POLITECNICO
MILANO 1863

DIPARTIMENTO DI MECCANICA

Advanced numerical methods for polymer materials under various strain rates

Dayou Ma, Andrea Manes

mecc

COMPORTAMENTO MECCANICO E MODELLAZIONE DEI POLIMERI AD ALTI STRAIN RATES

PRIMA GIORNATA DI STUDIO DEL GRUPPO DI LAVORO AIAS "XTREMA" (MATERIALS AT EXTREMES)

Mercoledi' 29 marzo 2023, Sala Consiglio del Dipartimento di Meccanica - Politecnico Di Milano - Via La Masa 1, 20156

Contents

Objective:

1. **Numerical methods for polymer** materials subject to **loading conditions under different strain rate**

2. Considering the **presence of** defects for a **better understanding of the fracture behaviour**

Outline:

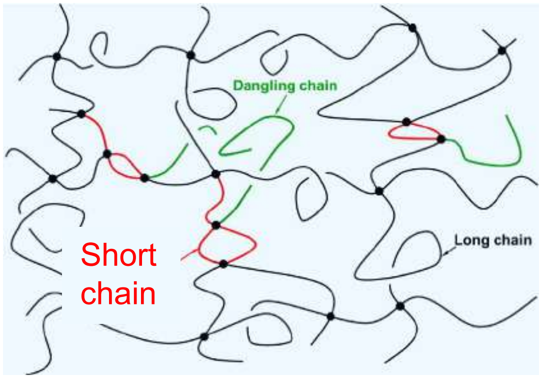
- Background
- Cohesive-based model under tension (strain rate effect oriented)
- Stochastic FE model under compression (present of defect oriented)
- Conclusions

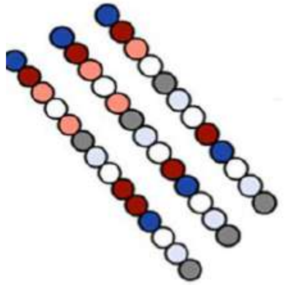
Background – existence of defects

Defects in polymer materials can hardly be avoided, their presence may be useful to **better understanding fracture behaviour** under **different strain rate** [1]

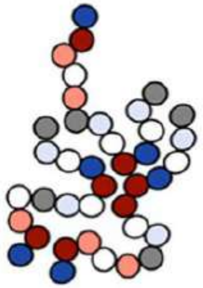
Defects in polymers

Molecular-scale defects, i.e., short chain, chain gathering…



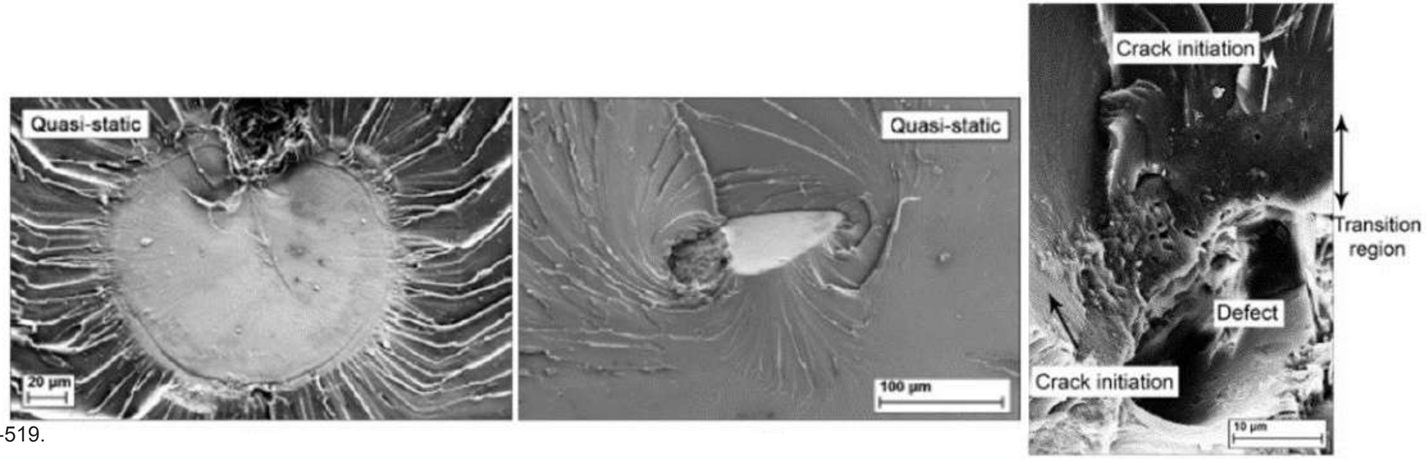


Aligned chains



Gethered chains

Macroscale defects, i.e., voids, scratches…



[1] Zhou, Fenghua, et al. *Engineering fracture mechanics 72.9 (2005): 1383-1410.*
[2] Chevalier, Jérémy, et al. *Journal of the Mechanics and Physics of Solids* 122 (2019): 502-519.

Background

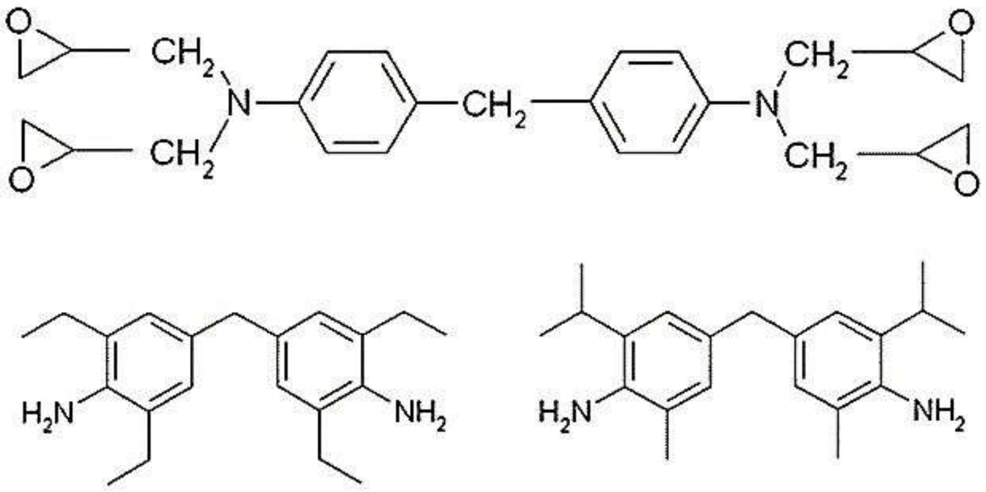
How to model the effect of defects for mechanical properties of polymers (under different strain rates)?

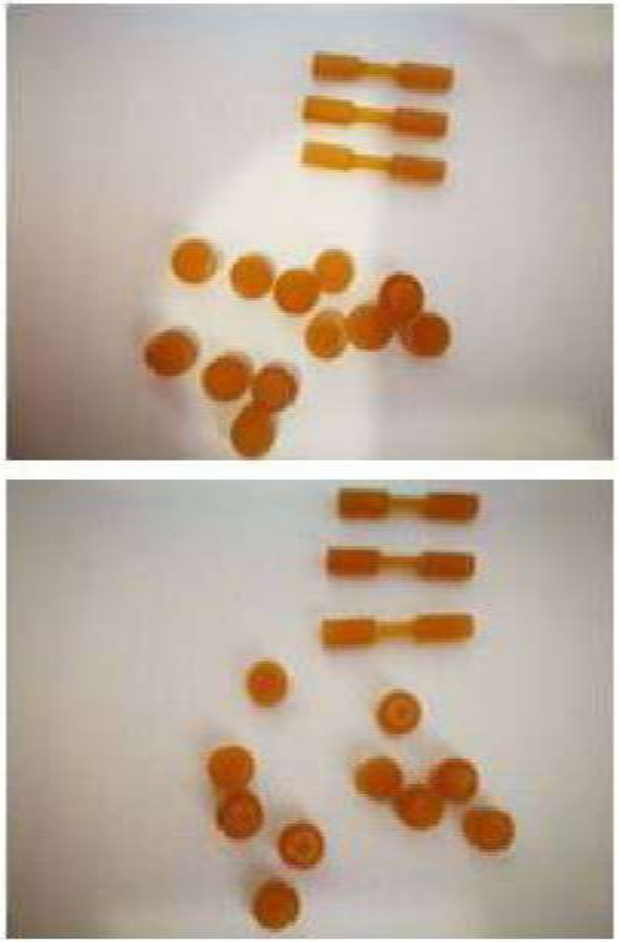
POLITECNICO MILANO 1863
mecc
COMPORTAMENTO MECCANICO E MODELLAZIONE DEI POLIMERI AD ALTI STRAIN RATES
PRIMA GIORNATA DI STUDIO DEL GRUPPO DI LAVORO AIAS "XTREMA" (MATERIALS AT EXTREMES)
Mercoledi' 29 marzo 2023, Sala Consiglio del Dipartimento di Meccanica - Politecnico Di Milano - Via La Masa 1, 20156

Background – RTM6 epoxy resin

RTM6 is a **premixed epoxy-amine system**, composed by the tetra-functional epoxy resin and the harder. In the current activies, tensile and compressive samples were prepared as the validation of the numerical methods.

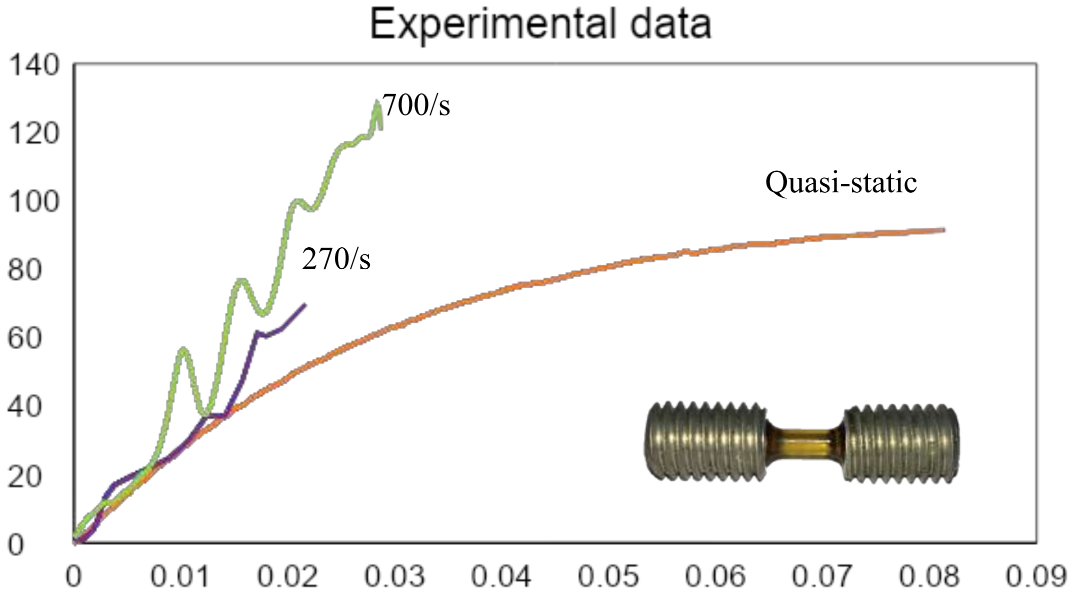
The matrix RTM6 was supplied by Hexcel Composites.

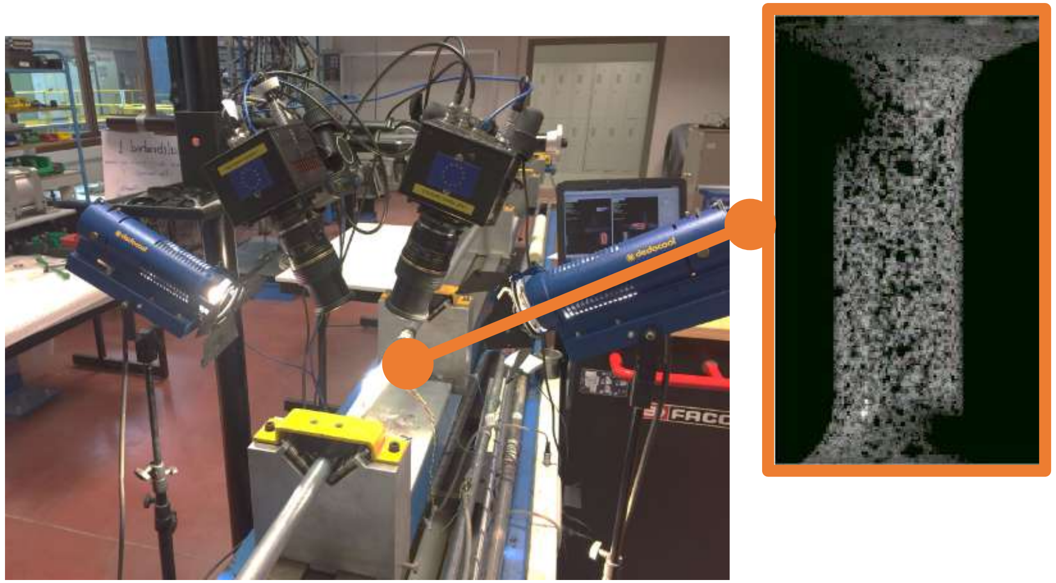




Cohesive-based model under tension
– experiments

Tensile tests were carried out in MST-DyMaLab (Ghent, Belgium) with an extremely small sample (Ø2.5×6 mm) **of RTM-6** using SHTB (Split Hopkinson **Tension** Bar). Additionally, high-speed camera was employed to capture the fracture behaviours during loading.



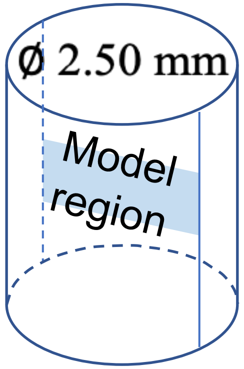


Special phenomena (neglecting oscillations):

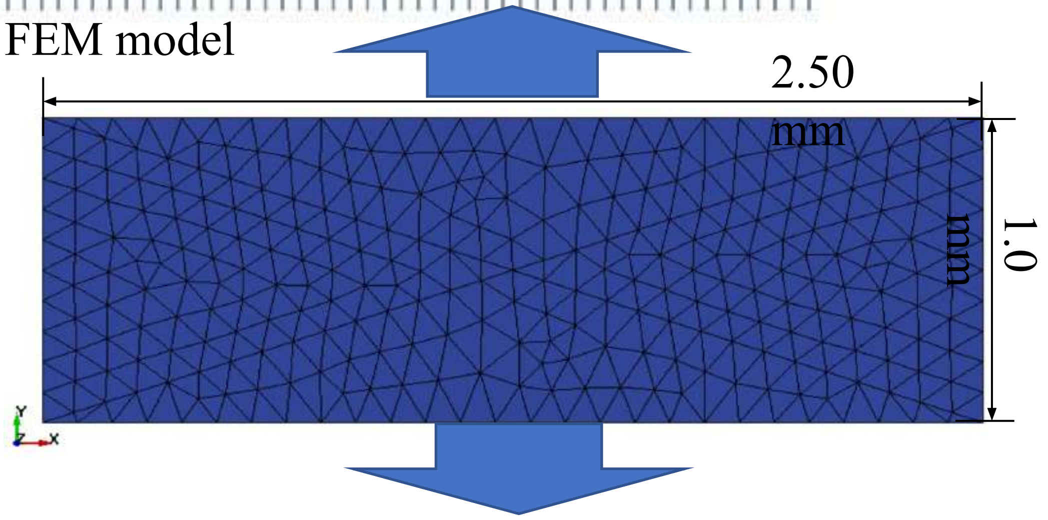
- **Nonlinearity** seems to be **reduced under** dynamic conditions
- **Modulus increased** noticeably under dynamic conditions
- **Failure strain decreased** under dynamic conditions but **increased** as the strain rate increased

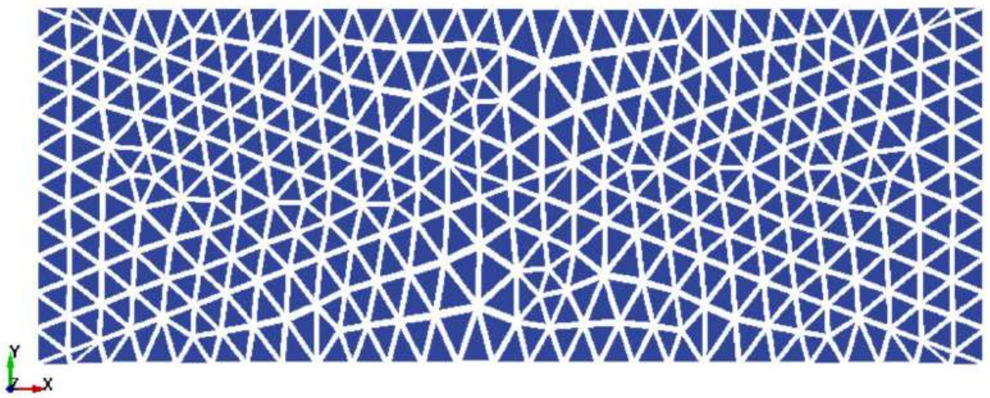
Cohesive-based model under tension
– numerical method

Gauge region



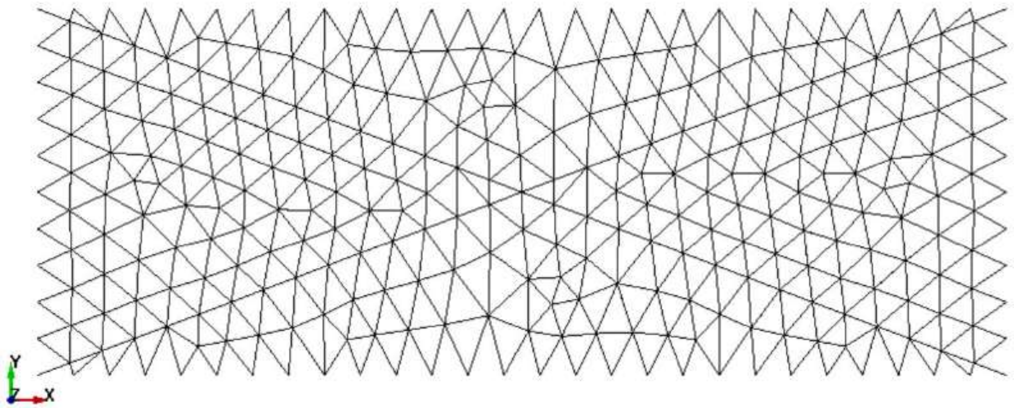
Select a slice
in the centre





Shell element + elastic mechanical properties

+



Zero-thickness shell cohesive element

Cohesive-based model under tension
– numerical method

- The nonlinear behaviour when $\Delta < \Delta_d$ is used to capture the **plasticity of RTM-6** under quasi-static condition.

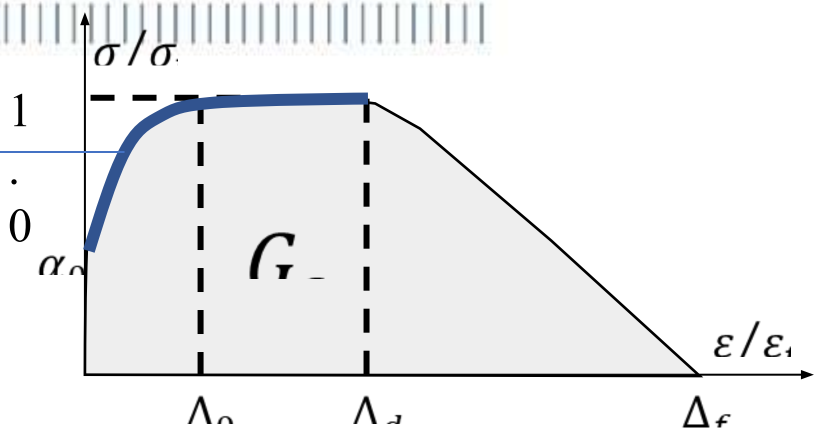
- Different behaviour for **cohesive element that suppose to replicate materials with defect** , and the peak arrives sooner in type – based on the fact that the possible stress concentration always occurs near defects, leading to an immediate peak.

Note: **Defected cohesive model does not describe the behaviour of defect itself, but of the material containing defects.**

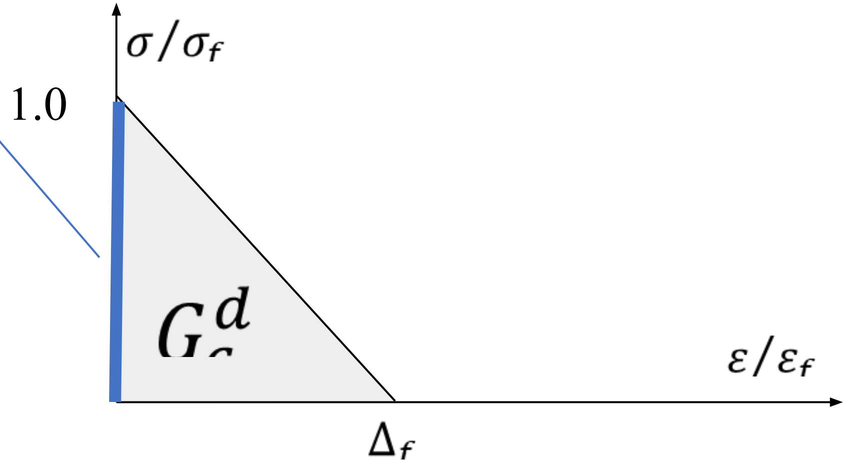
Herein, the parameters can be determined as:

$$\sigma_f = 200\ MPa\ [1], \tau_f = 47\ MPa\ [2],$$

$$\alpha_0 = 0.5, \Delta_0 = 0.1, \Delta_d = 0.2, \Delta_f = 1, \Delta_f^d = 0.3, G_{IC} = 113\ J/m^2\ [3]$$



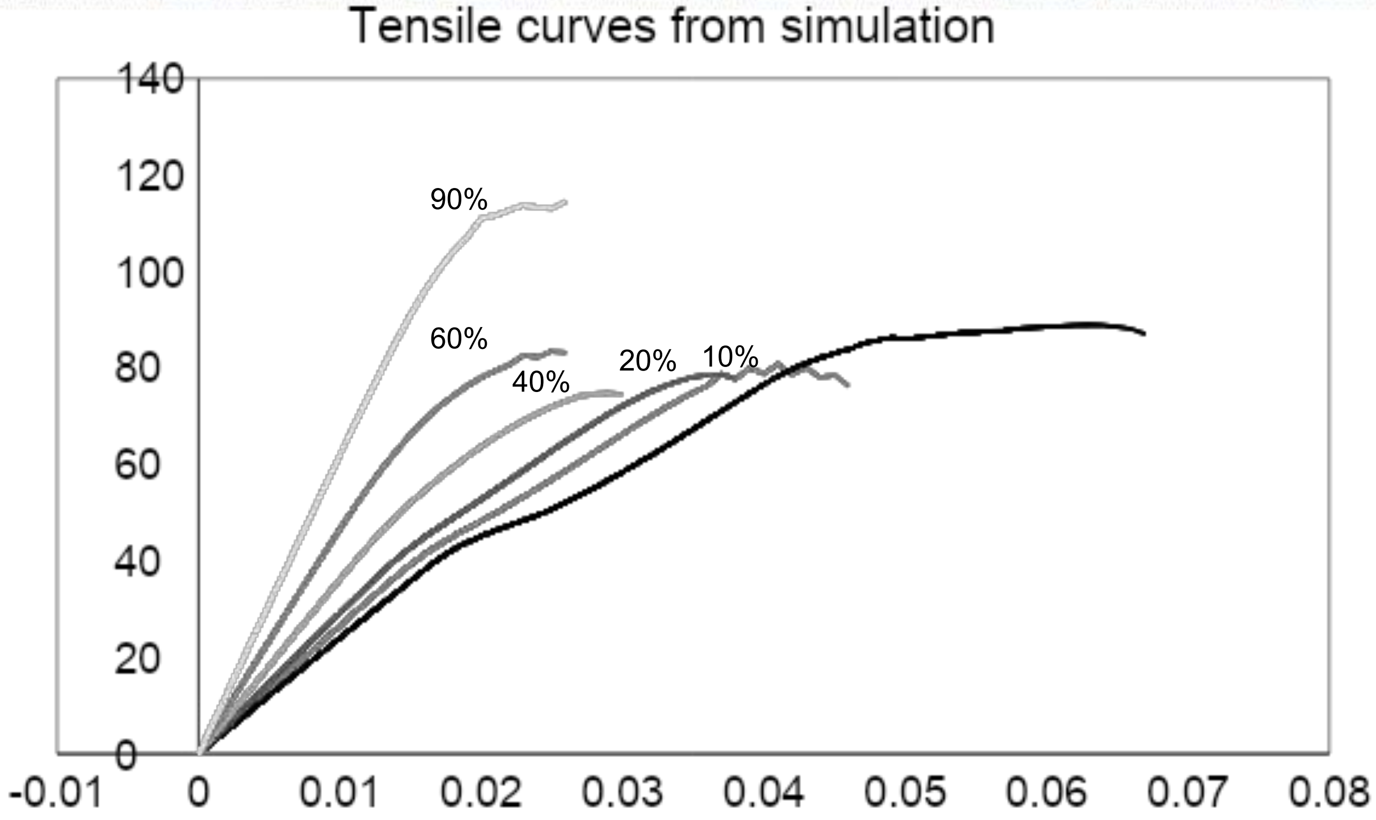
Type – I: cohesive model for material



Type – II: cohesive model for material with defect

[1] Gerlach, R., Siviour, C.R., Petrinic, N., Wiegand, J., 2008. Polymer (Guildf). 49, 2728–2737
[2] Tserpes, K.I., 2011. Advances in Composite Materials for Medicine and Nanotechnology. IntechOpen, Rijeka
[3] Zotti, A., Elmahdy, A., Zuppolini, S., Borriello, A., Verleysen, P., Zarrelli, M., 2020. Nanomaterials 10, 188. https://doi.org/10.3390/nano10020188

Cohesive-based model under tension – results



Summary:

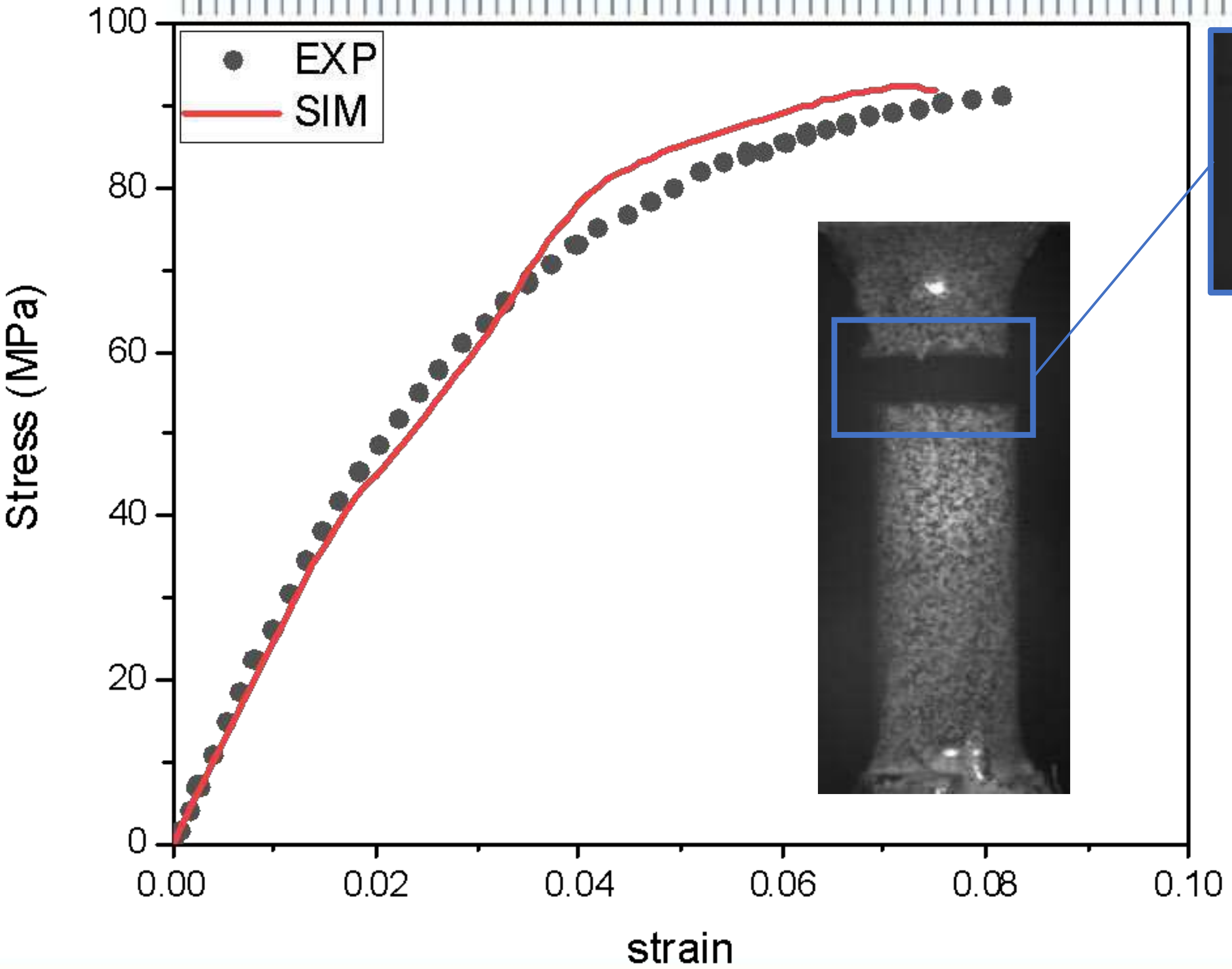
- The trend here depicted fit with experimental data
- With the change of the proportion about the defected elements, the curves can be altered.
- As the presence of defect increase of, the yield strength and modulus increase but the failure strain reduces.

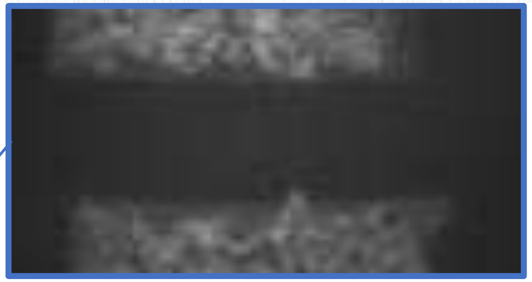
Does it look like dynamic test results?

Next step:

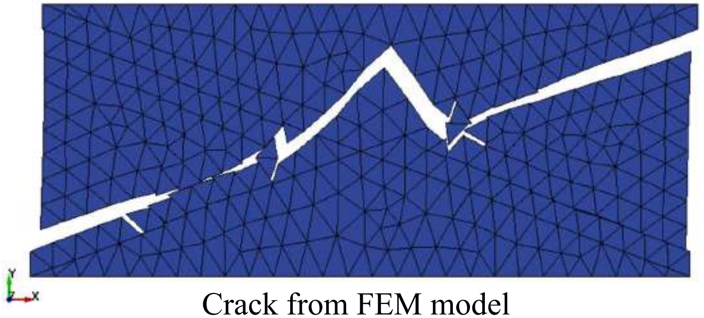
- Fit the curves of tensile simulation with dynamic tensile tests

Cohesive-based model under tension – results (QS)



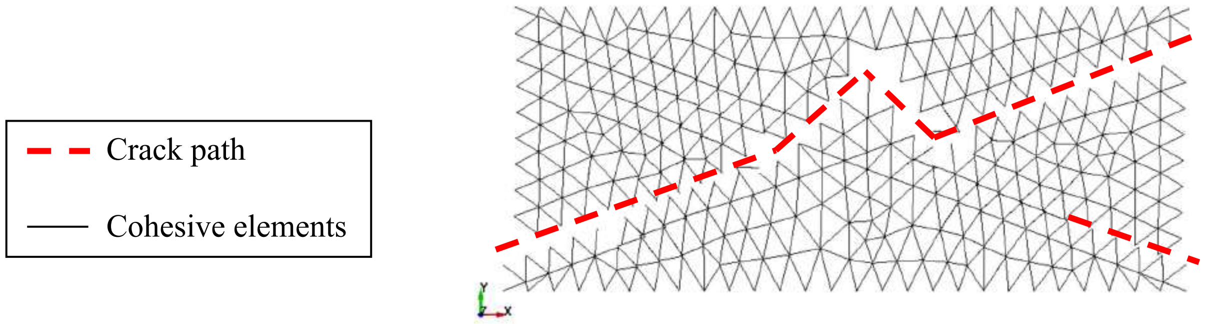


Crack of samples

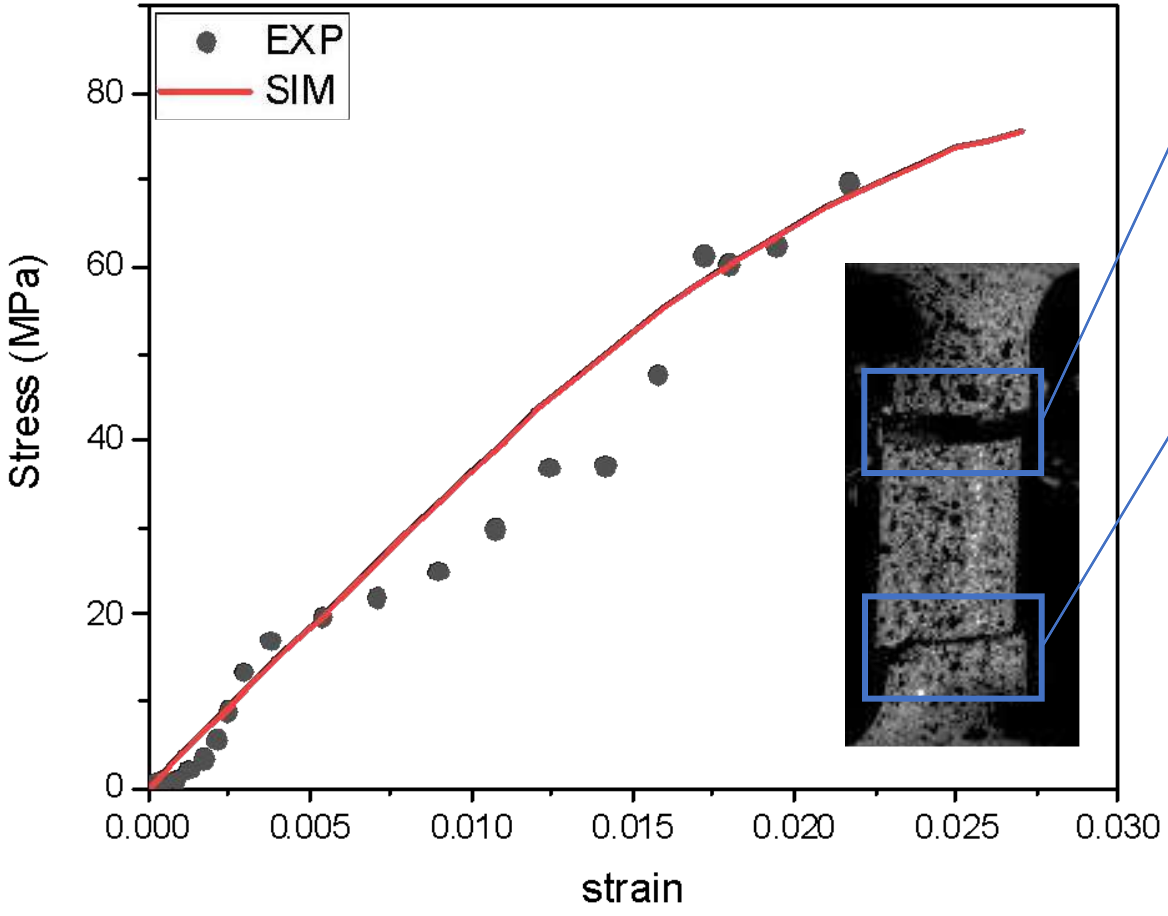


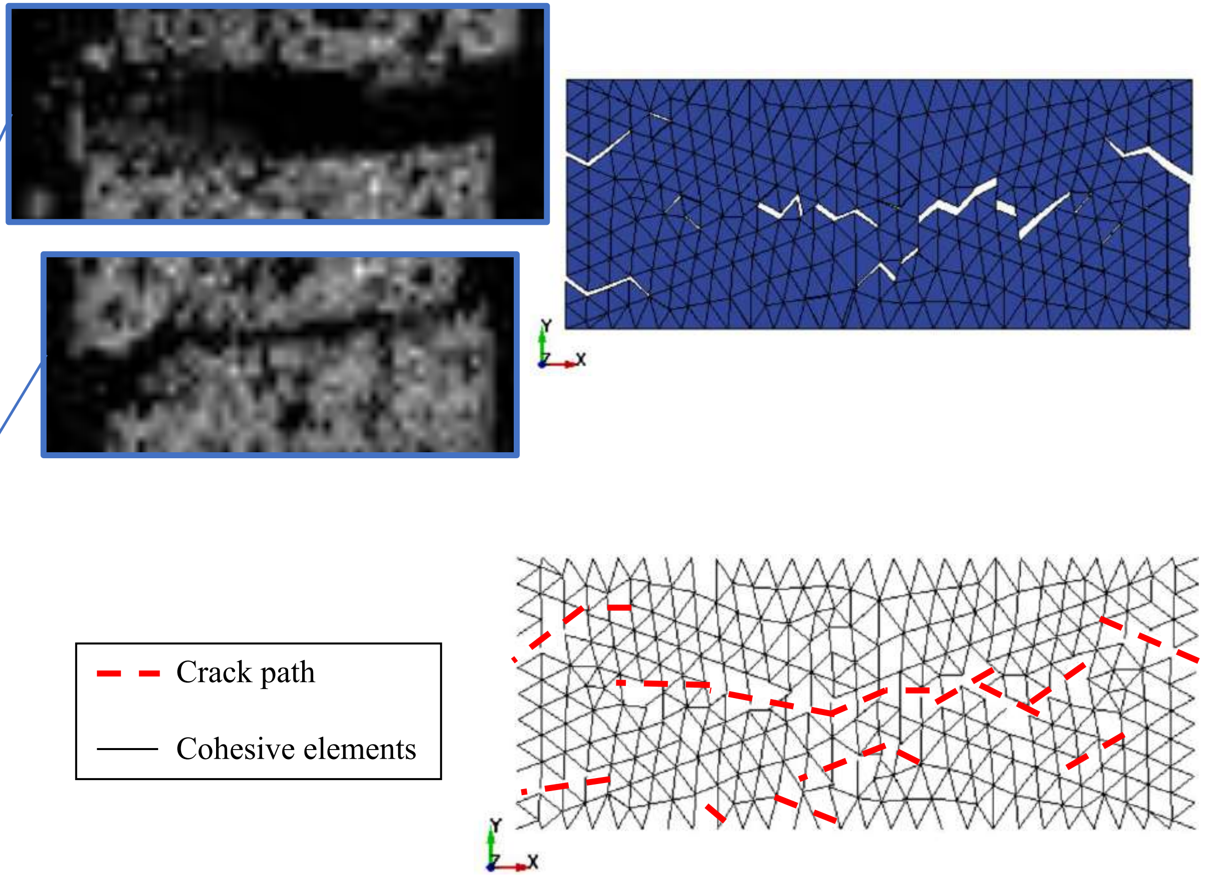
Crack from FEM model

Crack in cohesive elements

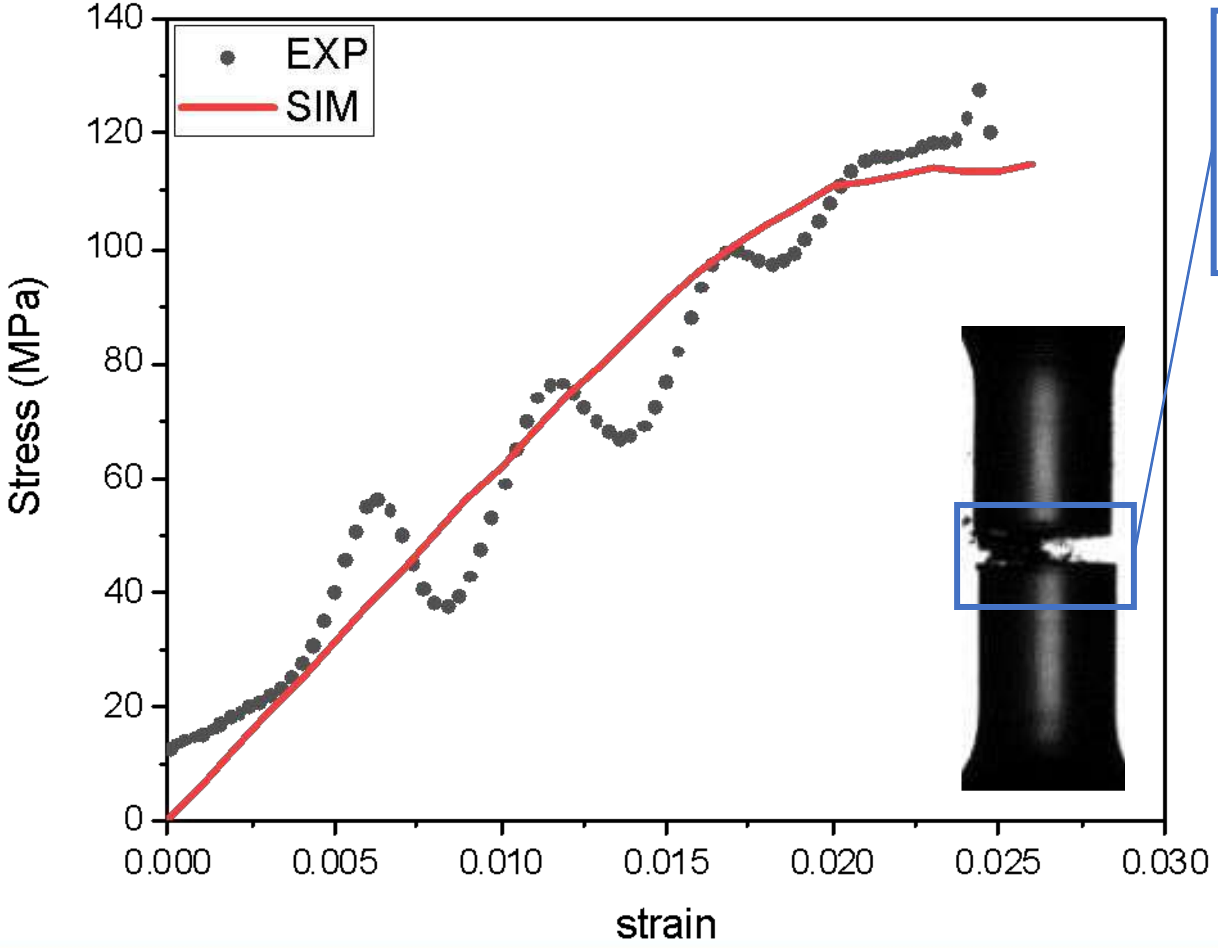


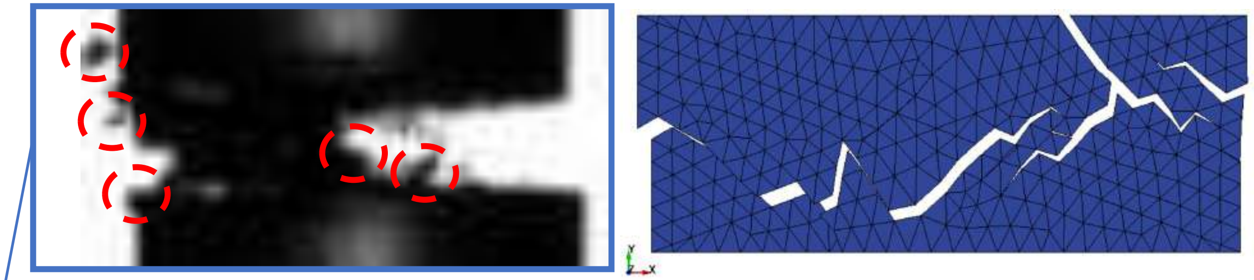
Cohesive-based model under tension – results (270/s)

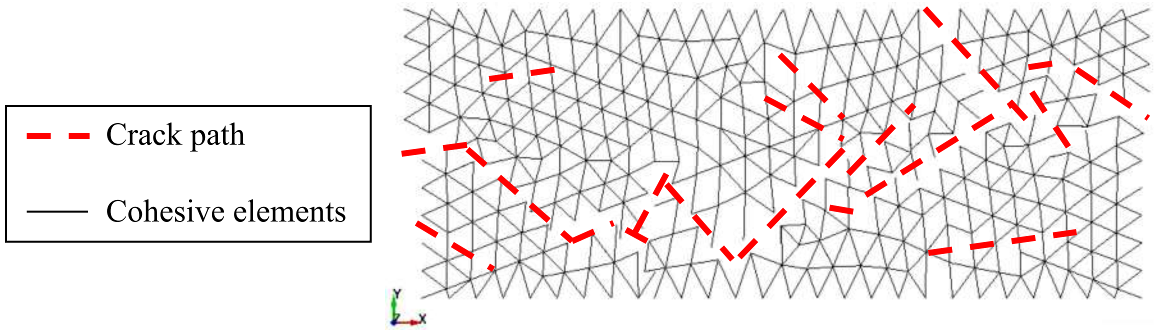




Cohesive-based model under tension
– results (700/s)



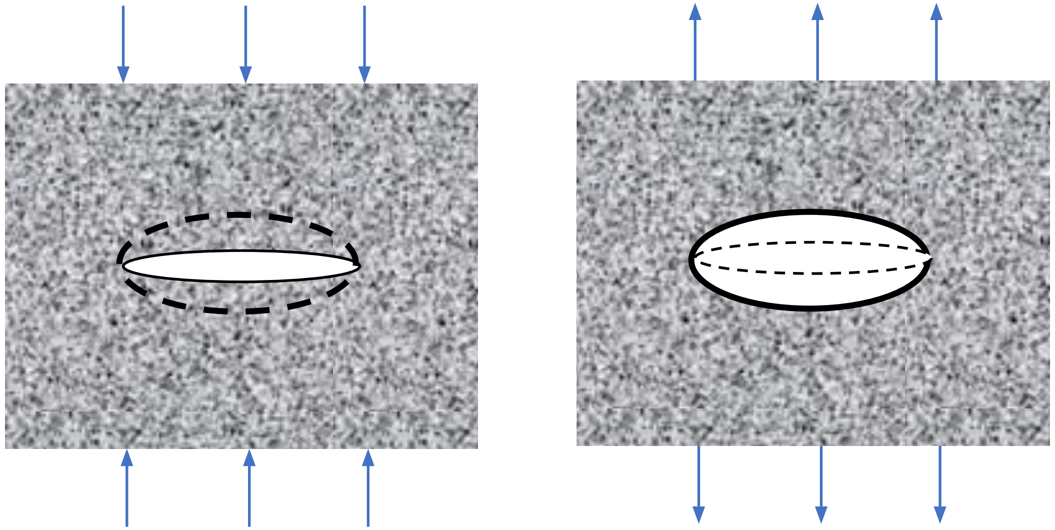




So…

After the simulations of tensile mechanical behaviors, considering the presence of defects, what about the compressive one?...

It should be more significant or less?...



But… **Let’s see!**

POLITECNICO MILANO 1863

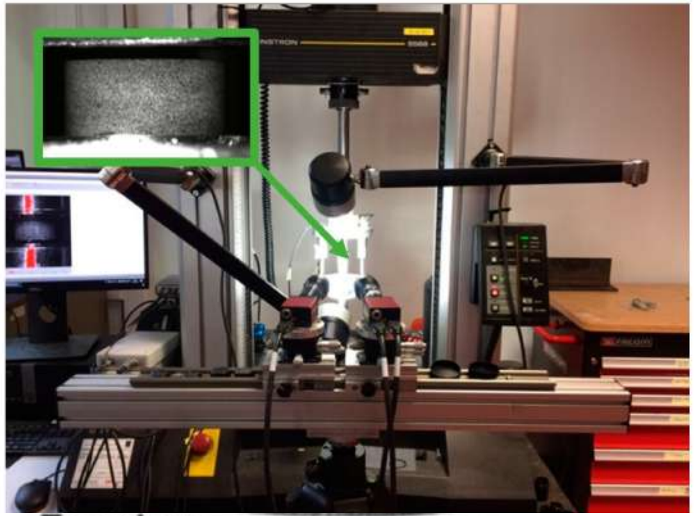
mecc

COMPORTAMENTO MECCANICO E MODELLAZIONE DEI POLIMERI AD ALTI STRAIN RATES

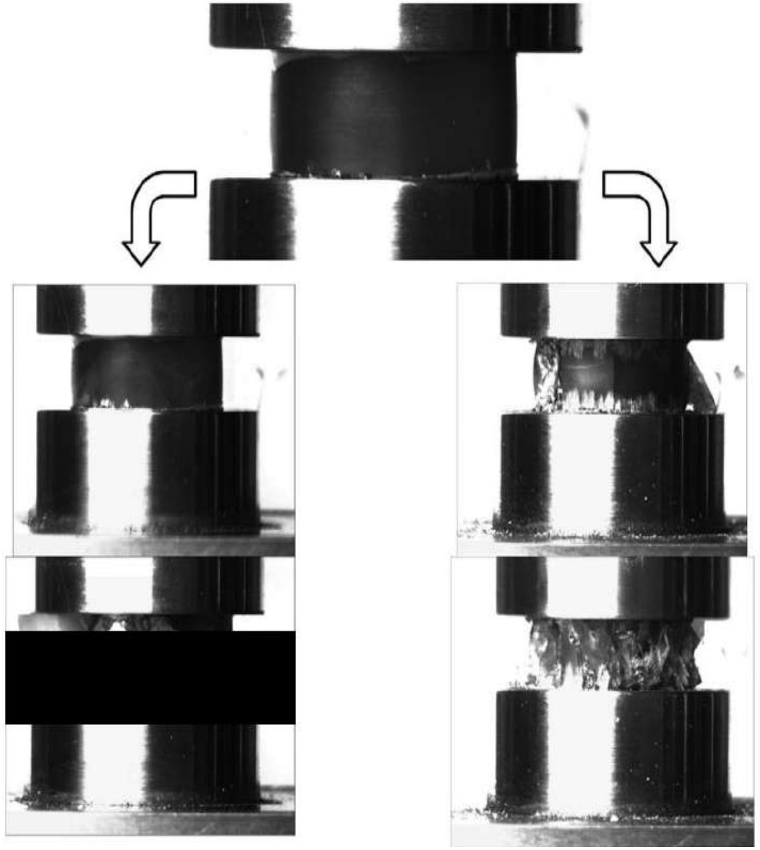
PRIMA GIORNATA DI STUDIO DEL GRUPPO DI LAVORO AIAS "XTREMA" (MATERIALS AT EXTREMES)

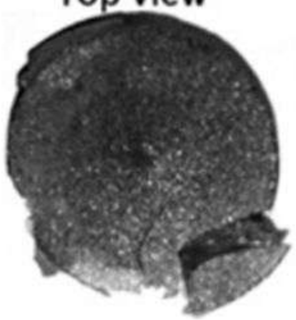
Mercoledi' 29 marzo 2023, Sala Consiglio del Dipartimento di Meccanica - Politecnico Di Milano - Via La Masa 1, 20156

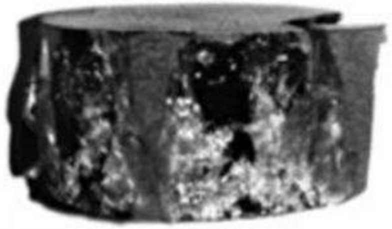
Stochastic FE model under compression – experiments



Part of tests were carried out in MST-DyMaLab (Ghent, Belgium) under **quasi-static compression.** Coupled with others experimental findings [1, 2], the **fracture behaviours of RTM6 under compression is variegated**: two types of failure can be found.



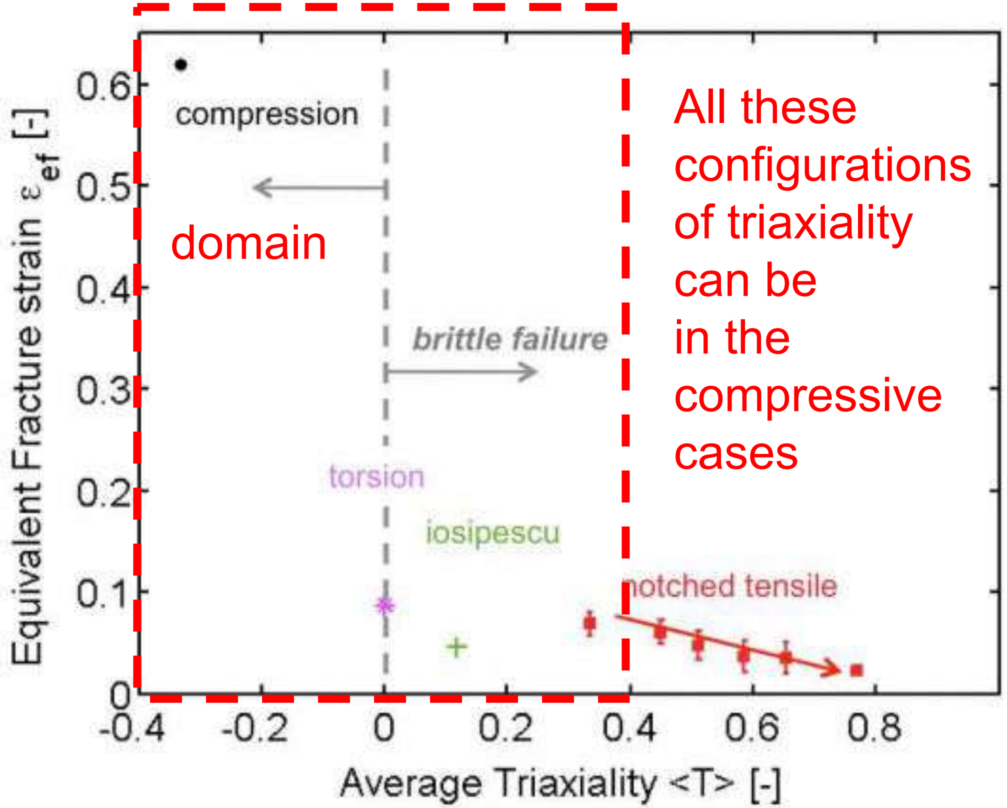


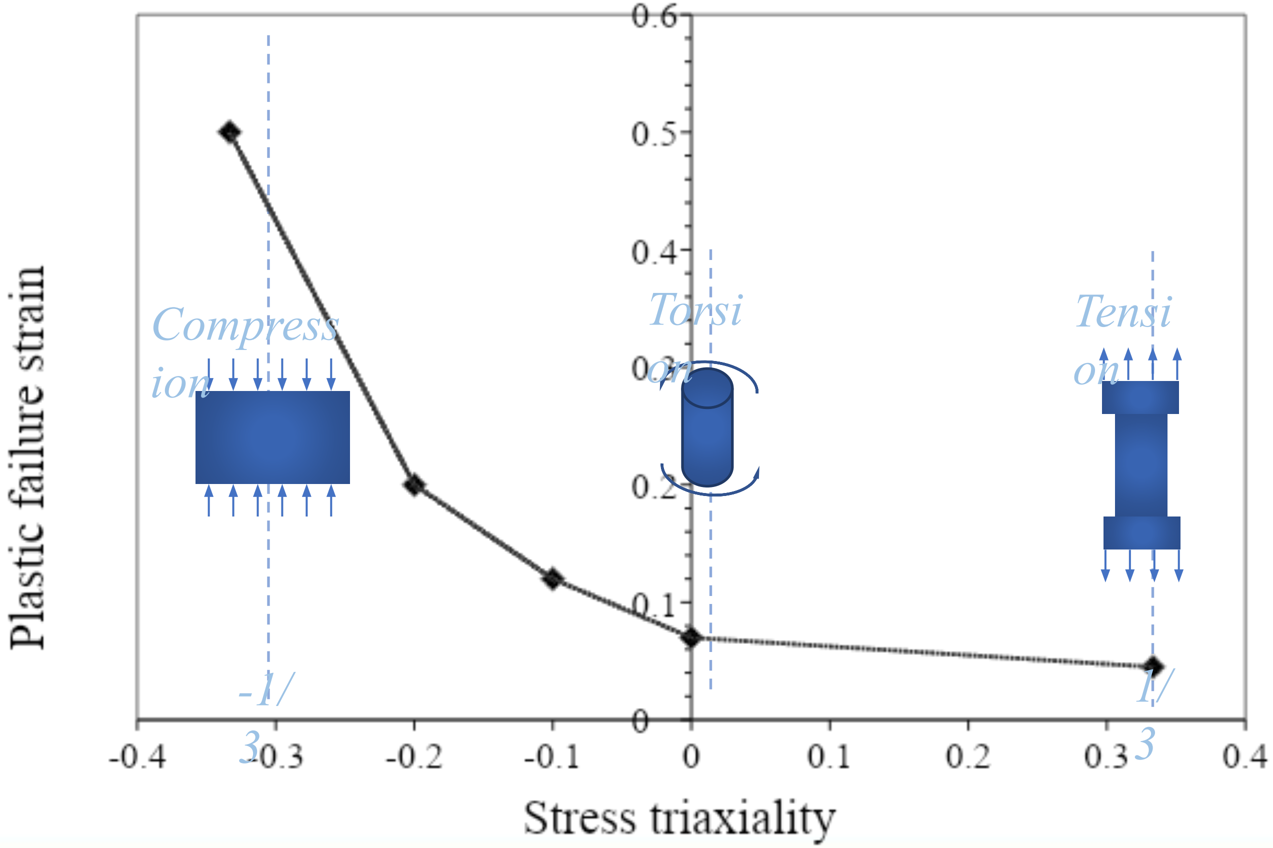


[1] Morelle, X. P., et al. Mechanics of Time-Dependent Materials 21 (2017): 419-454.
[2] Chevalier, Jérémy, et al. *Engineering Fracture Mechanics* 158 (2016): 1-12.

Stochastic FE model under compression
– numerical method

Unlike tensile case, introducing triaxiality dependance is important for simulations of compressive loading conditions because the stress state is complex.

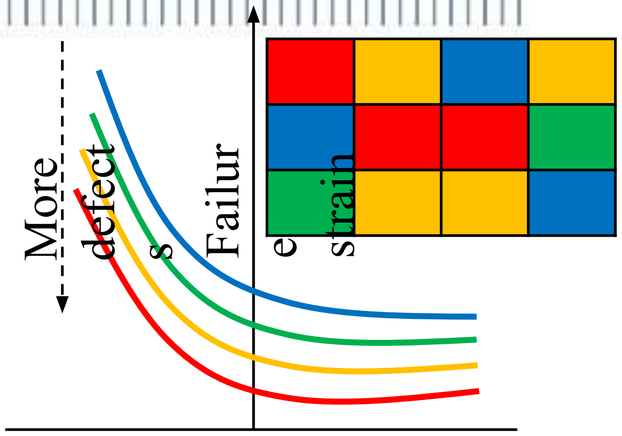


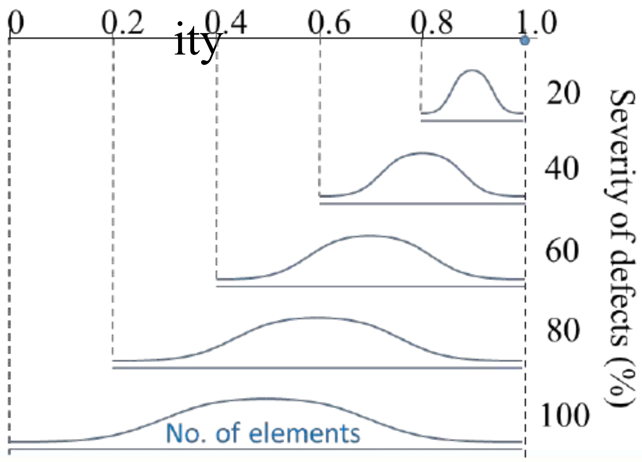


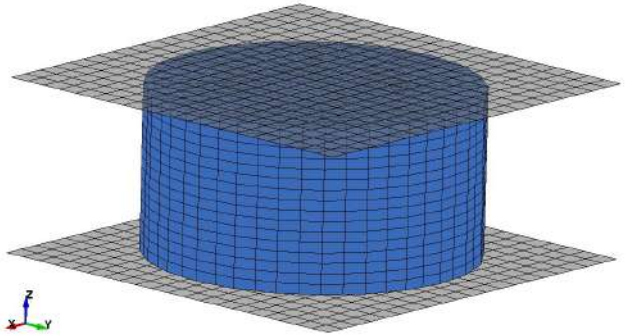
Stochastic FE model under compression
– numerical method

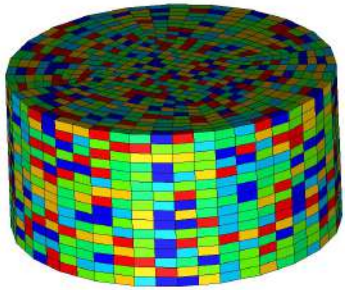
Considering the presence of defects:

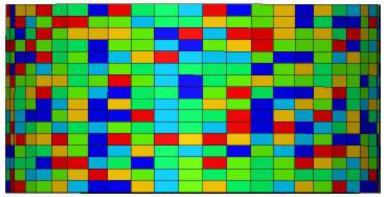
- The more the defects, the lower the failure strain. (accelarated failure)
- Material properties in each element is constant.
- Different strain-triaxiality relationships (for failure) were asigned on different elements for replicating the distribution of defects.
- Monte-Carlo simulation was used for different distributions.





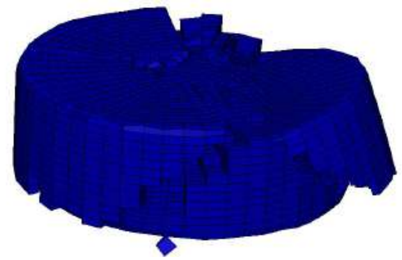
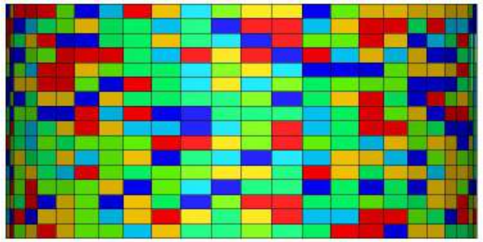
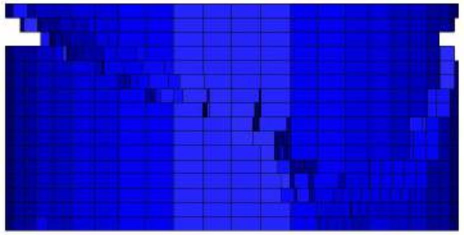
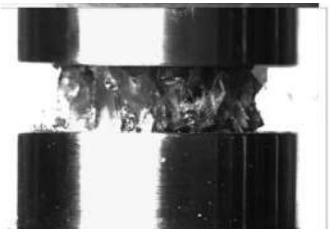




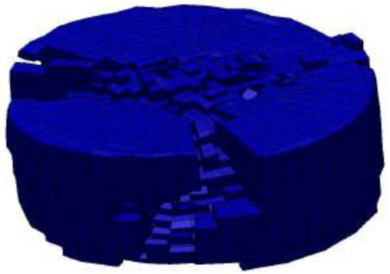
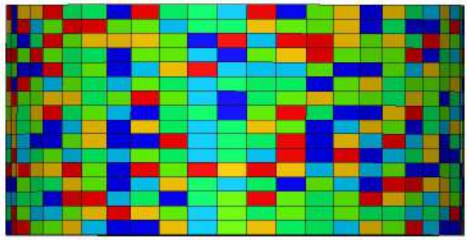
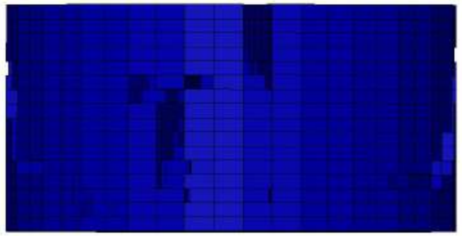
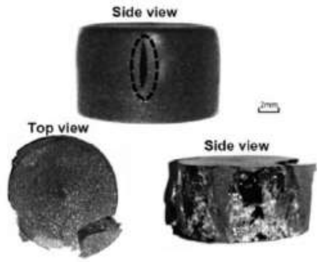


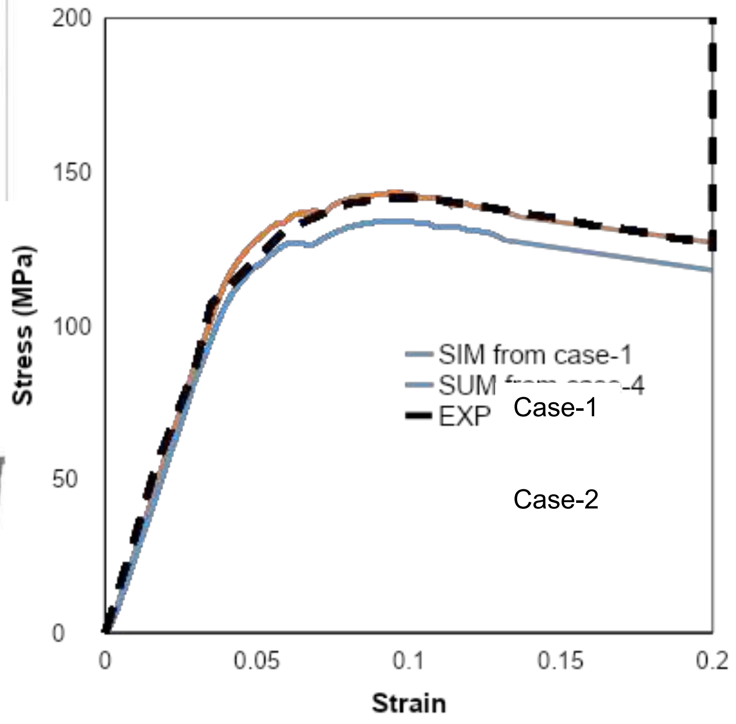
Stochastic FE model under compression – results

Defect increase

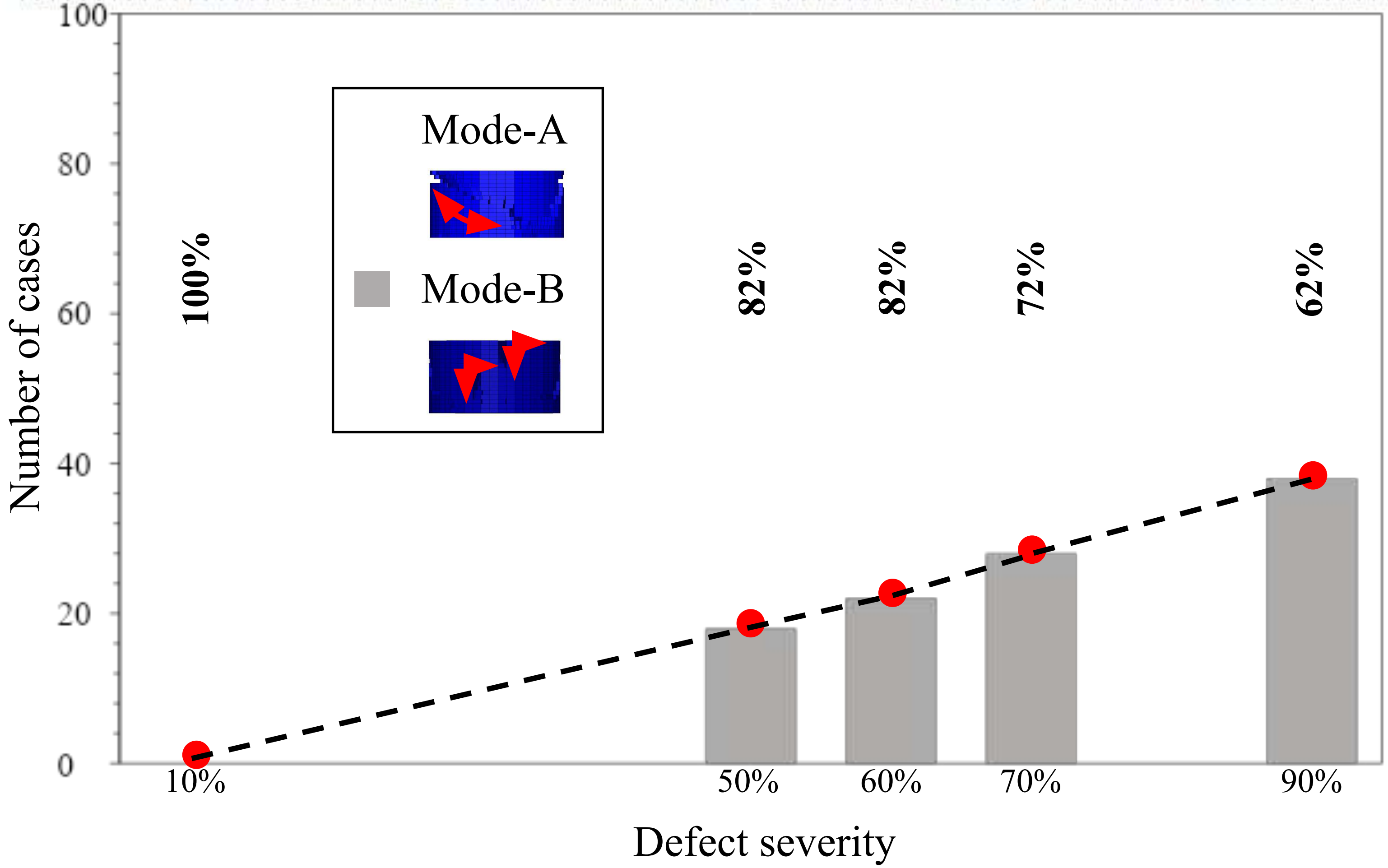
Case-1: Typical compressive failure, 45° failure crack, several large pieces



Case-2: Another failure mode, straight crack, sudden happen, many pieces

Stochastic FE model under compression – results



We can find:

- Two different modes might be due to the existance of the defects.
- The chance for straight cracking incrases as the increase of the defects.

Conclusions

- The fitting of the experimental curves with numerical models, by means of the proportion of defected elements (**simulated by cohesive element**), show that **more defects seems to be activated (in the tests) as the strain rate increases**, which leads to more cracks before the collapse of samples under high strain rates.
- **Presence of defects** seems to be one of the reasons for the **strain rate effect of polymer materials (RTM-6 epoxy)**.
- The existence of the **defects can influence both strain rate effect and the failure** process.
- The **defects might be one of the key reasons for the two different failure modes** as reported in the literatures.

More details can be found:

1. Tensile simulation: Ma, D., Elmahdy, A., Verleysen, P., Giglio, M., & Manes, A. (2020). Procedia Structural Integrity, 28, 1193–1203. https://doi.org/10.1016/j.prostr.2020.11.101
2. Compressive simulation: Ma, D., Giglio, M., & Manes, A. (2022). European Journal of Mechanics, A/Solids, 92, 104500. https://doi.org/10.1016/j.euromechsol.2021.104500

mecc
COMPORTAMENTO MECCANICO E MODELLAZIONE DEI POLIMERI AD ALTI STRAIN RATES
PRIMA GIORNATA DI STUDIO DEL GRUPPO DI LAVORO AIAS "XTREMA" (MATERIALS AT EXTREMES)
Mercoledi' 29 marzo 2023, Sala Consiglio del Dipartimento di Meccanica - Politecnico Di Milano - Via La Masa 1, 20156

CONTACTS

Dr. Dayou MA
dayou.ma@polimi.it
+39.02.2399.8474

Prof. Andrea MANES
andrea.manes@polimi.it
+39.02.2399.8630

www.mecc.polimi.it

@meccpolimi

GHENT UNIVERSITY

We would herein thank Prof. Patricia Verleysen at DyMaLab of Ghent University for her and her team's strong support on these activities.

DyMaLab

POLITECNICO MILANO 1863