hu F X, Shi G, Shi Y J. Constitutive model for full-range elasto-plastic behavior of structural steels with yield plateau: Calibration and validation. Engineering Structures, 2016, 118: 210-227.

References

- Hu F X, Shi G. Constitutive model for full-range cyclic behavior of high strength steels without yield plateau. Construction and Building Materials, 2018, 162: 596-607.



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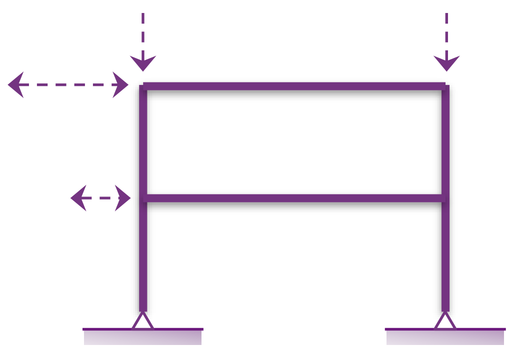

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