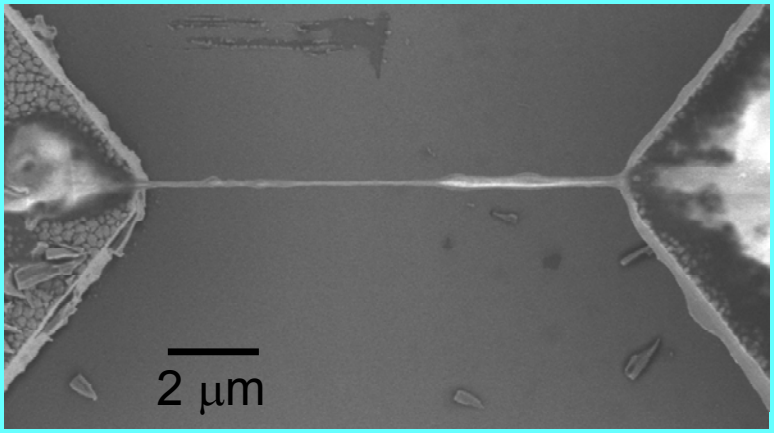
Tensile Testing of Collagen Fibrils Using a MEMS Platform



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Collaborators:

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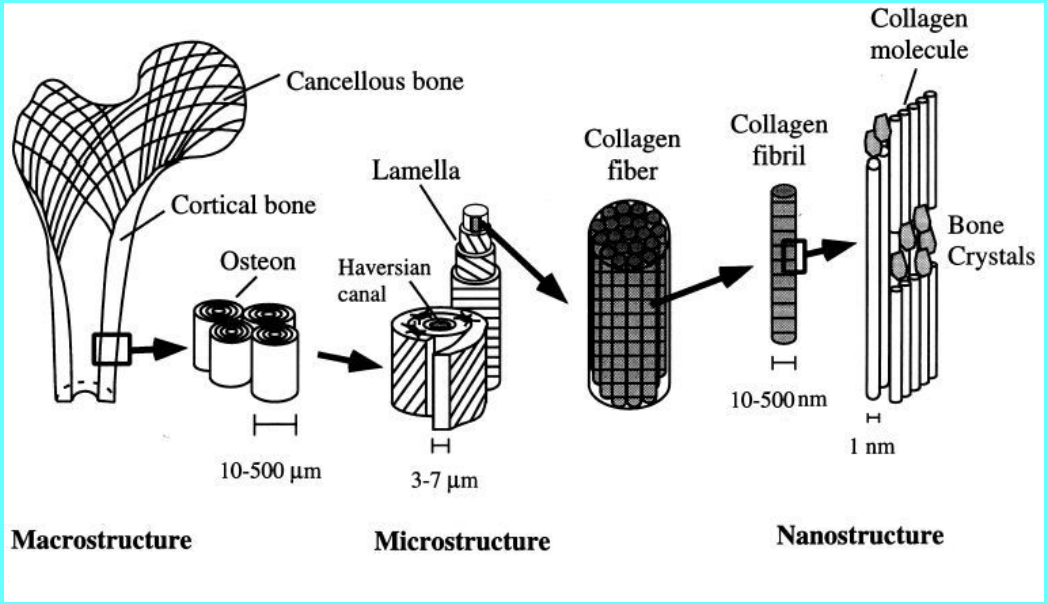
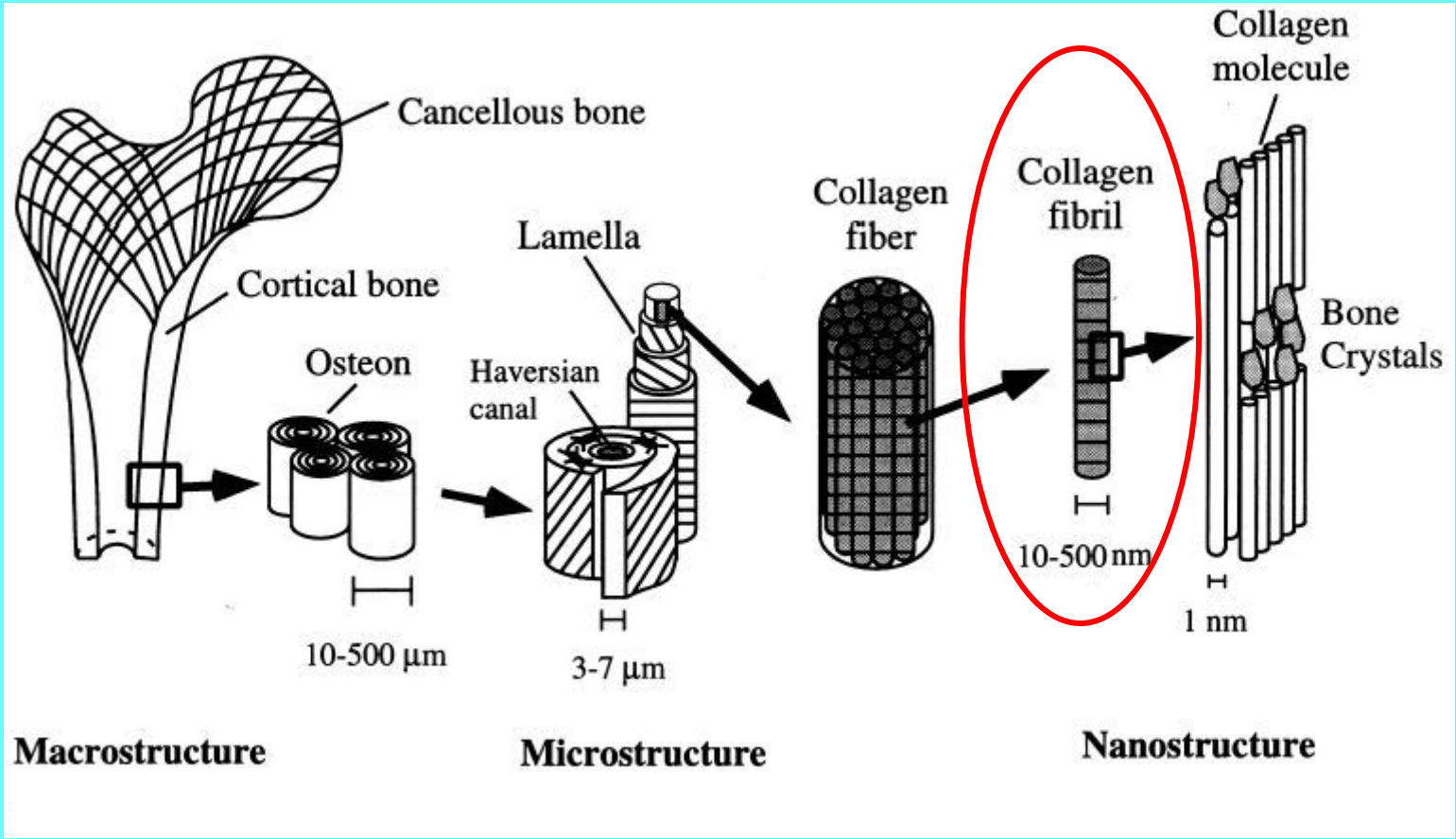
Case Western Reserve University



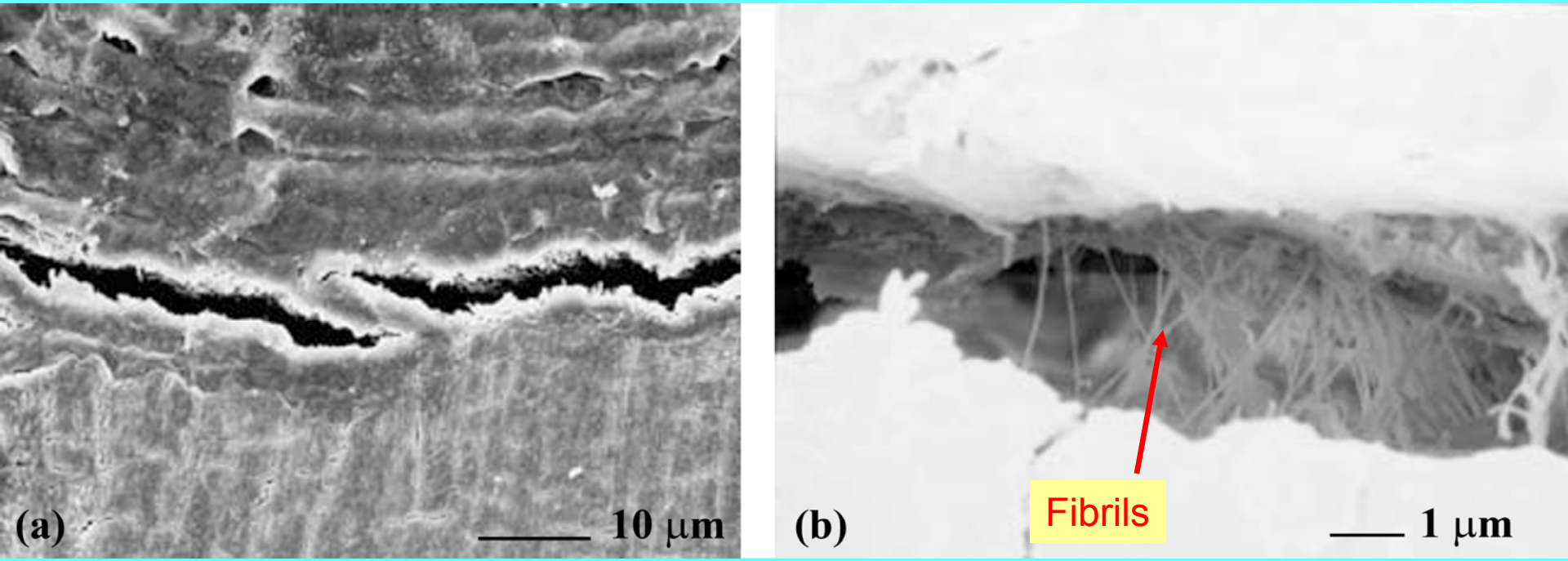
Sponsors:
NIH, NSF

IMECE ’08

Hierarchical Structure of Bone
What are the origins of its toughness?



J.Y. Rho, et al., *Medical Engineering & Physics*, 1998



Crack Bridging Mechanisms
(Nalla *et al.* 2005)

Bone:
Survival via continuous healing cycles

K_c ~3 MPa-m$^{1/2}$

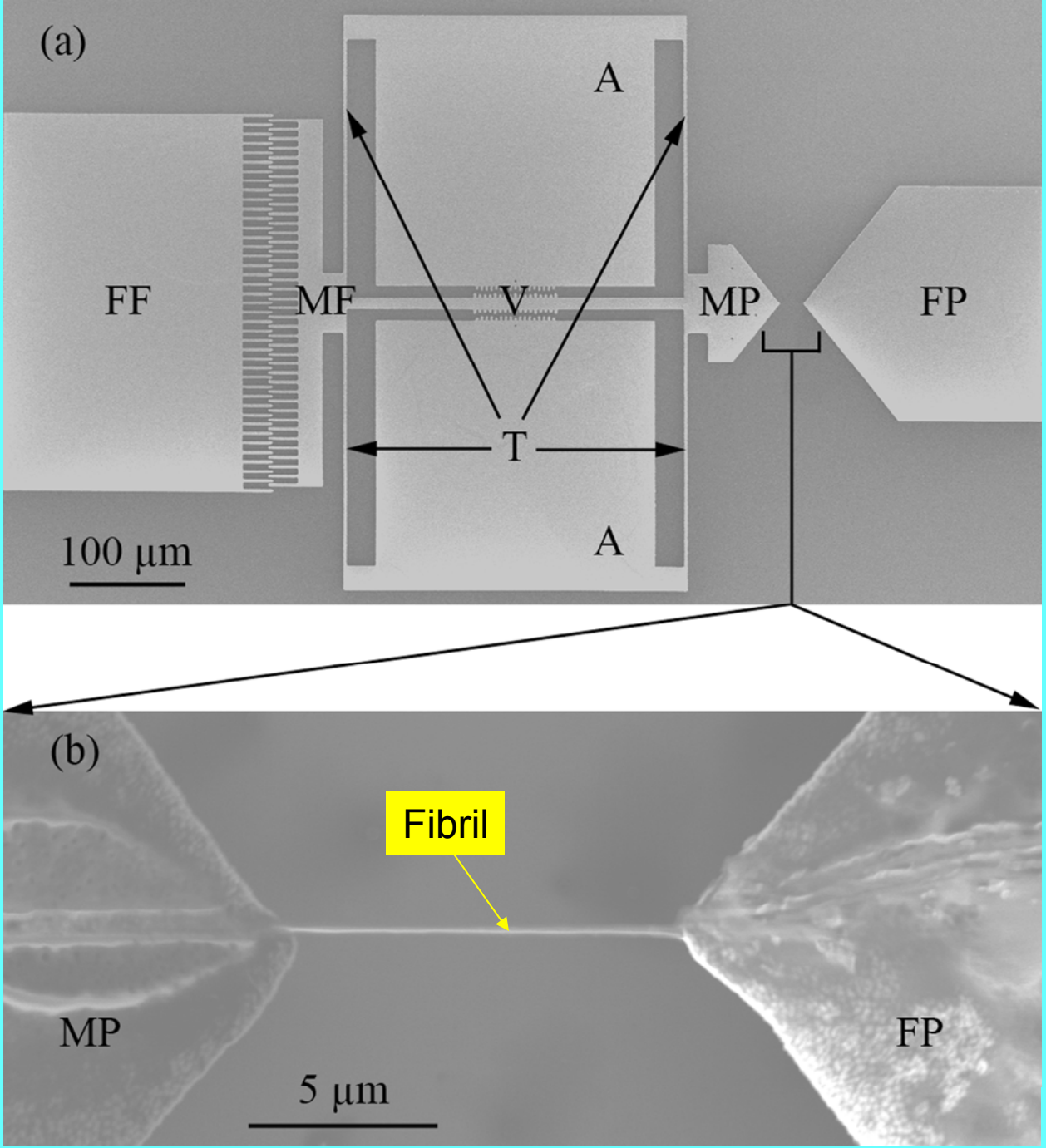
Operating stress, σ=200 MPa
Strength, σ_u=300 MPa

$$2a_{cr} = \left(K_c / \sigma\right)^2 / \pi \approx 140\,\mu m$$

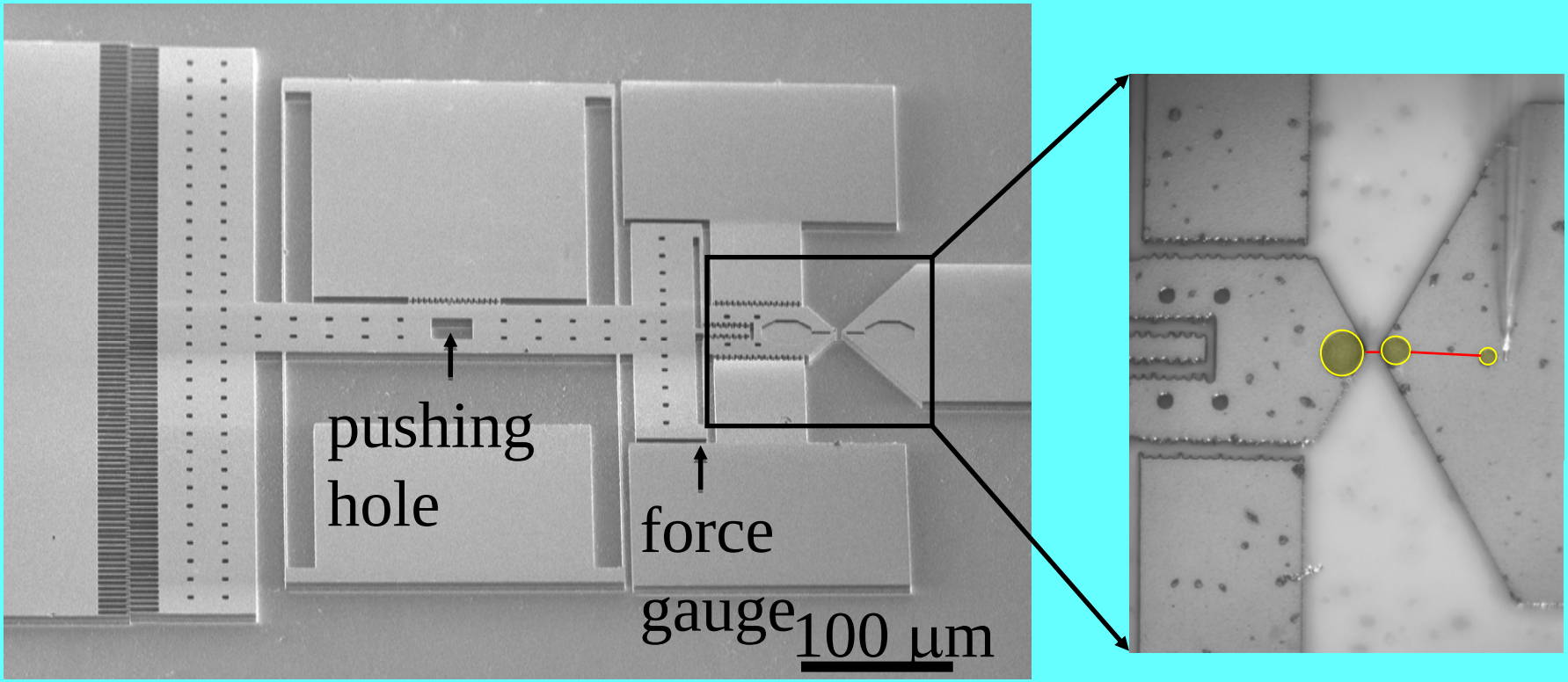
$$l_p = 0.1\left(K_c / \sigma_u\right)^2 \approx 10\,\mu m$$

~100 fibrils

How are such cracks mitigated?


(a)
A
FF
MF
V
MP
FP
T
A
100 µm
(b)
Fibril
MP
FP
5 µm

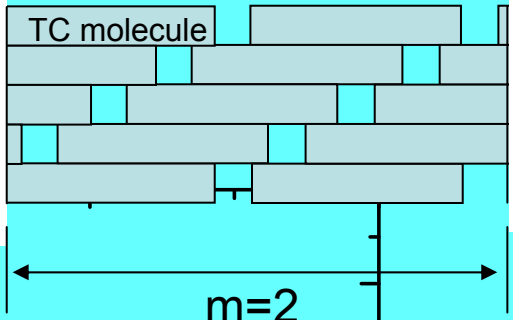
2nd Generation MEMS Device For In Fluid Experiments

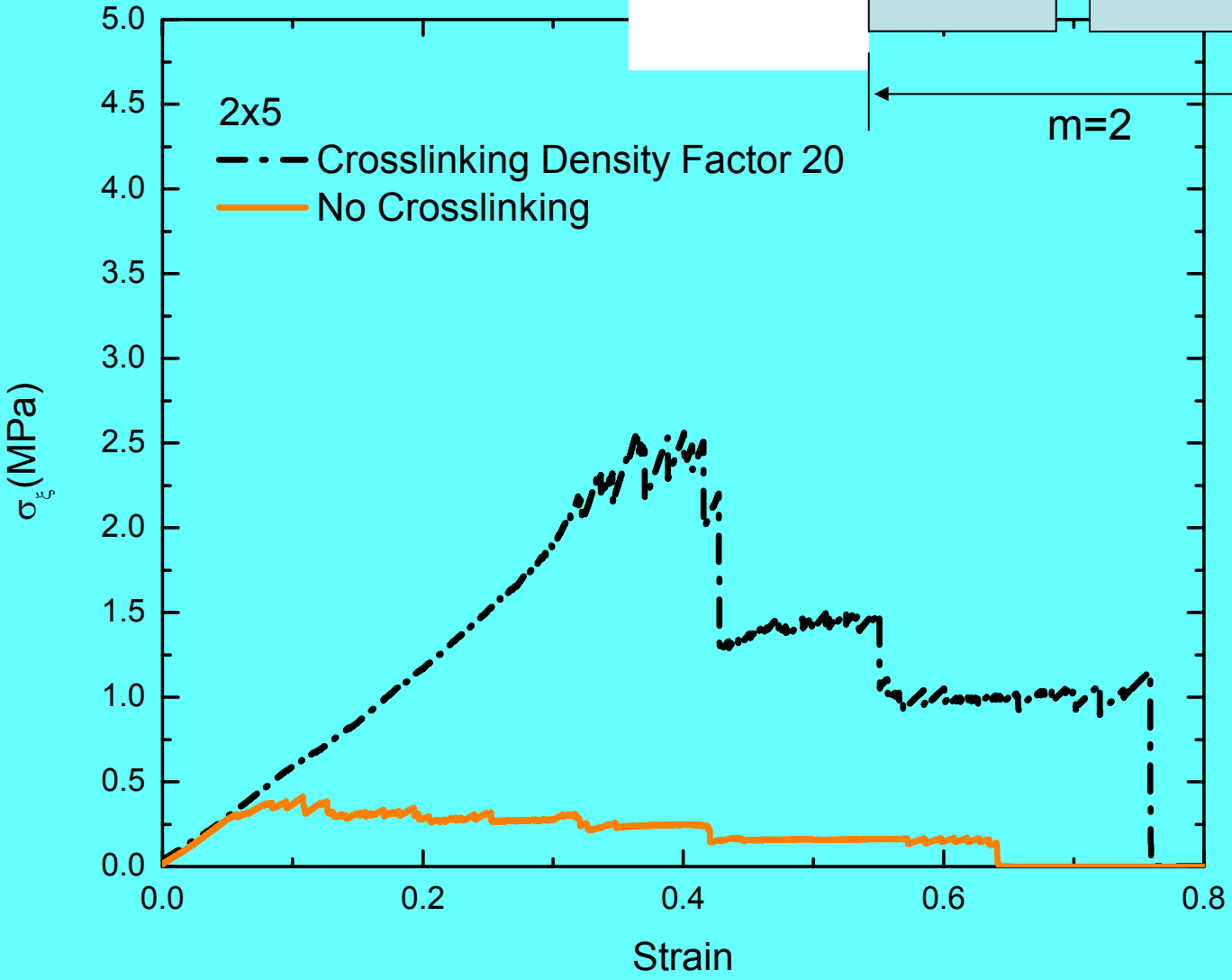


(1x Phosphate Buffered Saline)

Preliminary Results

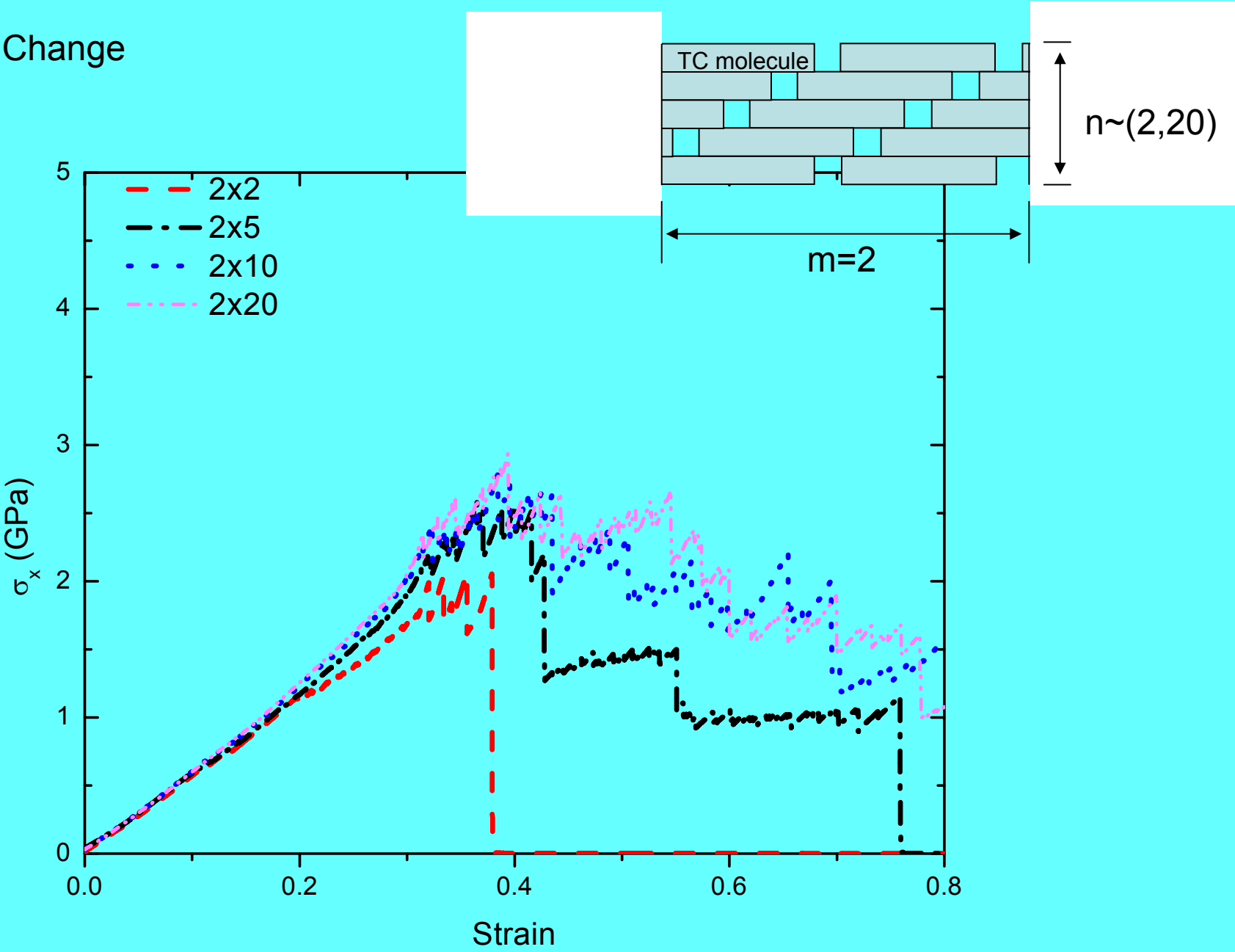
Crosslink Density Change





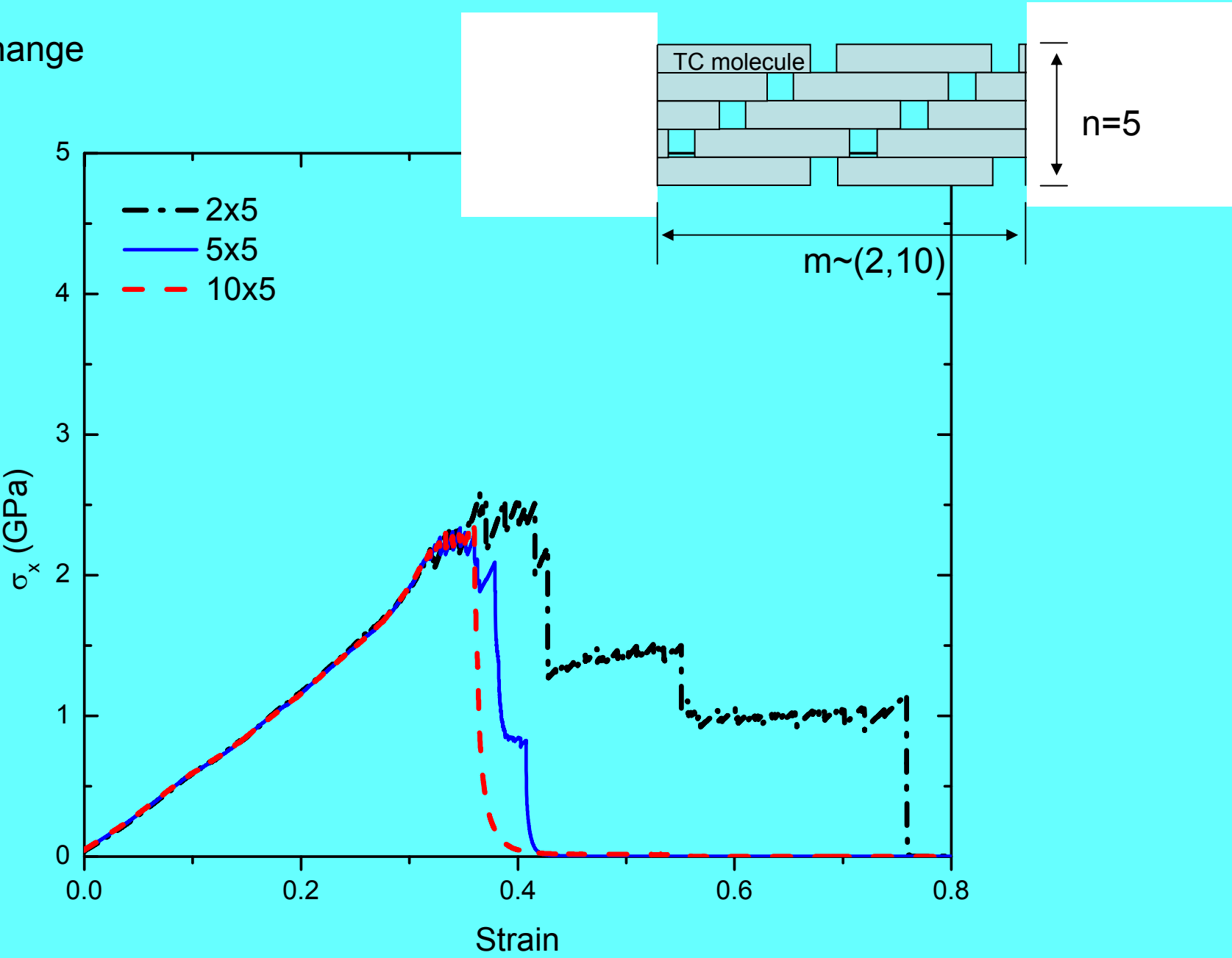
Preliminary Results

Diameter Change

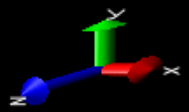


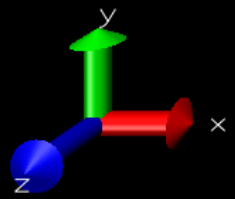
Preliminary Results

Length Change

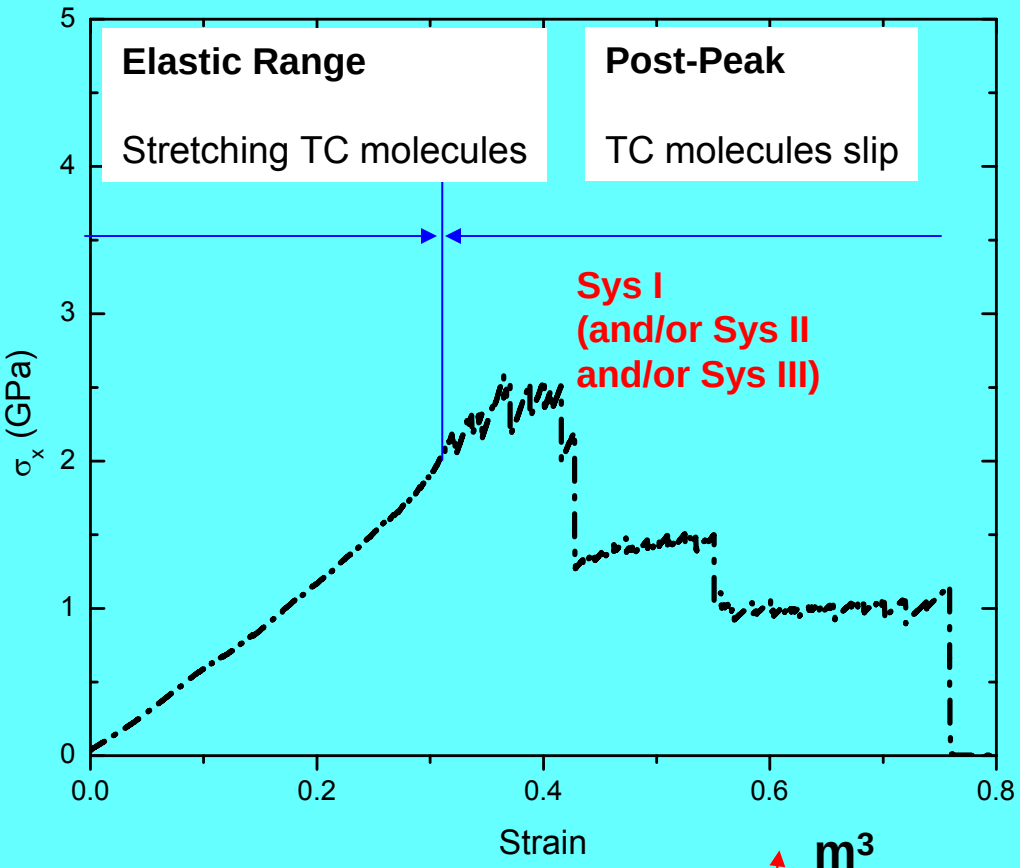


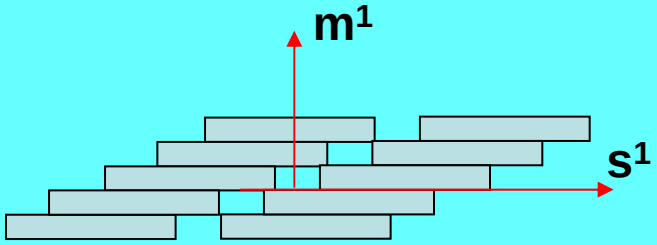
Micromechanisms



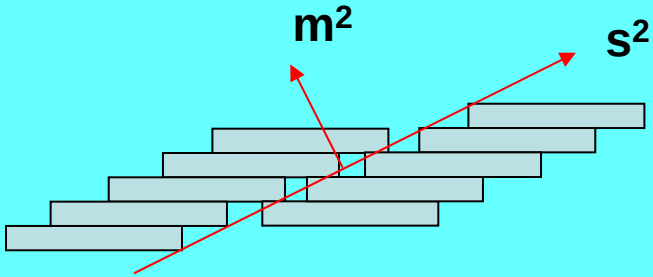


Micromechanisms

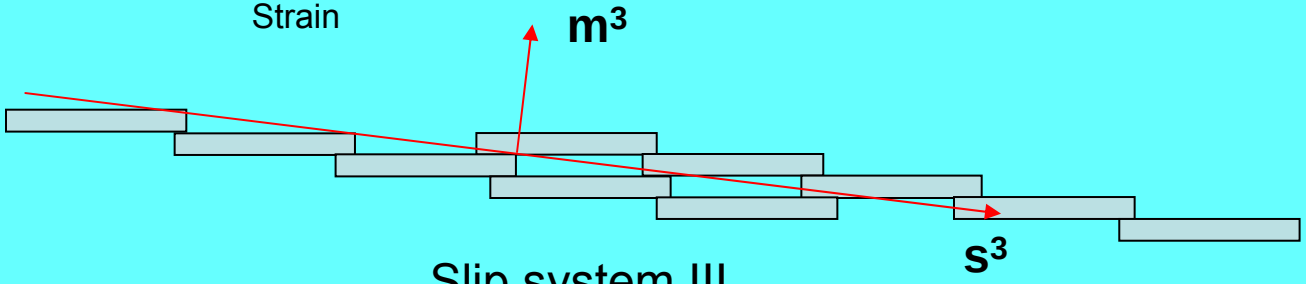




Slip system I

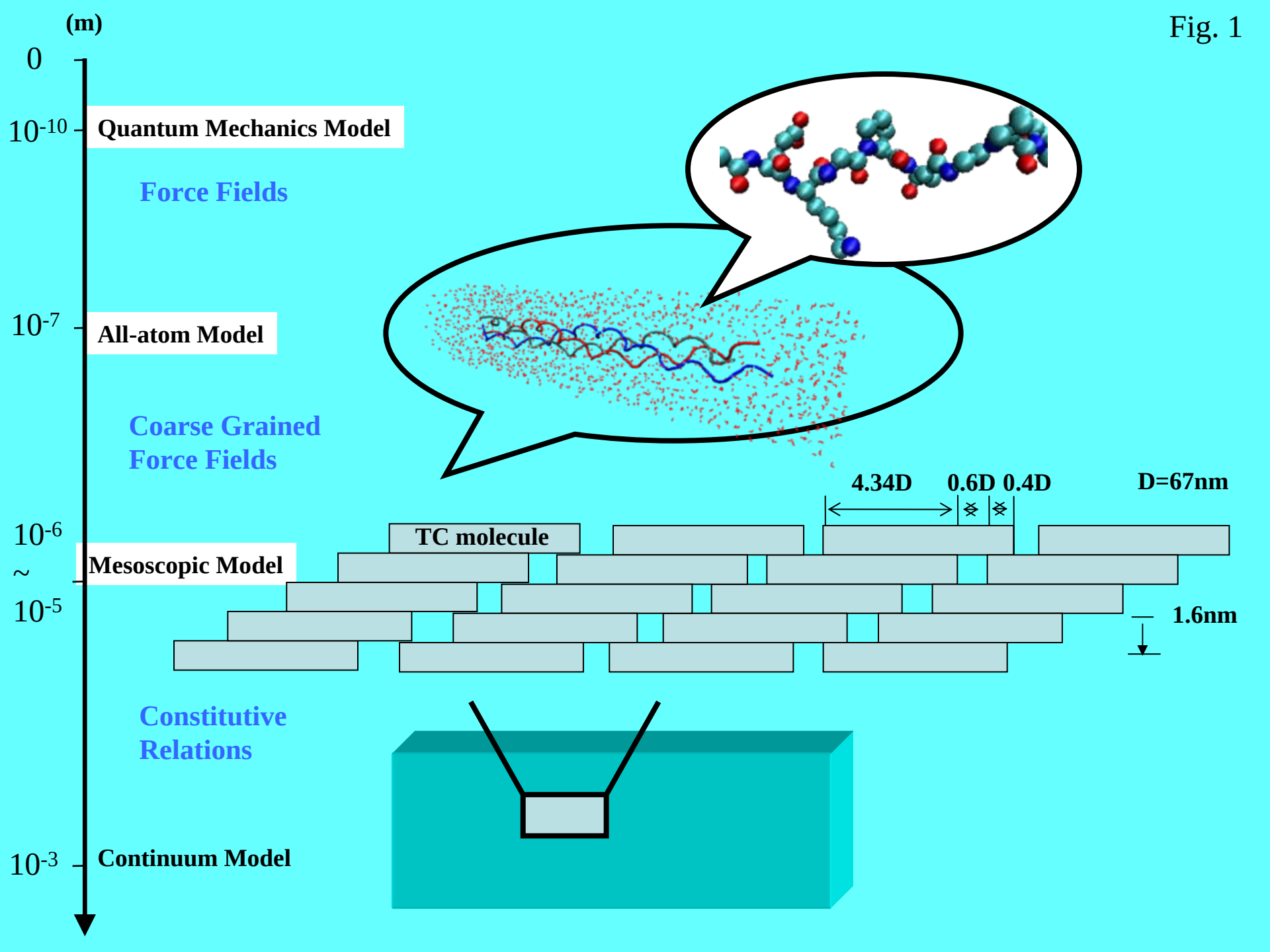


Slip system II



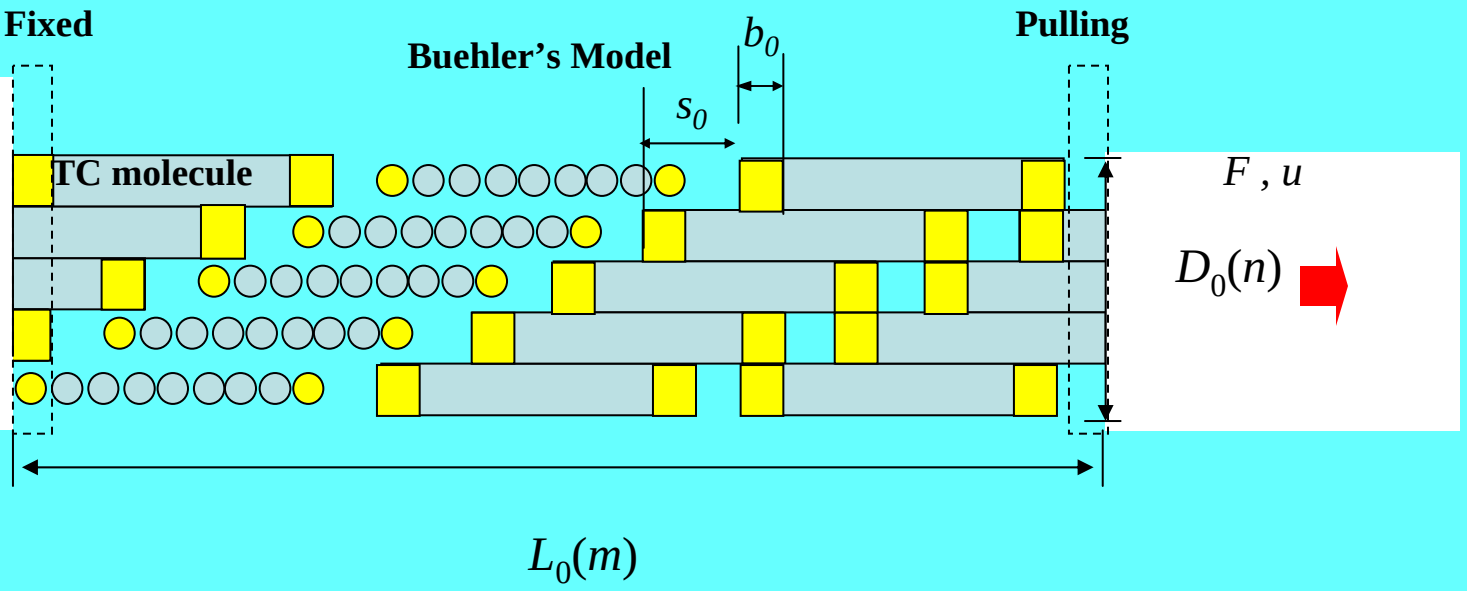
Slip system III

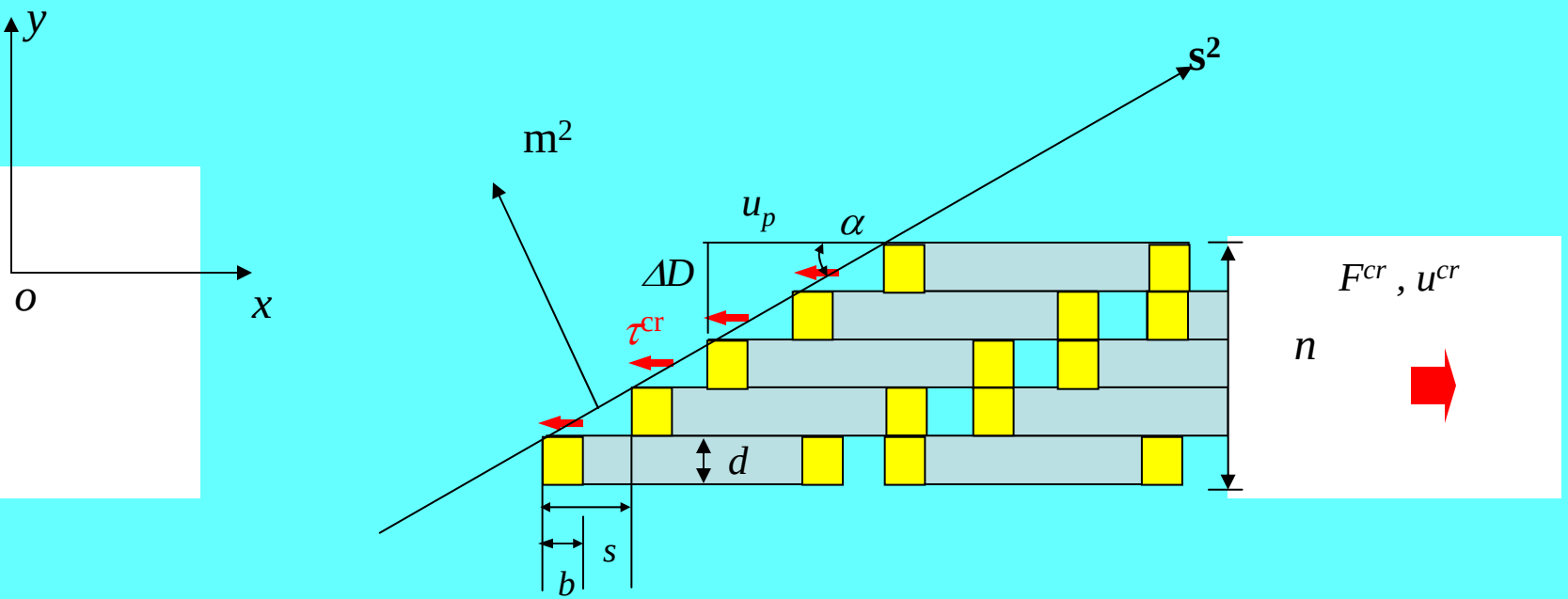
Fig. 1


(m)
0
10-10
Quantum Mechanics Model
Force Fields
10-7
All-atom Model
Coarse Grained
Force Fields
10-6
~
10-5
Mesoscopic Model
4.34D
0.6D
0.4D
D=67nm
TC molecule
1.6nm
Constitutive
Relations
10-3
Continuum Model

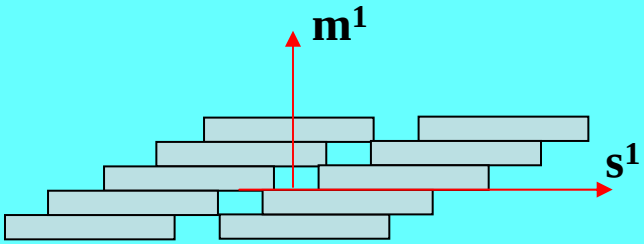
(A)

Fig. 2


Fixed
Buehler's Model
b_0
Pulling
s_0
TC molecule
F , u
$D_0(n)$
$L_0(m)$

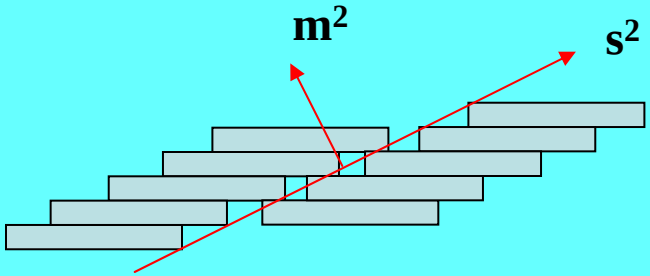

y
o
x
s^2
m^2
u_p
α
ΔD
τ^{cr}
d
s
b
F^{cr} , u^{cr}
n

(B)



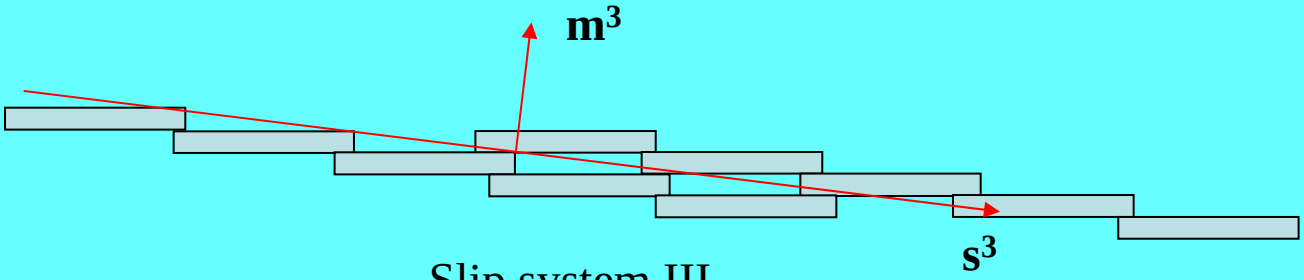
Slip system I

(C)



Slip system II

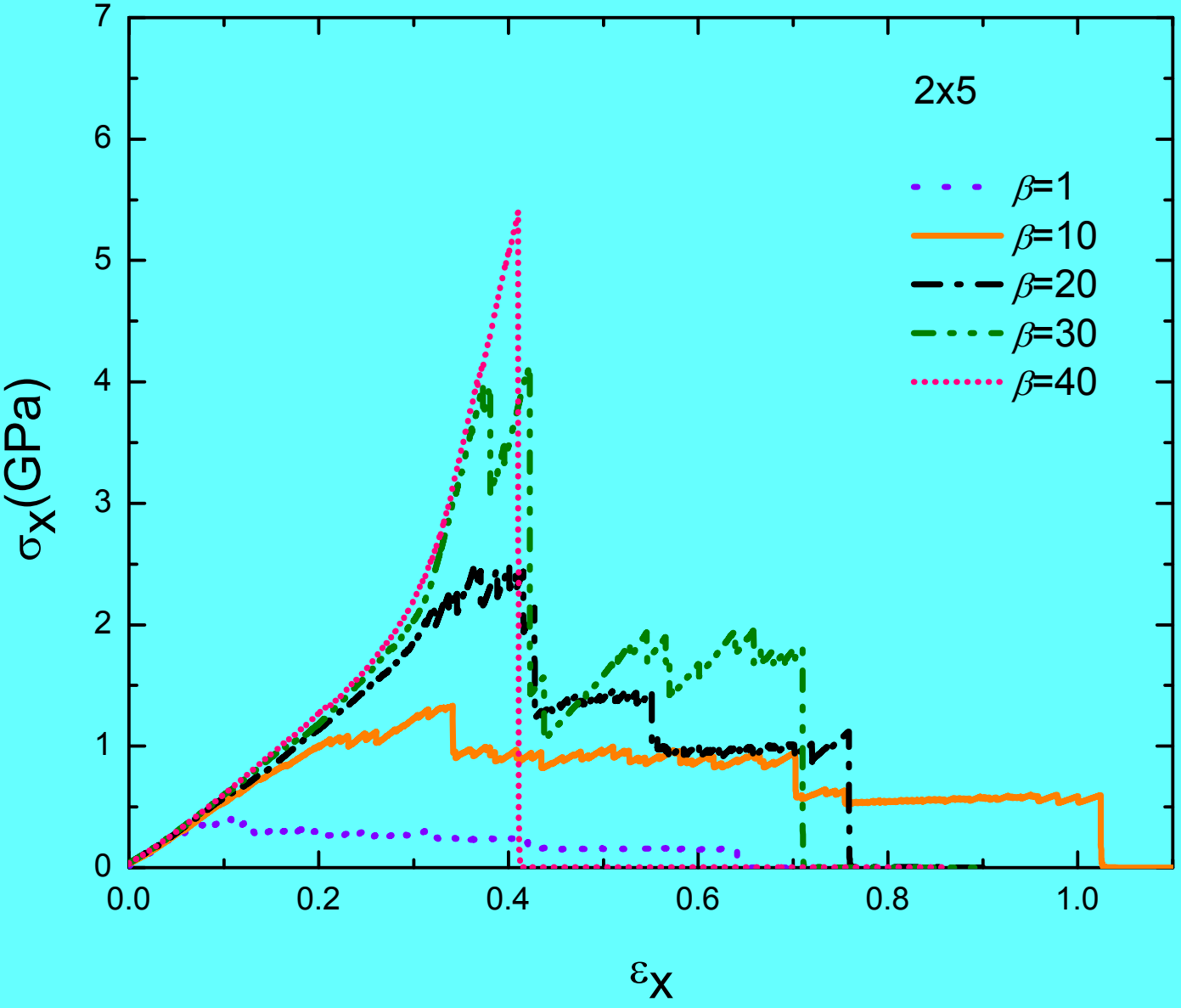
(D)



Slip system III

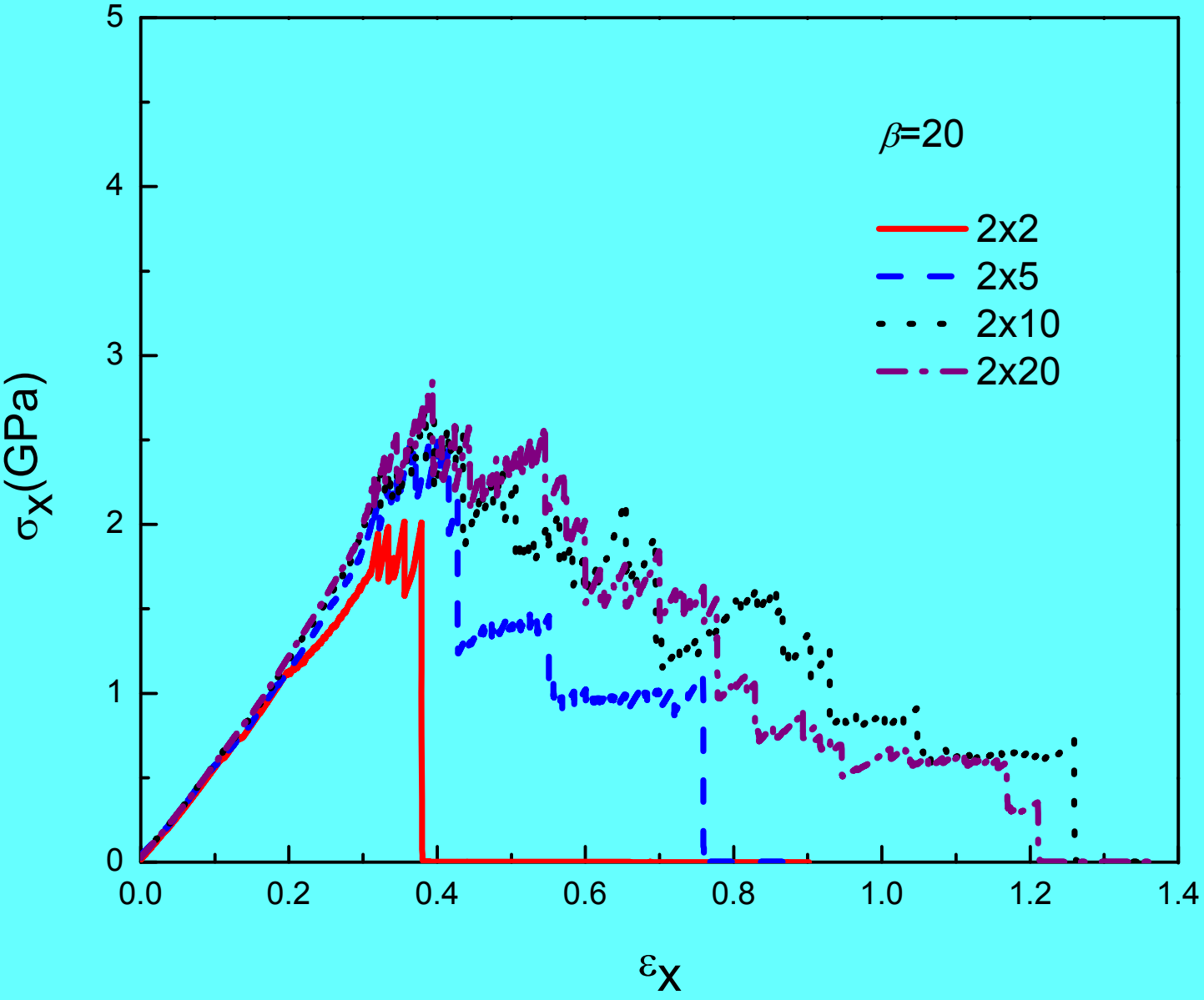
(A)

Fig. 3



(B)

Fig. 3



(C)

Fig. 3

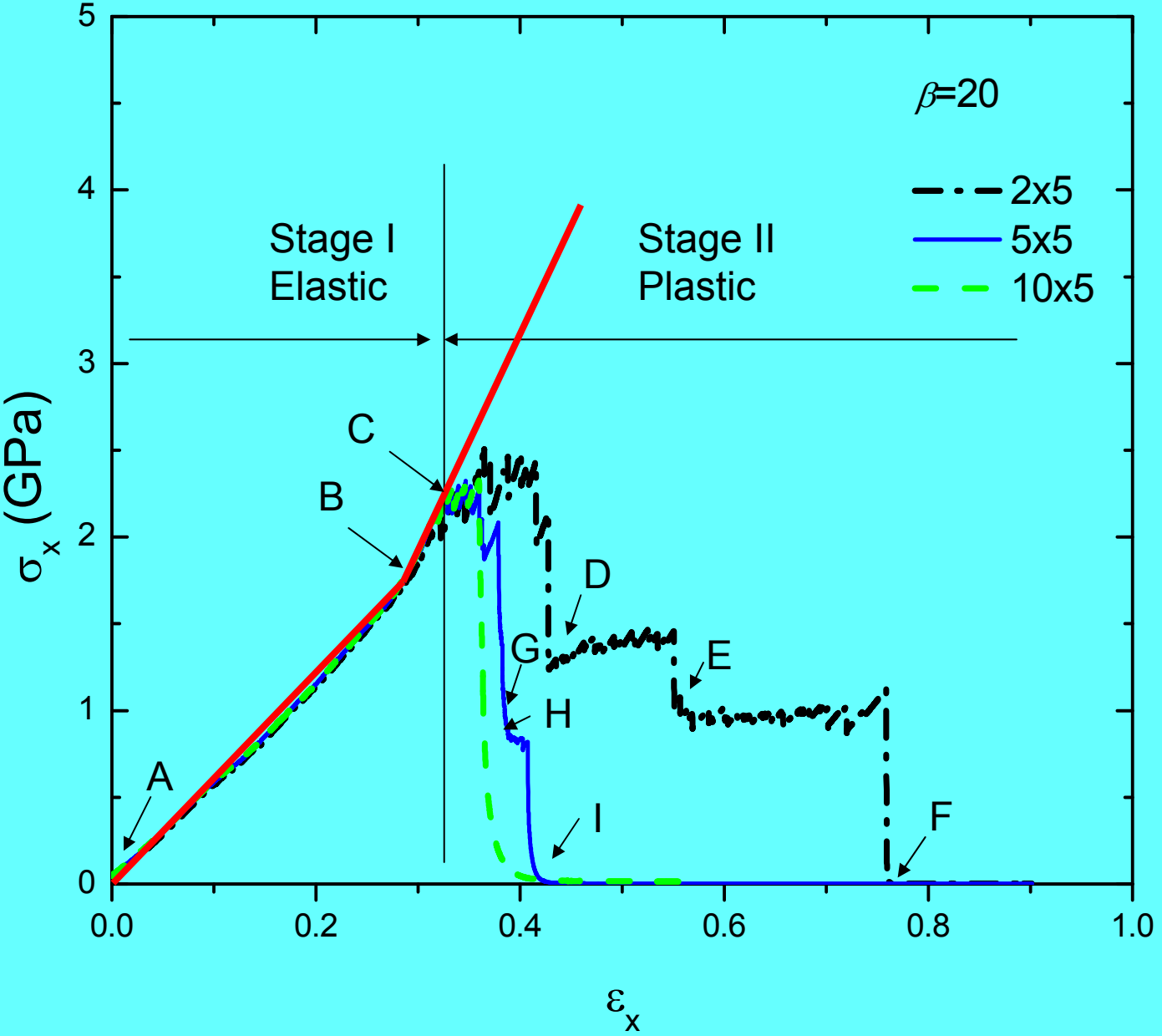
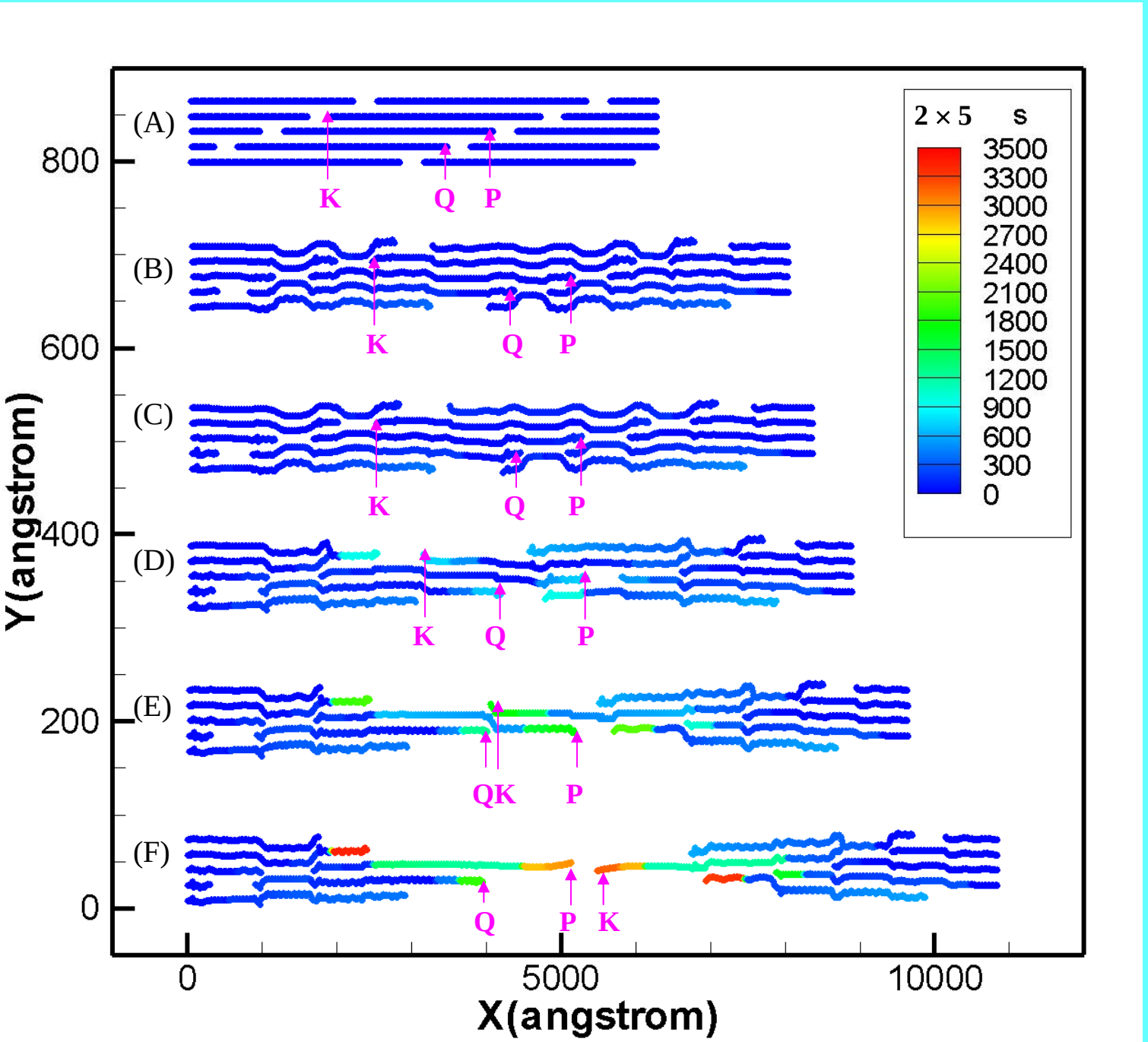
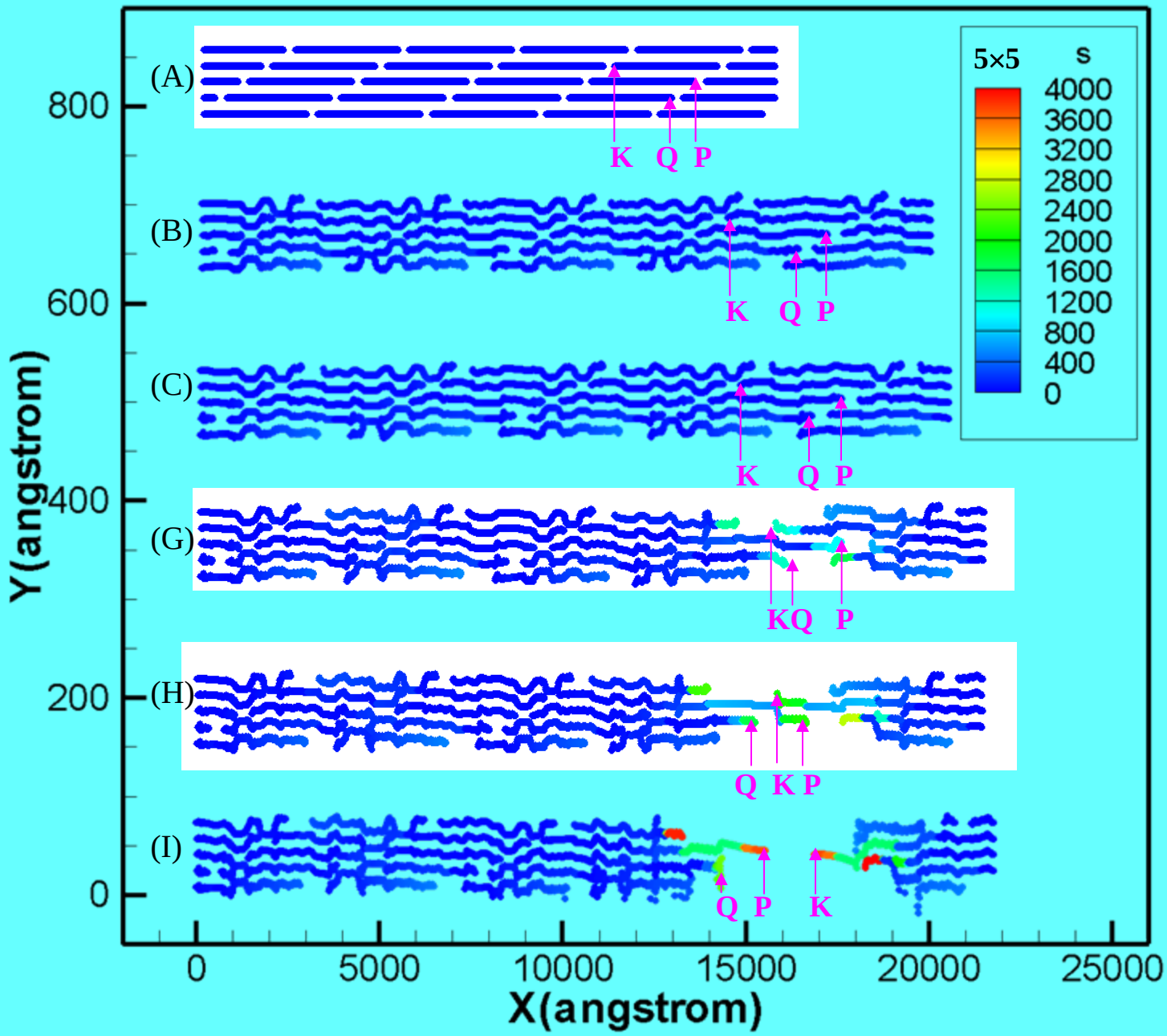

β=20
2x5
5x5
10x5
Stage I
Elastic
Stage II
Plastic
A
B
C
D
E
F
G
H
I
σx (GPa)
εx
0
1
2
3
4
5
0.0
0.2
0.4
0.6
0.8
1.0

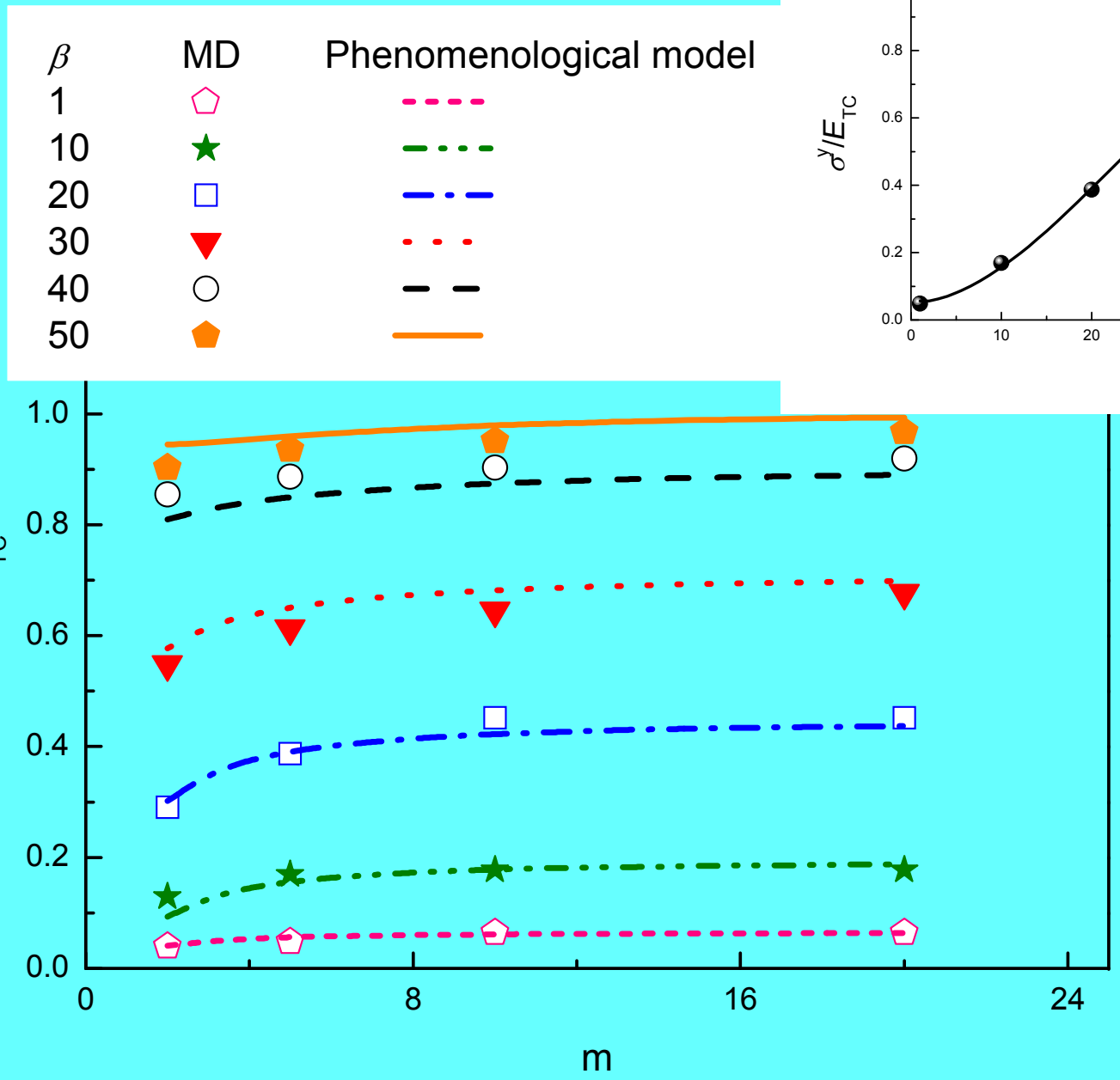
Fig. 4

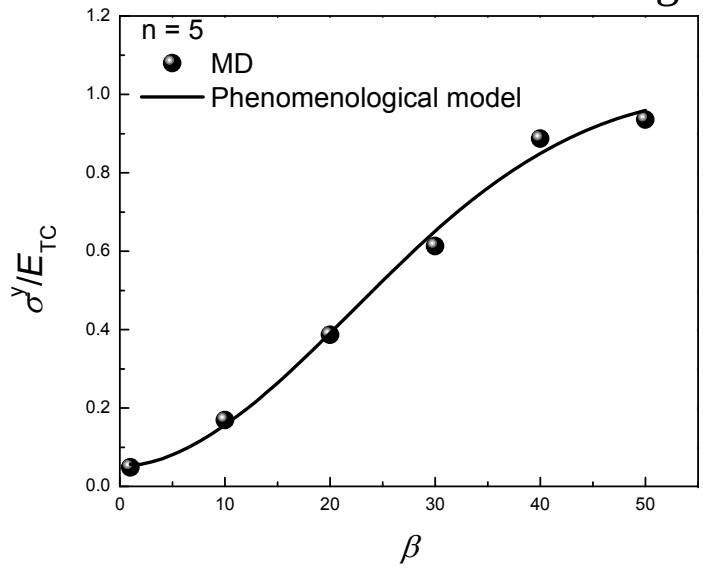

(A)
(B)
(C)
(D)
(E)
(F)
K
Q
P
QK
2 × 5 s
3500
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
800
600
400
200
0
Y(angstrom)
0
5000
10000
X(angstrom)


5×5
s
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
(A)
(B)
(C)
(G)
(H)
(I)
K Q P
K Q P
K Q P
KQ P
Q K P
Q P K
800
600
400
200
0
Y(angstrom)
0
5000
10000
15000
20000
25000
X(angstrom)

(A)

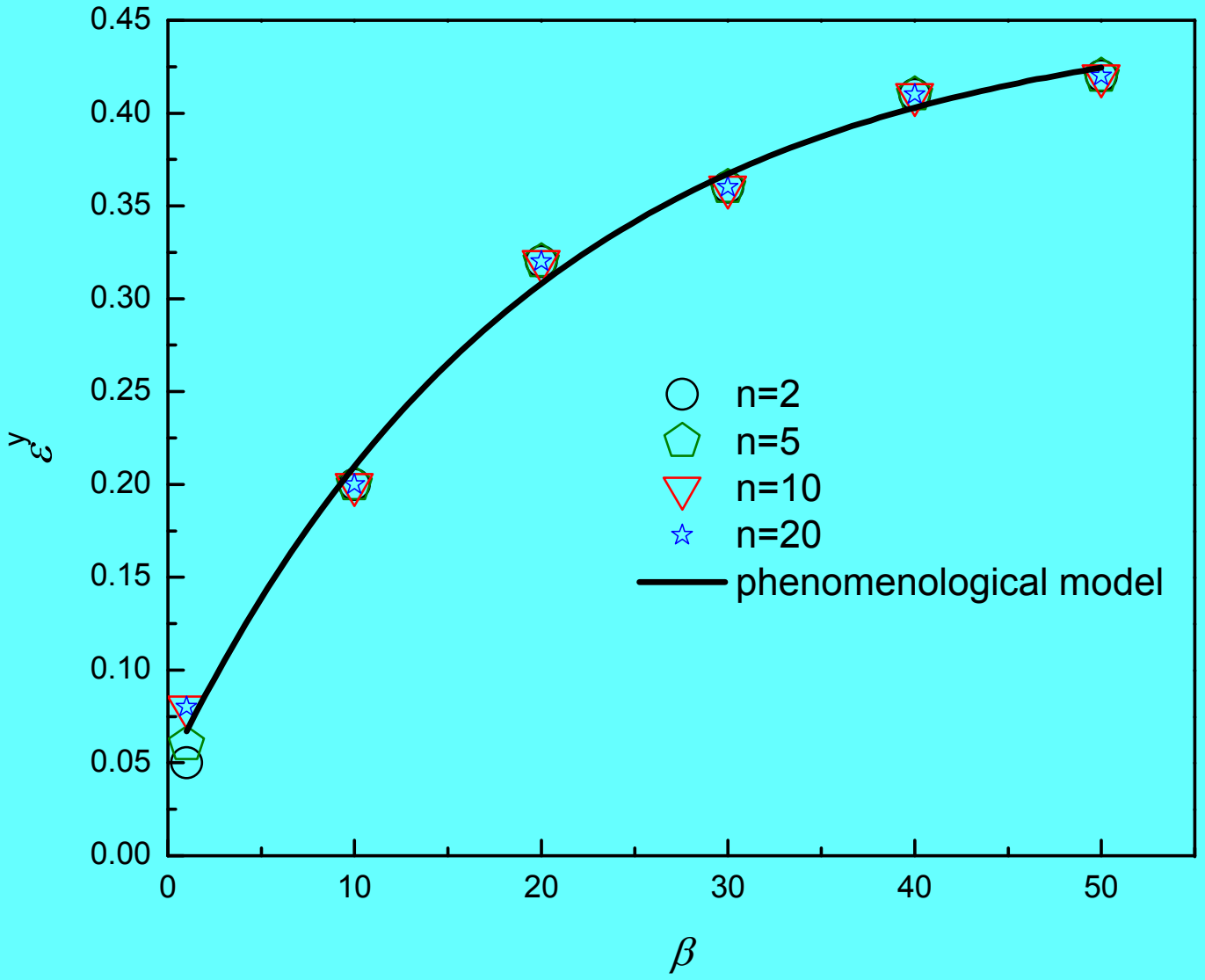
Fig. 5


β
MD
Phenomenological model
1
10
20
30
40
50
σ^y/E_{TC}
m
0
8
16
24
0.0
0.2
0.4
0.6
0.8
1.0


n = 5
MD
Phenomenological model
σ^y/E_{TC}
β
0
10
20
30
40
50
0.0
0.2
0.4
0.6
0.8
1.0
1.2

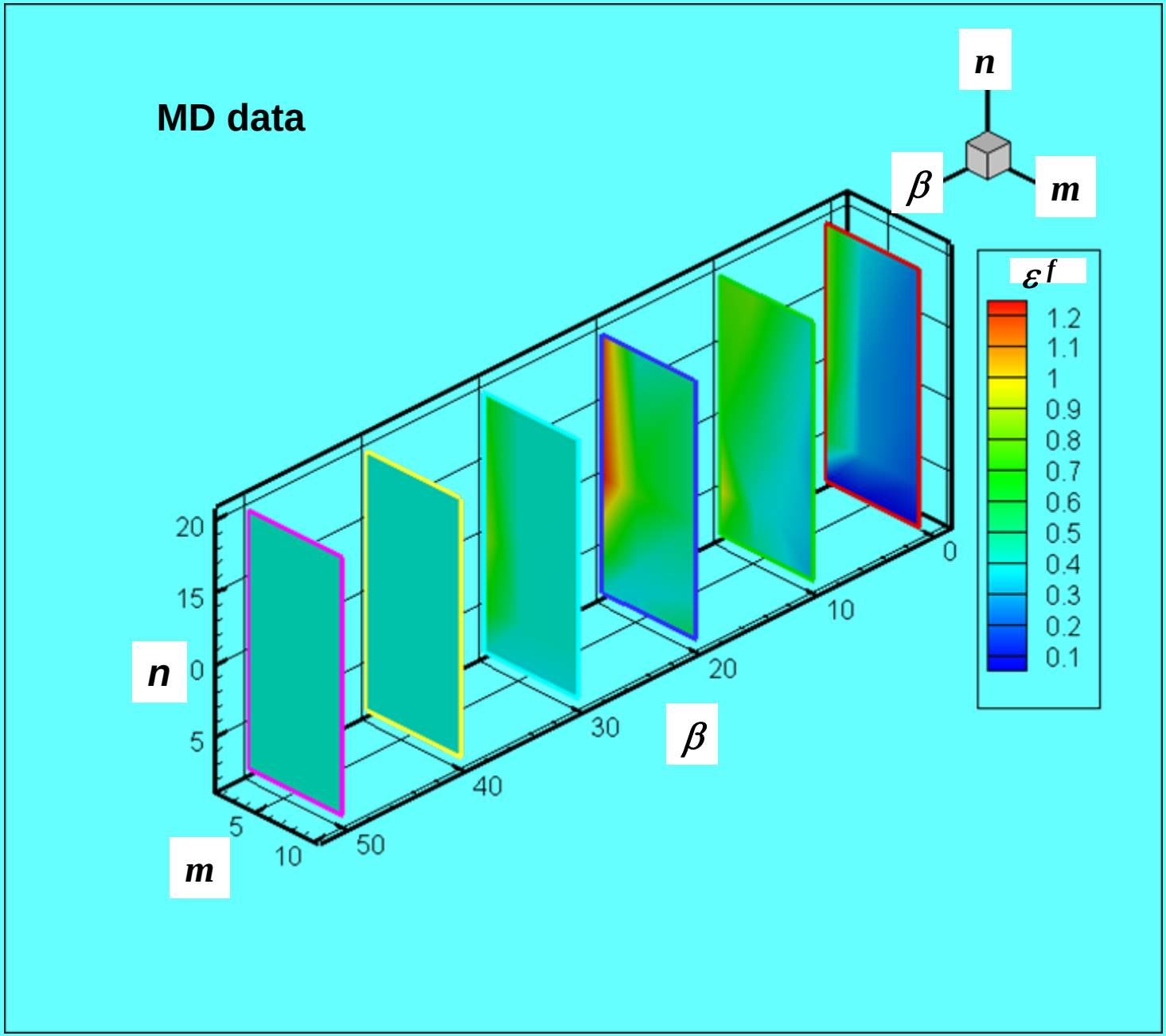
(B)

Fig. 5


0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
ε_y
0
10
20
30
40
50
β
n=2
n=5
n=10
n=20
phenomenological model

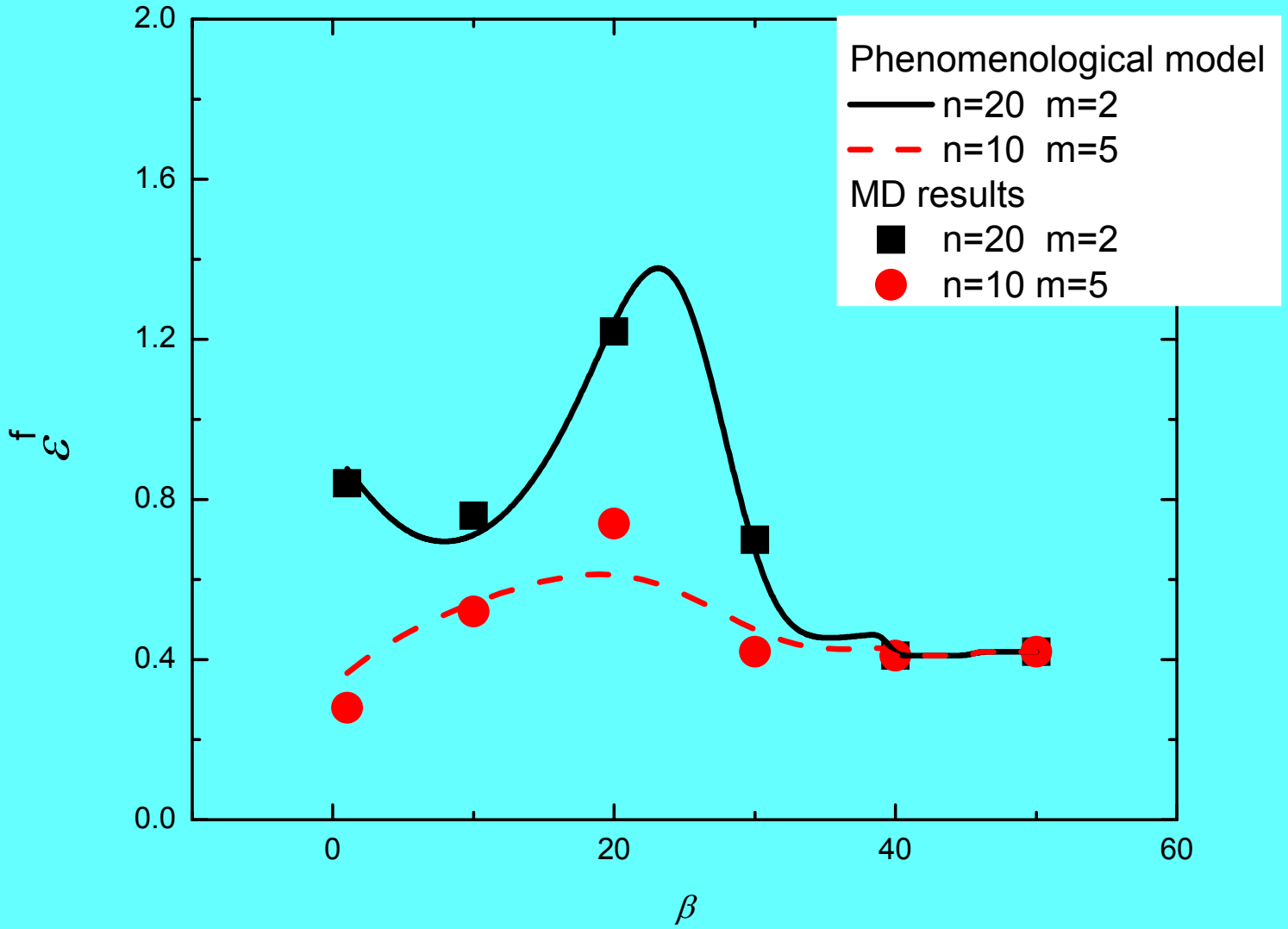
(C)

Fig. 5


MD data
n
β
m
εf
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20
15
n
0
5
m
5
10
50
40
30
β
20
10
0

(D)

Fig. 5


Phenomenological model
n=20 m=2
n=10 m=5
MD results
n=20 m=2
n=10 m=5
2.0
1.6
1.2
0.8
0.4
0.0
ε_f
0
20
40
60
β