CAOD LAB

2025 KNS Spring Conference

제3분과 원자력시설해체 및 방사성폐기물관리 3

Evaluation of Optimization Algorithms for Fracture Parameter Calibration in Spent Nuclear Fuel Cladding with Reoriented Hydrides

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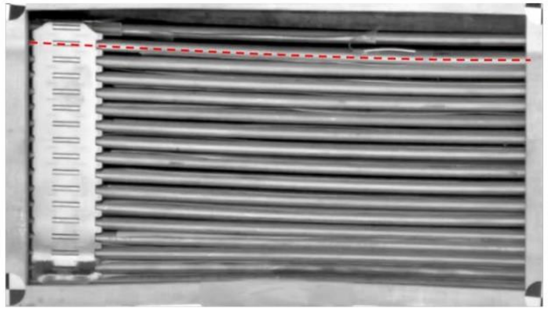
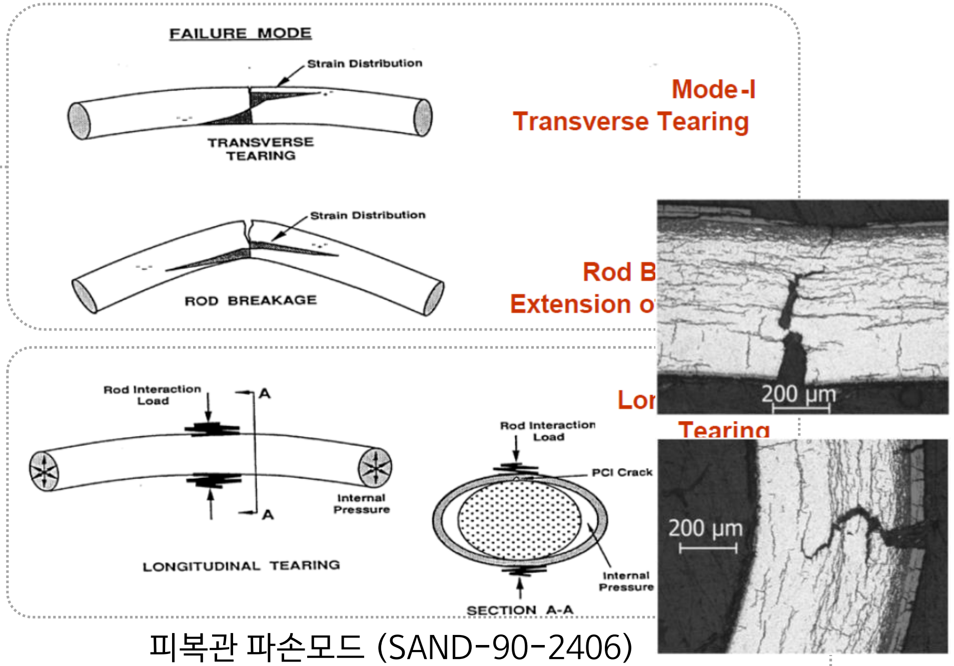
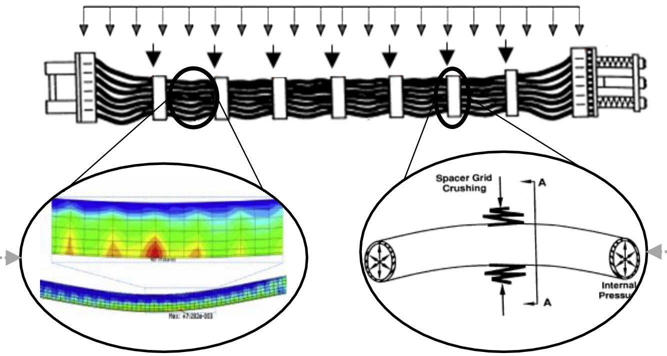
캐스크 육상&해상 선박 운송 (PNNL-SA-147626)



30cm 낙하 연료봉 변형 형상 (PNNL-30495)



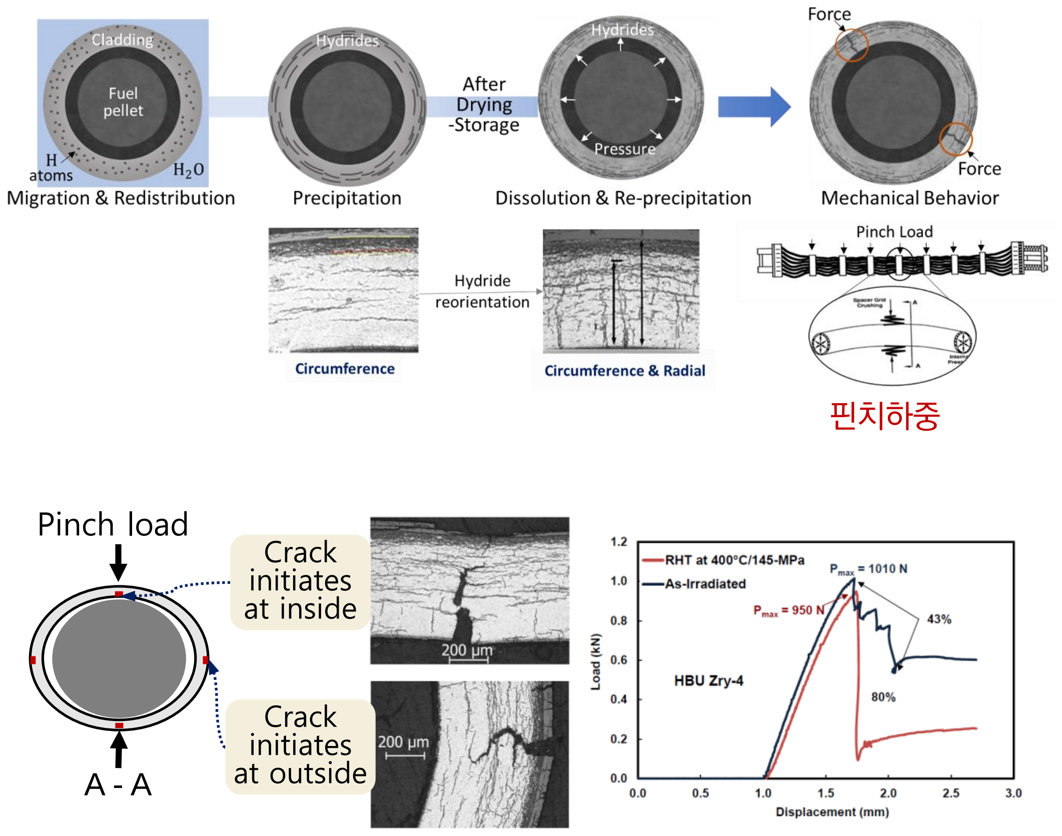
피복관 파손모드 (SAND-90-2406)



1) 굽힘하중 2) 핀치하중

- ✓ **수평낙하사고**에 대한 **연료봉 파손확률** 평가 계획
  → 미국 연방 규정 CFR Test 명시
- ✓ 파손확률 평가는 저장 안전성 평가 측면에서 중요한 과정
  → 피복관 **파손모드**와 연료봉이 받게 되는 **충격하중** 고려

Introduction



RCT metallographic image of as-irradiated HBU Zry-4

*Credit: ANL-15/21

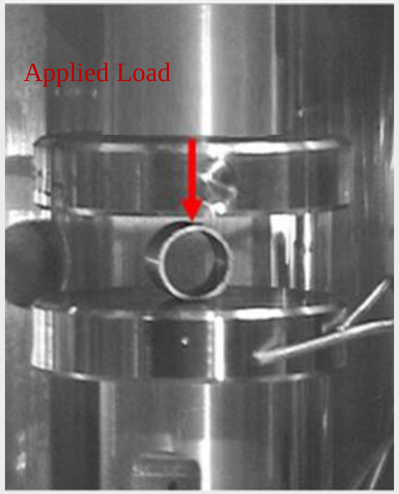
SNF봉 피복관 → 반경방향 수소화물 석출 → 핀치하중 → 균열 전파 용이성 증가 → 취성 파괴 모드 → 파손저항성 저하

- **한계점**

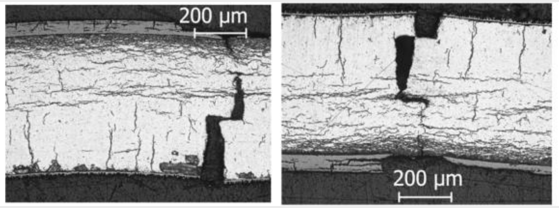
  - 수소화물로 인한 피복관의 기계적 특성의 저하 가능성에도 불구하고, **수소화물이 석출된 피복관의 파괴 특성을 정량적으로 평가한 실험적 연구는 매우 제한적임**.

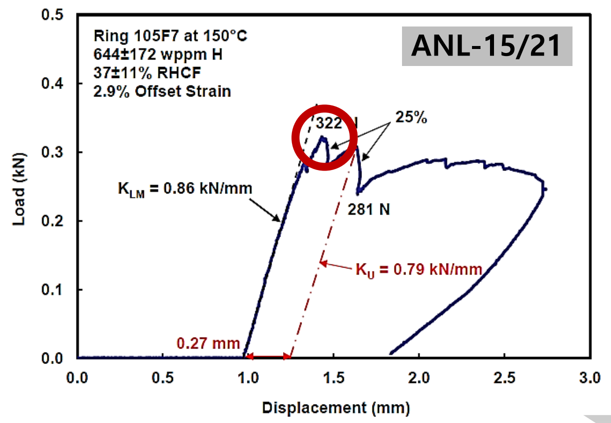
I Introduction

Experiment

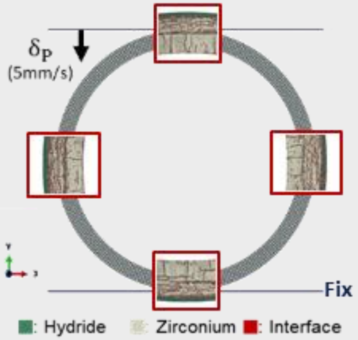


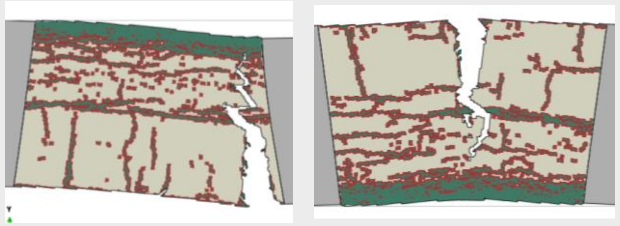
Credit: ANL-15/21

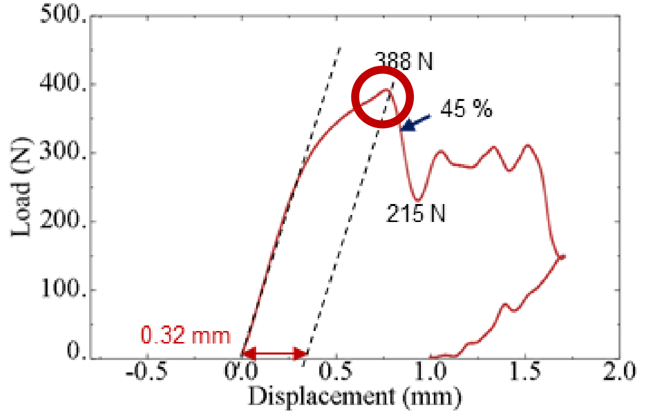




Simulation







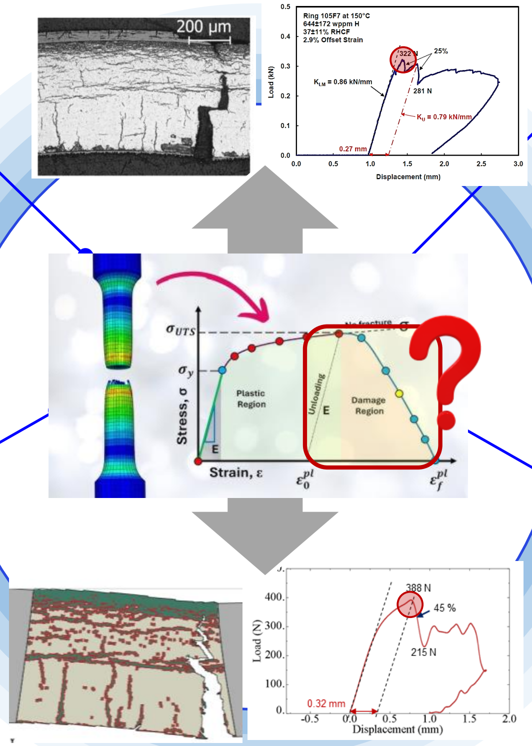
수소화물 석출 피복관의 파손저항성 평가를 위한 수치해석적 방법론 개발

이미지 기반 전산모델 개발

- 금속학적 이미지 전처리
- Zr 매트릭스, 수소화물, 계면 영상분할
- 픽셀 기반 FE 모델 자동생성 코드 구축
- 손상·파괴역학 기반 영역별 재료 모델링 적용

연속체 손상역학 기반 균열 모사

- 연속체 손상역학 모델 적용
- 손상 누적에 따른 균열개시 및 전파 거동 수치적 모사
- 복합적인 연성/취성 전이 거동을 손상 진전 차이를 통해 재현
- 주요 파괴변수 선정



Kriging 메타모델 구축

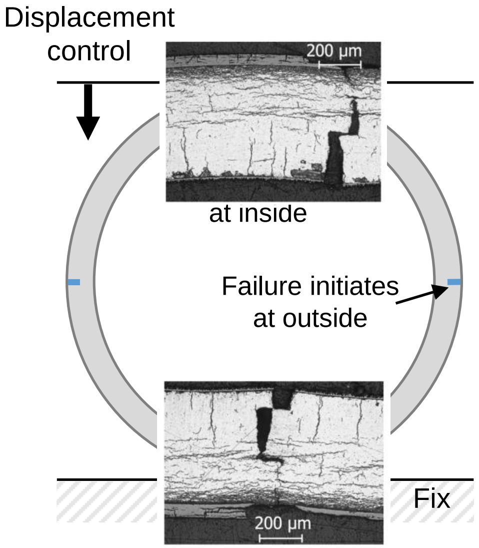
- 균열개시하중 예측 문제정의
- 실험계획법 기반 데이터수집
- 시뮬레이션 근사 메타모델 구축

파괴변수 추정

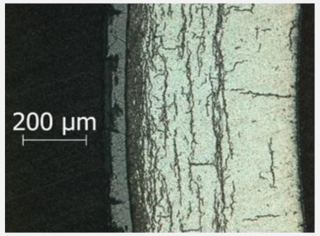
- 최적화를 통한 미지의 파괴변수 추정
- 균열 전파 양상 분석
- 파손저항성 평가

- RCT: Ring Compression Test

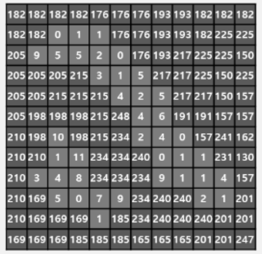
► 이미지 기반 유한요소모델 생성



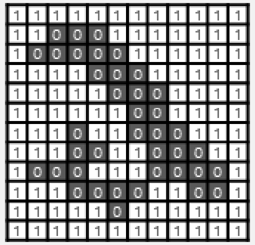
픽셀 기반 유한요소모델 생성 흐름



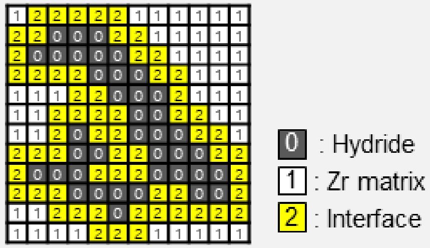
(a) 금속학적 이미지



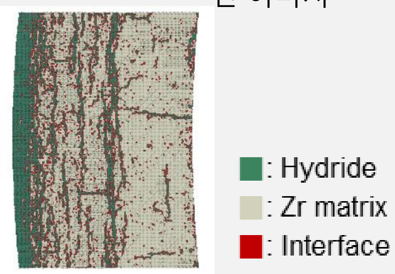
(b) 기존 RGB 이미지



(c) 수소화물 분할 이진 이미지

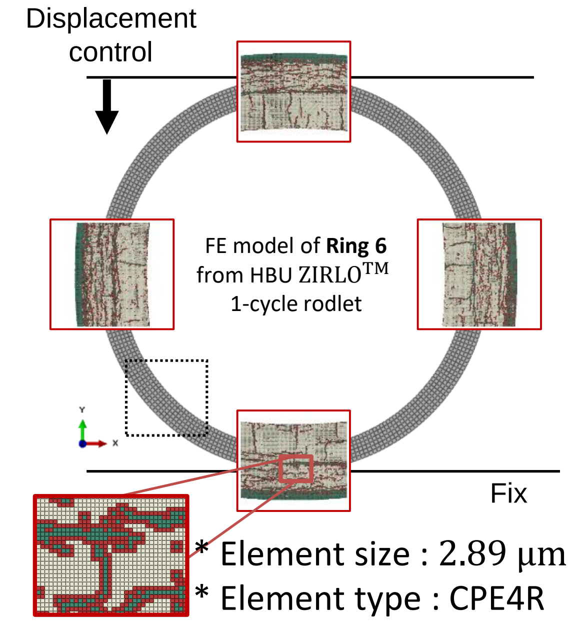


(d) Zr/수소화물 계면 요소 세분화

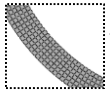


(e) 픽셀 기반 FE 모델

RCT simulation model



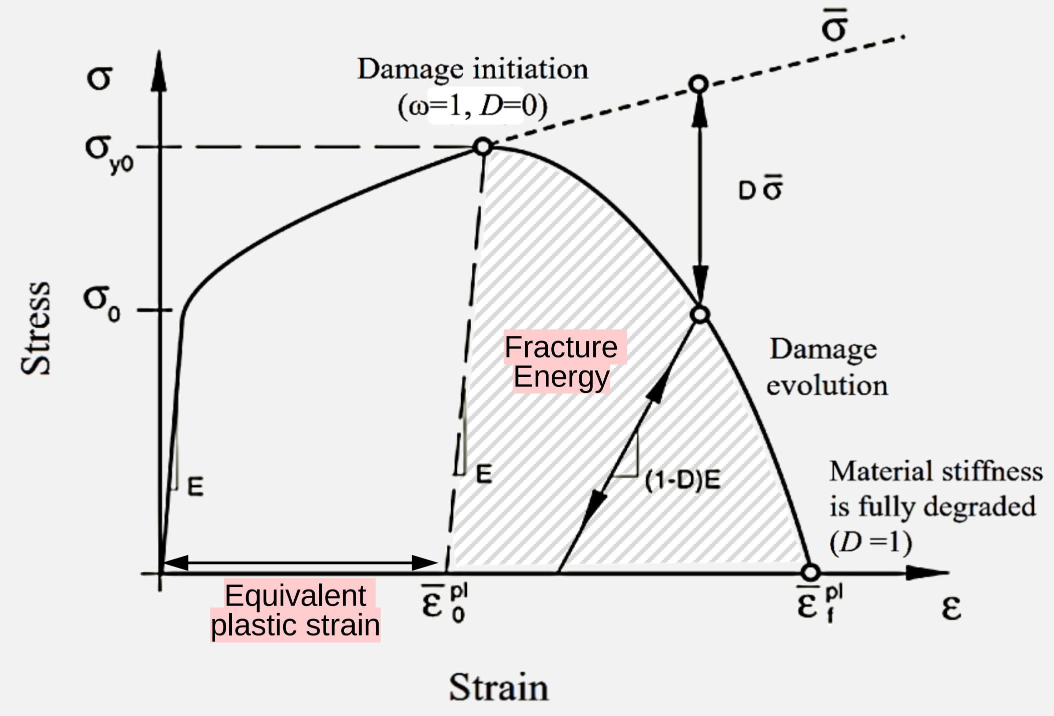
* Element size : 2.89 μm
* Element type : CPE4R



*단일 재료 영역
: RCT 힘-변위 데이어를 통해 물성 도출 [50-54]

► 연속체 손상역학 모델

점진적인 손상 축적을 동반한 응력-변형률 곡선



– 연속체 손상역학 선정

- Mesoscale과 macroscale 관점에서 Zr matrix, hydride 그리고 Zr /hydride interface의 공극이 균일하게 분포한다 가정
- 국부적 손상이 재료의 거시적 거동에 미치는 영향 파악

• Damage initiation criterion

$$\omega_D = \int \frac{d\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_0^{pl}(\eta, \dot{\bar{\varepsilon}}^{pl})}$$

• Fracture energy

$$G_f = \int_{\bar{\varepsilon}_0^{pl}}^{\bar{\varepsilon}_f^{pl}} L\sigma_y \, d\bar{\varepsilon}^{pl}$$

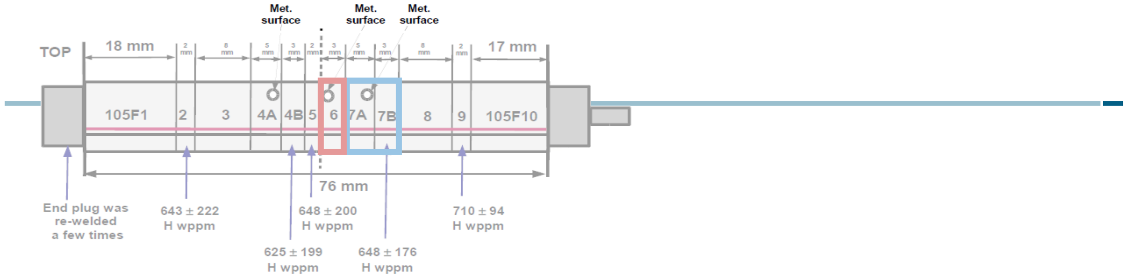
* $d\bar{\varepsilon}^{pl}$: Micro-plastic deformations
* $\bar{\varepsilon}_0^{pl}$: Equivalent plastic strain at damage initiation
* η : Stress triaxiality
* $\dot{\bar{\varepsilon}}^{pl}$: Strain rate
* $\bar{\varepsilon}_f^{pl}$: Equivalent plastic strain at failure
* σ_y: Yield stress
* L : Characteristic element length

Fracture Parameter	
G_f	: Fracture Energy
$\bar{\varepsilon}_0^{pl}(\eta)$	: Equivalent plastic strain at damage initiation

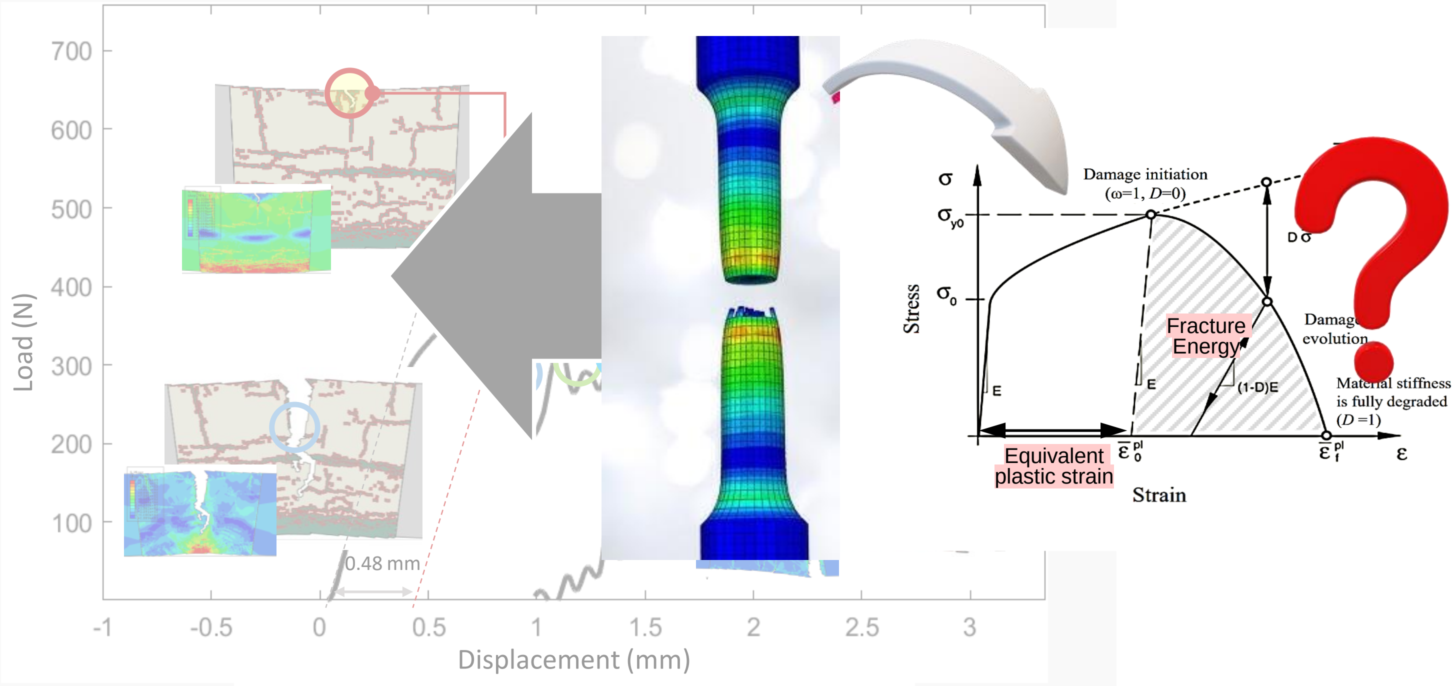
- RCT: Ring Compression Test

RCT 시뮬레이션 모델

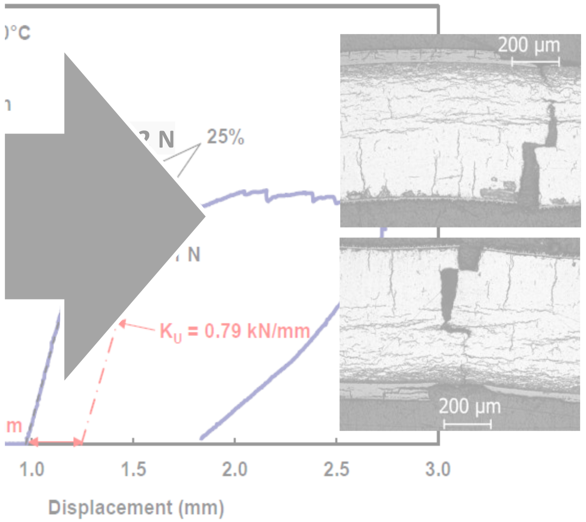
하중-변위 곡선에 대한 균열 형상 및 응력 분포



RCT simulation of **Ring 6** from HBU ZIRLO^{TM} 1-cycle rodlet



RCT of **Ring 7** from HBU ZIRLO^{TM} 1-cycle rodlet

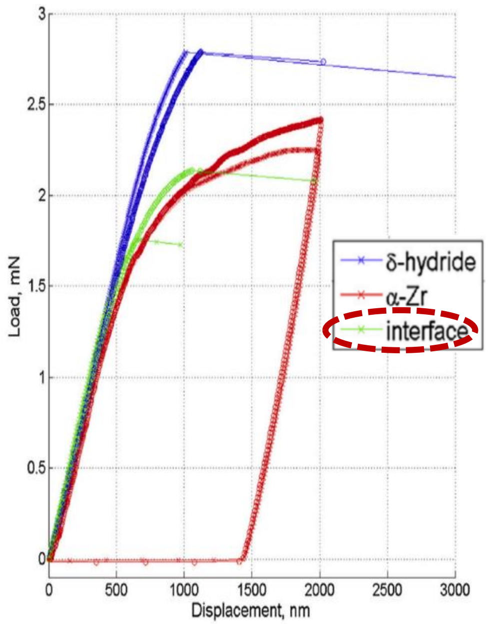


• RCT: Ring Compression Test

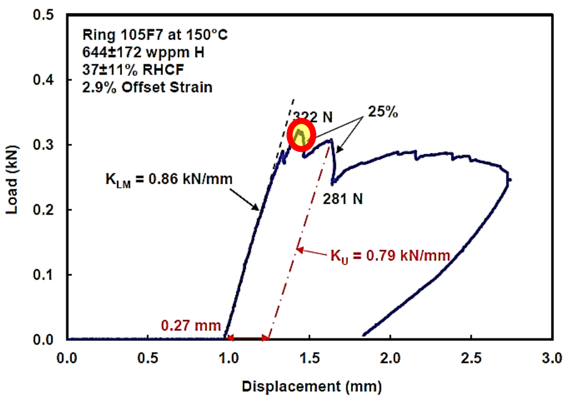
► 균열개시에 대한 주요 파괴변수

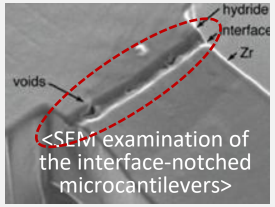
Interface 물성에 의존적인 균열개시

Load-displacement curve of microcantilever fracture test

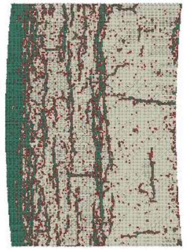


Load-displacement curve of Ring 8





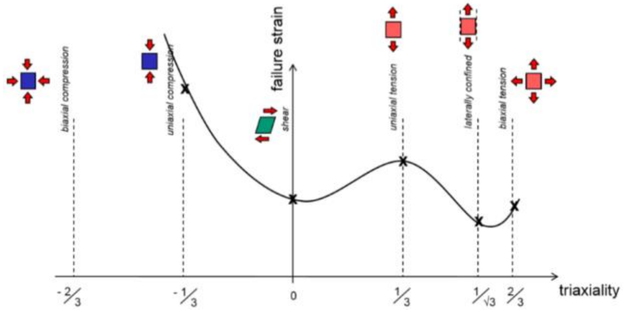
■: Hydride
■: Zr matrix
■: Interface



Comp.	Parameter
■: Interface	G_f : Fracture Energy $\bar{\varepsilon}_0^{pl}(\eta)$: Equivalent plastic strain at damage initiation

응력 삼축도를 고려한 주요 파괴변수

Factor	Fracture parameters
$X1$	G_f : Fracture Energy
$X2$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0}$: Equivalent plastic strain at damage initiation ($\eta = 0$, pure shear)
$X3$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$: Equivalent plastic strain at damage initiation ($\eta = 0.33$, uniaxial tension)
$X4$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$: Equivalent plastic strain at damage initiation ($\eta = 0.58$, plane strain)



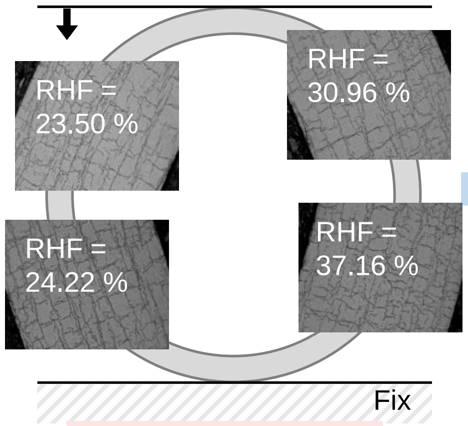
*Credit: www.dynamore.de

*Credit: ANL-15/21
*Credit: H. Chan et al., Journal of Nuclear Materials, vol. 475, pp. 105–112 (2016)

• RHF : Radial Hydride Fraction

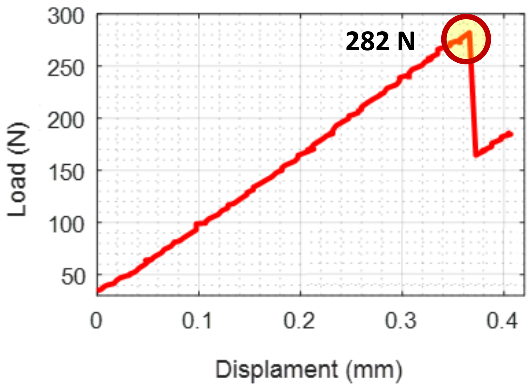
균열개시 예측 문제정의

수소장입 Zr 합금 피복관 RCT 데이터



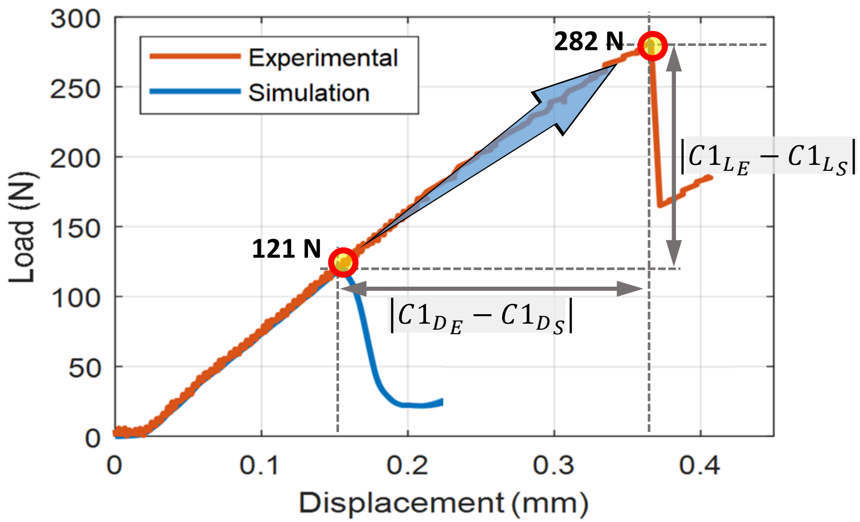
▶ 다양한 RHF 분포 변화

RHF : Radial Hydride Fraction



* Credit: Nuclear Fuel Materials and Safety Lab at SNU

Hydrogen Concentration	Applied Hoop Stress	Ave. RHF	Length	Outer Radius	Thickness
243.3 wppm	140 MPa	28.95 %	7.50 mm	4.28 mm	0.56 mm



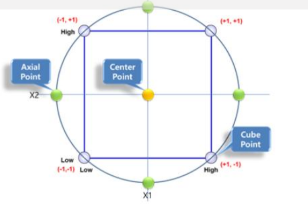
Find $\boldsymbol{\theta} = [X_1, X_2, X_3, X_4]$ such that
Minimize $f(\boldsymbol{\theta}) = |CL_E - CL_S| + |CD_E - CD_S|$
Subject to $\boldsymbol{\theta}_{lb} \le \boldsymbol{\theta} \le \boldsymbol{\theta}_{ub}$

*$\boldsymbol{\theta}$: 파괴변수 벡터 ($X1$~$X4$)
*CL : 1st 균열 개시 하중
*CD: 1st 균열 개시 변위
* exp : 실험 데이터
* sim: 전산모델 데이터

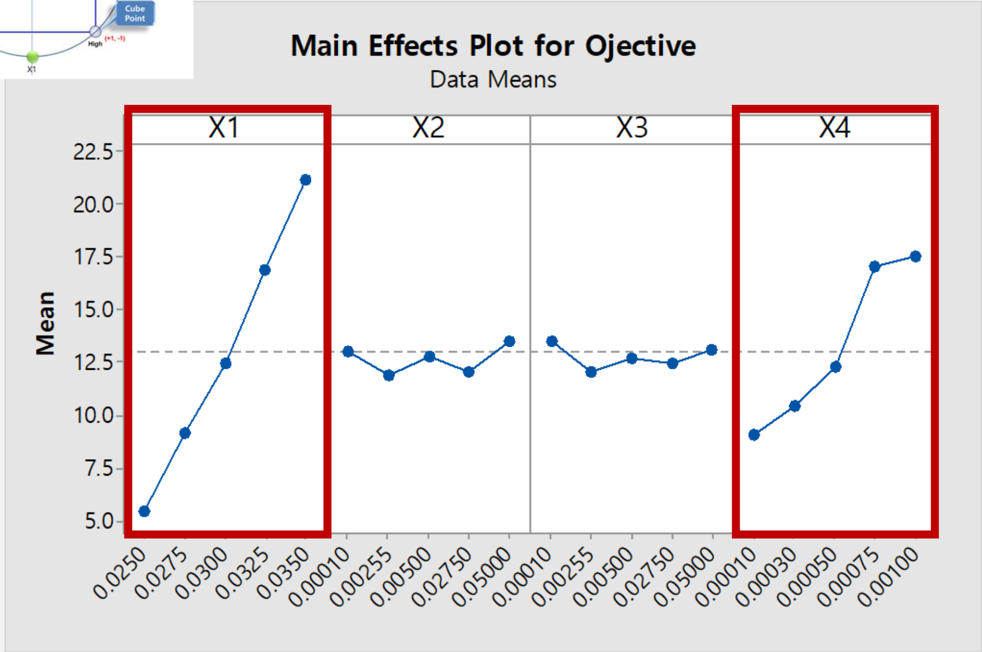
■ : Interface	
Factor	Fracture parameters
$X1$	G_f
$X2$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0}$
$X3$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$
$X4$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$

► 균열개시에 대한 파괴변수 영향 평가

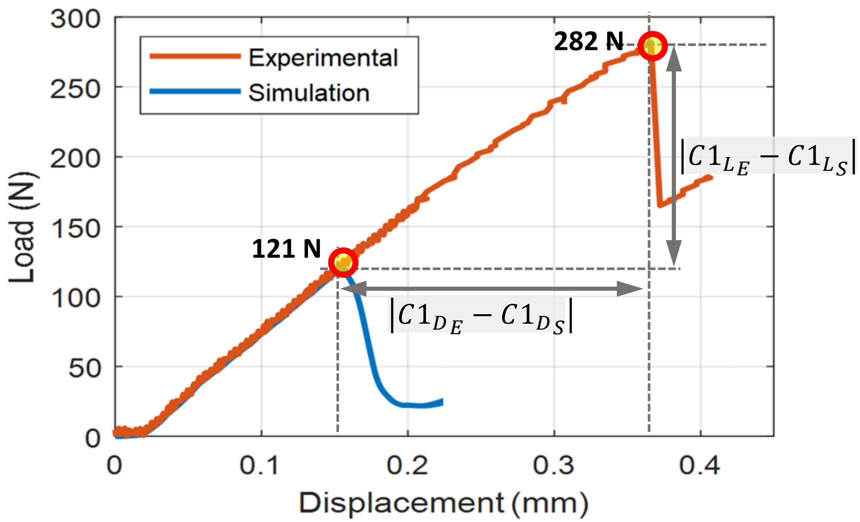
Central Composite Design



주효과도



✓ 균열개시에 유의미한 영향을 미치는 주요 파괴변수 평가



Find $\boldsymbol{\theta} = [X_1, X_2, X_3, X_4]$ such that
Minimize $f(\boldsymbol{\theta}) = |CL_E - CL_S| + |CD_E - CD_S|$
Subject to $\boldsymbol{\theta}_{lb} \leq \boldsymbol{\theta} \leq \boldsymbol{\theta}_{ub}$

*$\boldsymbol{\theta}$: 파괴변수 벡터 ($X1$~$X4$)
*CL : 1st 균열 개시 하중
*CD: 1st 균열 개시 변위
* exp : 실험 데이터
* sim: 전산모델 데이터

■: Interface

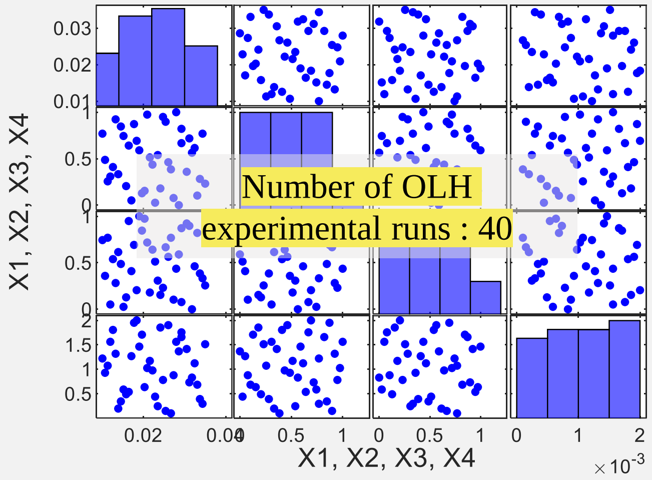
Factor	Fracture parameters
$X1$	G_f
$X2$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0}$
$X3$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$
$X4$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$

- OLH : Optimal Latin Hyper Cube sampling

► 파괴변수 추정을 위한 메타모델 구축

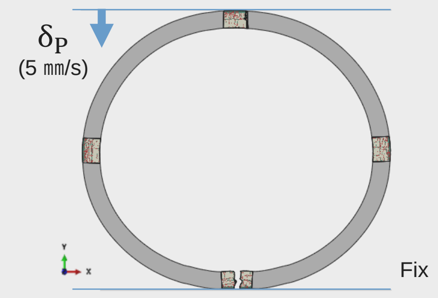
수치해석적 실험 데이터 수집

Data scatter plot of 4 parameters

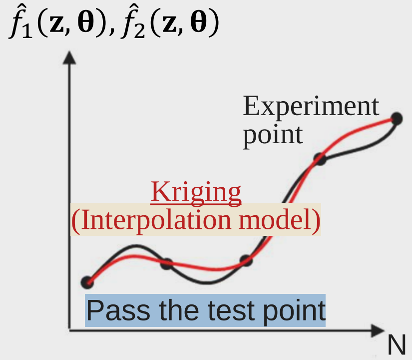


Bounds	Value			
	$X_1: G_f$	$X_2: \bar{\varepsilon}^{pl}_{0:\eta=0}$	$X_2: \bar{\varepsilon}^{pl}_{0:\eta=0.33}$	$X_4: \bar{\varepsilon}^{pl}_{0:\eta=0.58}$
Lower	0.0100	0.0001	0.0001	0.0001
Upper	0.0350	1.0000	1.0000	0.0020

Simulation model ↔ **Kriging metamodel**



- 해석 시 시간/비용 많이 소요
- 설계영역 탐색에 많은 횟수의 해석 요구

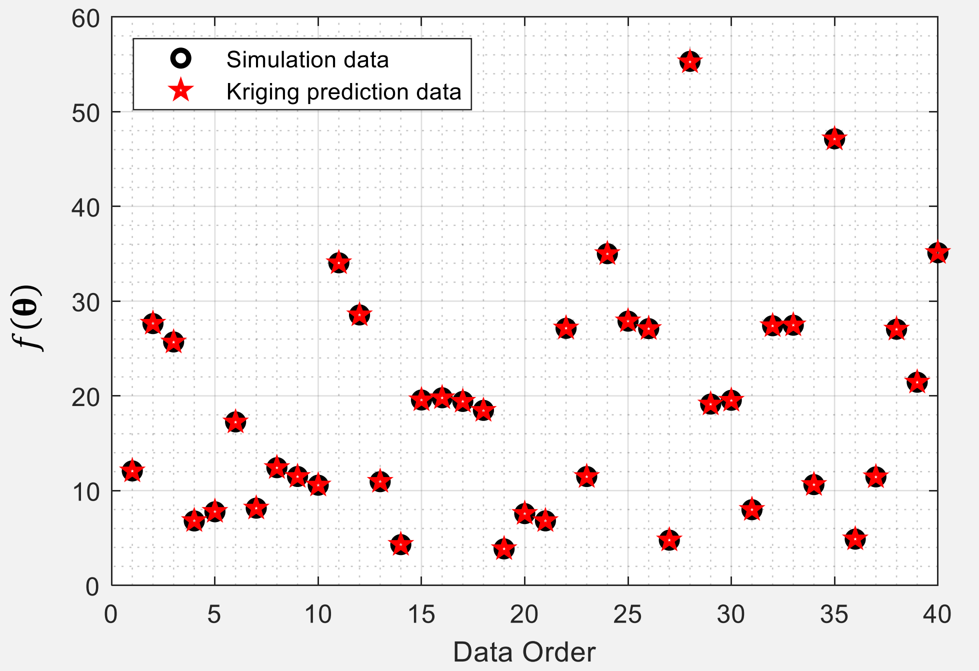


- 특성치 계산 수치적 부담 x
- 설계영역 탐색, 최적설계 적합

▶ 복잡한 Full Simulation을 근사하여 높은 계산 비용을 줄일 수 있는 Kriging metamodel 구축

파괴변수 추정을 위한 메타모델 구축

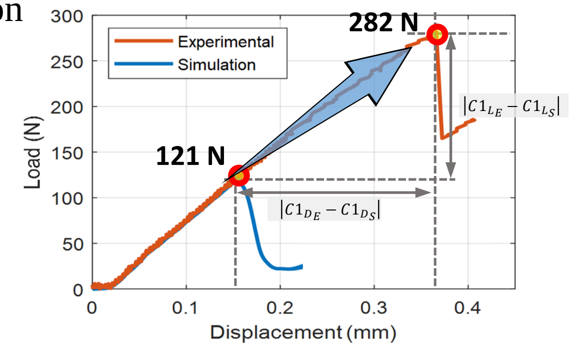
OLH 파괴변수 공간에 대한 메타모델 예측 데이터



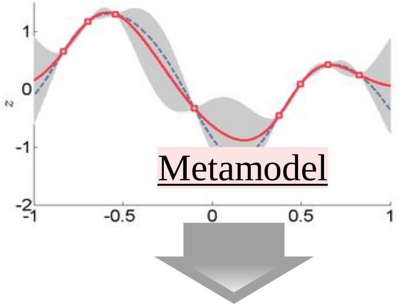
▶ 파괴변수에 대해 균열개시지점을 정량적으로 예측 가능

Experiment ⟺ Simulation
Minimize $f(\boldsymbol{\theta})$

Factor	Fracture parameters
$X1$	G_f
$X2$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0}$
$X3$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$
$X4$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$

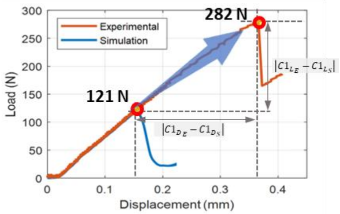


$$\boldsymbol{\theta} = [X_1, X_2, X_3, X_4]$$



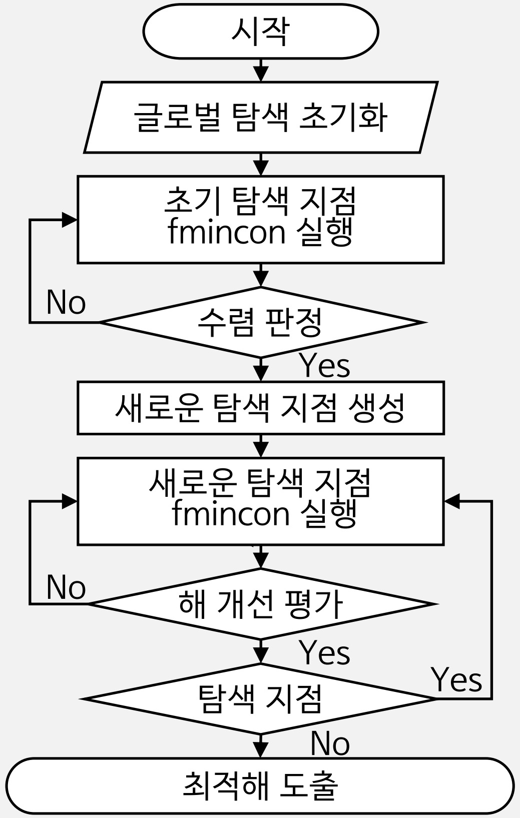
메타모델을 활용하여 효율적인 파괴변수 추정가능

► 최적화 알고리즘을 통한 파괴변수 추정

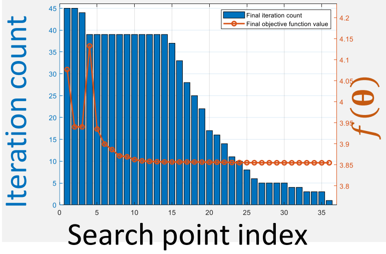


Find $\boldsymbol{\theta} = [X_1, X_2, X_3, X_4]$ such that
Minimize $f(\boldsymbol{\theta}) = |CL_E - CL_S| + |CD_E - CD_S|$

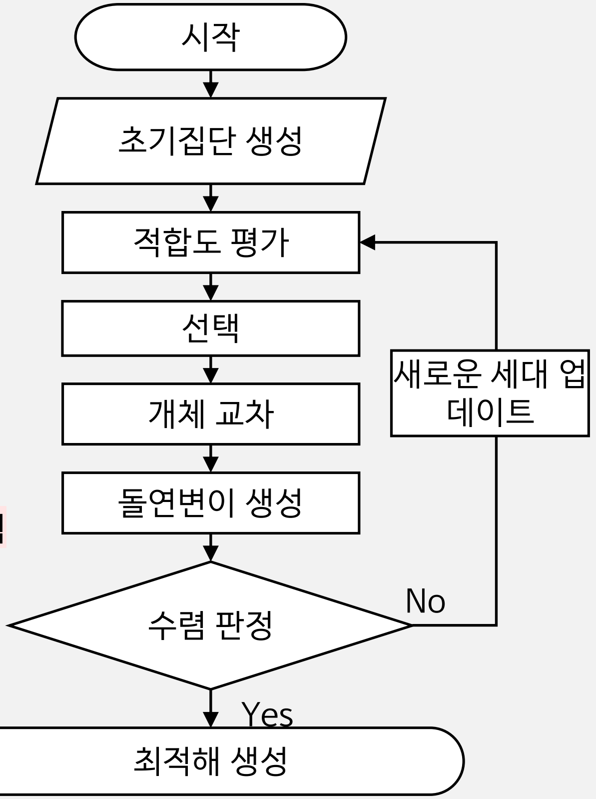
Global Search Algorithm(GSA) 최적화



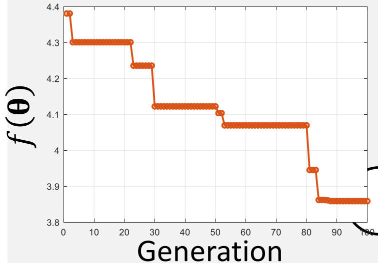
GSA 탐색지점별 수렴 횟수와 목적함수 이력



Genetic Algorithm (GA) 최적화



GA 세대별 목적함수 이력



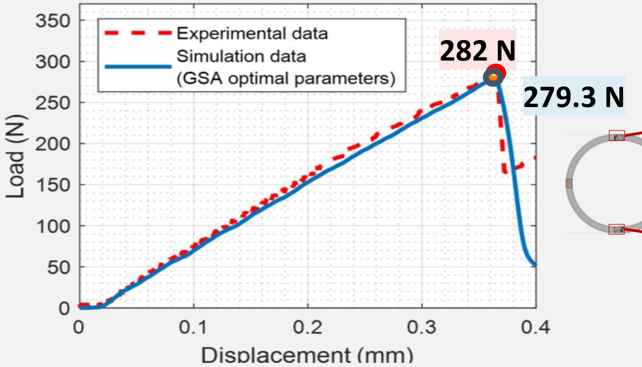
Result

► 최적화 알고리즘을 통한 파괴변수 추정

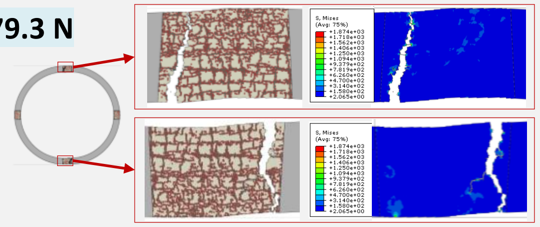
Find $\boldsymbol{\theta} = [X_1, X_2, X_3, X_4]$ such that
Minimize $f(\boldsymbol{\theta}) = |CL_E - CL_S| + |CD_E - CD_S|$

Global Search Algorithm(GSA) 최적화 결과

실행 시간 (sec)		18.19
Interface 파괴변수, θ	**$X_1 : G_f$**	**0.0132**
	$X_2 : \bar{\varepsilon}^{pl}_{0:\eta=0.00}$	**0.9188**
	$X_3 : \bar{\varepsilon}^{pl}_{0:\eta=0.33}$	**0.2801**
	$X_4 : \bar{\varepsilon}^{pl}_{0:\eta=0.58}$	**0.0013**
균열개시 하중, CL_S (N)		279.3
균열개시 변위, CD_S (mm)		0.363
균열개시지점 예측 함수, $f(\theta)$		3.8551

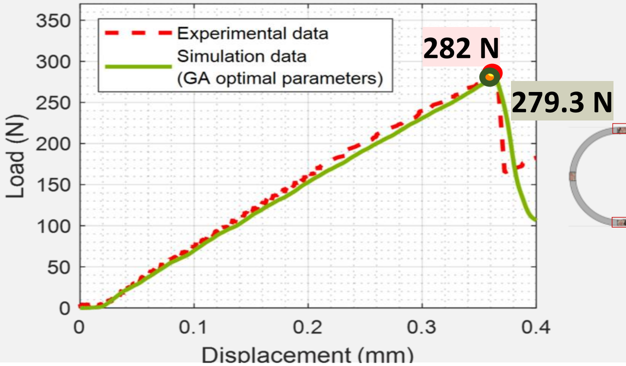


RHF= 30.96 % FE모델

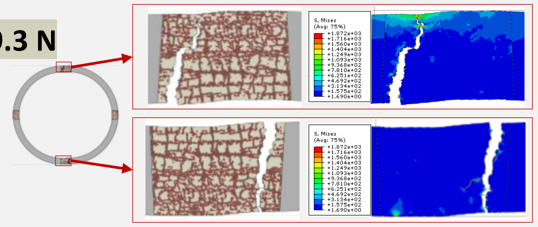


Genetic Algorithm (GA) 최적화 결과

실행 시간 (sec)		18.62
Interface 파괴변수, θ	**$X_1 : G_f$**	**0.0132**
	$X_2 : \bar{\varepsilon}^{pl}_{0:\eta=0.00}$	**0.9163**
	$X_3 : \bar{\varepsilon}^{pl}_{0:\eta=0.33}$	**0.2814**
	$X_4 : \bar{\varepsilon}^{pl}_{0:\eta=0.58}$	**0.0013**
균열개시 하중, CL_S (N)		279.3
균열개시 변위, CD_S (mm)		0.363
균열개시지점 예측 함수, $f(\theta)$		3.8613



RHF= 30.96 % FE모델

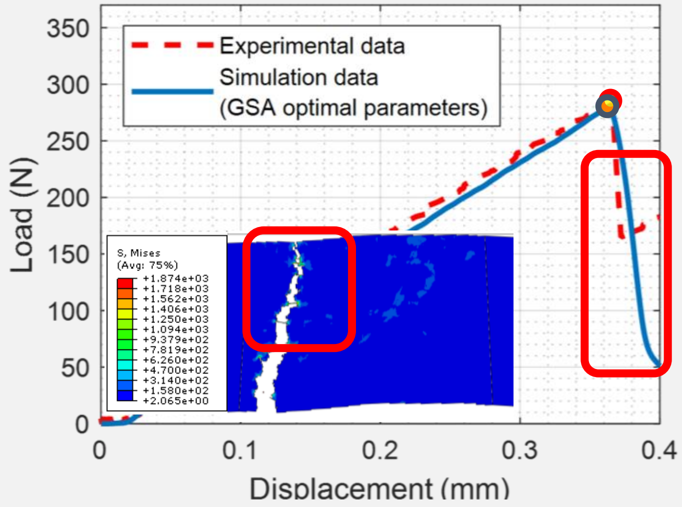


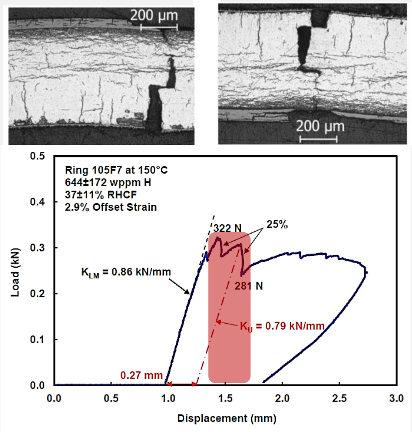
► 최적화 알고리즘을 통한 파괴변수 추정

Find $\boldsymbol{\theta} = [X_1, X_2, X_3, X_4]$ such that
Minimize $f(\boldsymbol{\theta}) = |CL_E - CL_S| + |CD_E - CD_S|$

Global Search Algorithm(GSA) 최적화 결과

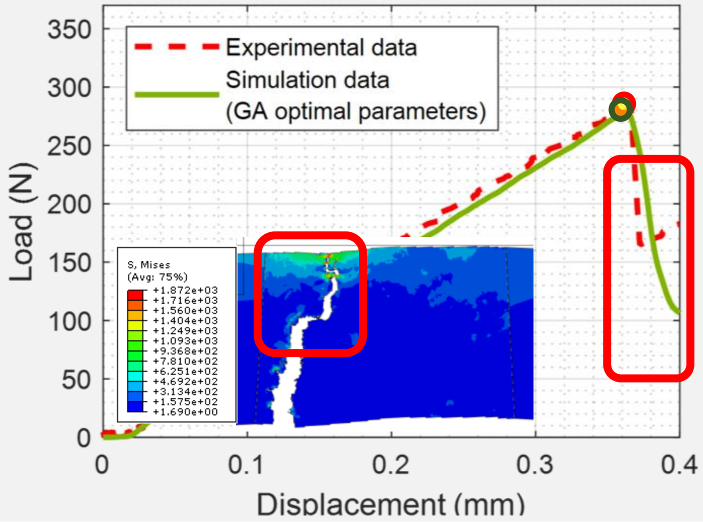
실행 시간 (sec)		18.19
Interface 파괴변수, θ	X_4: $\varepsilon_{0:\eta=0.58}$	0.0013





Genetic Algorithm (GA) 최적화 결과

실행 시간 (sec)		18.62
	X_4: $\varepsilon_{0:\eta=0.58}$	0.0013

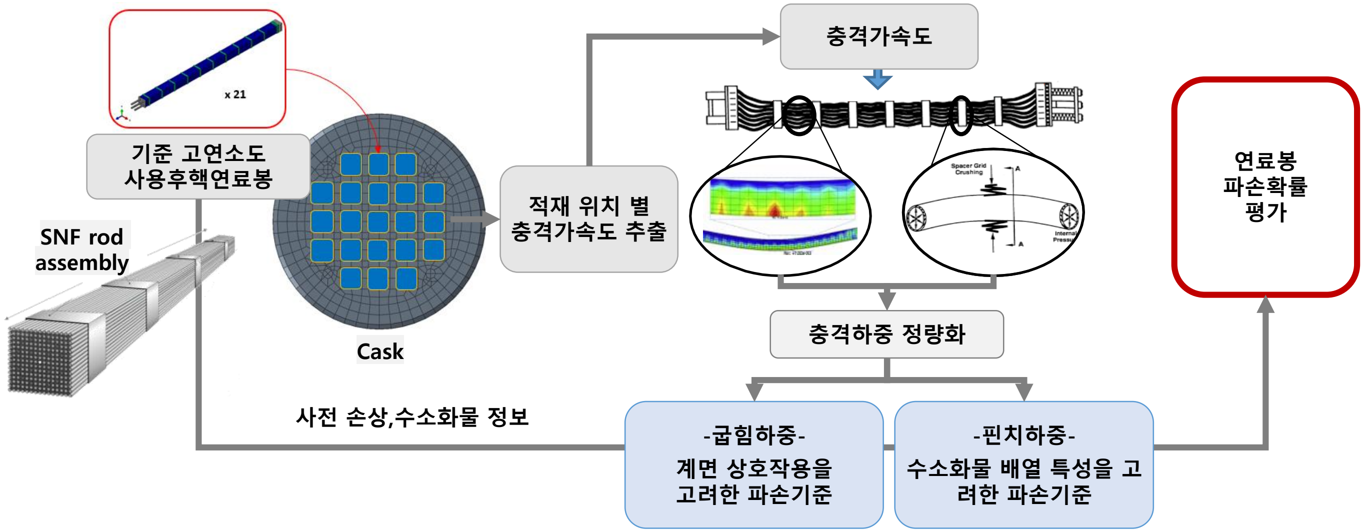


정확한 파손저항성을 평가하기 위해 균열지연 거동에 영향을 미치는 파괴변수에 대한 추가적인 연구 필요

V Conclusions

Metamodel과 최적화 기법을 이용한 파괴 매개변수 추정 프레임워크 제안
→ 수소화물이 석출된 피복관의 균열개시를 정량적으로 예측할 수 있는 기반을 마련

수평낙하충격에 대한 사용후핵연료봉의 기계적 건전성 평가



핀치하중에 대한 SNF봉 피복관의 파손저항성을 정량적으로 평가하여
수소화물 배열 특성에 따른 파손기준을 제시

감사합니다.

■ 참고문헌

[1] Korea Institute of Nuclear Safety, 2024, *사용후 핵연료 발생현황 보고서DB*, Daejeon. [Online]. Available: https://www.kins.re.kr/wacid/sf02?catId=06. [Accessed: 28-Nov-2024].

[2] U.S. NRC, 2014, *Spent Nuclear Fuel Transportation Risk Assessment-Final Report (NUREG-2125)*, Washington, DC.

[3] U.S. NRC, 2007, *A Pilot Probabilistic Risk Assessment of a Dry Storage System at a Nuclear Power Plant. (NUREG-1864)*, Washington, DC.

[4] Kim, S., and Lee, S., 2024, "Methodology for Numerical Evaluation of Fracture Resistance under Pinch Loading of Spent Nuclear Fuel Cladding Containing Reoriented Hydrides," Nuclear Engineering and Technology.

[5] U.S. NRC, 2020, *Dry Storage And Transportation Of High Burnup Spent Nuclear Fuel – Final Report (NUREG-2224)*, Washington DC.

[6] James, R., Rashid, J., Dunham, R., and Zhang, L., 2005, *Spent Fuel Transportation Applications: Fuel Rod Failure Evaluation under Simulated Cask Side Drop Conditions*, EPRI Technical Reports, 1009929, California.

[7] Rashid, J., Rashid, M., Dunham, R., and Machiels, A. J., 2004, *Development of a Metal/Hydride Mixture Model for Zircaloy Cladding with Mixed Hydride Structure*.

[8] Billone, M. C., Burtseva, T. A., and Martin-Rengel, M. A., 2015, *Effects of Lower Drying-Storage Temperatures on the DBTT of High-Burnup PWR Cladding*, Argonne National Lab.(ANL), Argonne, IL (United States).

[9] Billone, M., and Liu, Y., 2013, *Ductile-to-Brittle Transition Temperatures for High-Burnup PWR Cladding Alloys*.

[10] Billone, M. C., Burtseva, T. A., and Einziger, R. E., 2013, "Ductile-to-Brittle Transition Temperature for High-Burnup Cladding Alloys Exposed to Simulated Drying-Storage Conditions," Journal of Nuclear Materials, **433**(1–3), pp. 431–448. https://doi.org/10.1016/j.jnucmat.2012.10.002.

[11] Qin, W., Szpunar, J. A., and Kozinski, J., 2015, "Hydride-Induced Degradation of Zirconium Alloys: A Criterion for Complete Ductile-to-Brittle Transition and Its Dependence on Microstructure," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Royal Society of London. https://doi.org/10.1098/rspa.2015.0192.

[12] Billone, M. C., Burtseva, T. A., and Yan, Y., 2013, *Ductile-to-Brittle Transition Temperature for High Burnup Zircaloy-4 and ZIRLO (TM) Cladding Alloys Exposed to Simulated Drying Storage Conditions.*, Argonne National Lab.(ANL), Argonne, IL (United States).

[13] Motta, A. T., Capolungo, L., Chen, L. Q., Cinbiz, M. N., Daymond, M. R., Koss, D. A., Lacroix, E., Pastore, G., Simon, P. C. A., Tonks, M. R., Wirth, B. D., and Zikry, M. A., 2019, "Hydrogen in Zirconium Alloys: A Review," Journal of Nuclear Materials, **518**, pp. 440–460. https://doi.org/10.1016/j.jnucmat.2019.02.042.

[14] Ells, C. E., 1968, "Hydride Precipitates in Zirconium Alloys (A Review)," Journal of Nuclear Materials, **28**(2), pp. 129–151.

[15] Suman, S., Khan, M. K., Pathak, M., Singh, R. N., and Chakravartty, J. K., 2015, "Hydrogen in Zircaloy: Mechanism and Its Impacts," Int J Hydrogen Energy, **40**(17), pp. 5976–5994. https://doi.org/10.1016/j.ijhydene.2015.03.049.

[16] Perovic, V., Weatherly, G. C., and Simpson, C. J., 1986, "Hydride Precipitation in α/β Zirconium Alloys," *Perspectives in Hydrogen in Metals*, Elsevier, pp. 469–479.

[17] Carpenter, G. J. C., 1973, "The Dilatational Misfit of Zirconium Hydrides Precipitated in Zirconium," Journal of Nuclear Materials, **48**(3), pp. 264–266.

[18] Cinbiz, M. N., Koss, D. A., and Motta, A. T., 2016, "The Influence of Stress State on the Reorientation of Hydrides in a Zirconium Alloy," Journal of Nuclear Materials, **477**, pp. 157–164.

[19] Needleman, A., 1987, "A Continuum Model for Void Nucleation by Inclusion Debonding."

[20] Ahn, D. C., Sofronis, P., and Dodds, R., 2007, "Modeling of Hydrogen-Assisted Ductile Crack Propagation in Metals and Alloys," Int J Fract, **145**, pp. 135–157.

[21] Chan, H., Roberts, S. G., and Gong, J., 2016, "Micro-Scale Fracture Experiments on Zirconium Hydrides and Phase Boundaries," Journal of Nuclear Materials, **475**, pp. 105–112.

[22] Kearns, J. J., and Woods, C. R., 1966, "Effect of Texture, Grain Size, and Cold Work on the Precipitation of Oriented Hydrides in Zircaloy Tubing and Plate," Journal of Nuclear Materials, **20**(3), pp. 241–261. https://doi.org/10.1016/0022-3115(66)90036-5.

[23] Kim, Y.-J., Kook, D.-H., Kim, T.-H., and Kim, J.-S., 2015, "Stress and Temperature-Dependent Hydride Reorientation of Zircaloy-4 Cladding and Its Effect on the Ductility Degradation," J Nucl Sci Technol, **52**(5), pp. 717–727. https://doi.org/10.1080/00223131.2014.978829.

[24] Alam, A. M., and Hellwig, C., 2008, "Cladding Tube Deformation Test for Stress Reorientation of Hydrides," J ASTM Int, **5**(2). https://doi.org/10.1520/JAI101110.

[25] Billone, M. C., Burtseva, T. A., and Einziger, R. E., 2013, "Ductile-to-Brittle Transition Temperature for High-Burnup Cladding Alloys Exposed to Simulated Drying-Storage Conditions," Journal of Nuclear Materials, **433**(1–3), pp. 431–448. https://doi.org/10.1016/j.jnucmat.2012.10.002.

[26] Kleijnen, J. P. C. ., 1987, *Statistical Tools for Simulation Practitioners*, Marcel Dekker. [Online]. Available: https://research.tilburguniversity.edu/en/publications/statistical-tools-for-simulation-practitioners. [Accessed: 28-Nov-2024].

[27] Box, G. E. P., Hunter, W. H., and Hunter, S., 1978, *Statistics for Experimenters*, John Wiley and sons New York.

[28] Smith, M., 1993, *Neural Networks for Statistical Modeling*, Thomson Learning.

[29] Cheng, B., and Titterington, D. M., 1994, "Neural Networks: A Review from a Statistical Perspective," Statistical science, pp. 2–30.

[30] Sacks, J., Welch, W. J., Mitchell, T. J., and Wynn, H. P., 1989, "Design and Analysis of Computer Experiments," https://doi.org/10.1214/ss/1177012413, **4**(4), pp. 409–423. https://doi.org/10.1214/SS/1177012413.

[31] Booker, A. J., Dennis, J. E., Frank, P. D., Serafini, D. B., Torczon, V., and Trosset, M. W., 1999, "A Rigorous Framework for Optimization of Expensive Functions by Surrogates," Structural optimization, **17**, pp. 1–13.

[32] Friedman, J. H., 1991, "Multivariate Adaptive Regression Splines," The annals of statistics, **19**(1), pp. 1–67.

[33] Barthelemy, J.-F. M., and Haftka, R. T., 1993, "Approximation Concepts for Optimum Structural Design—a Review," Structural optimization, **5**, pp. 129–144.

[34] Simpson, T. W., Peplinski, J., Koch, P. N., and Allen, J. K., 1997, "On the Use of Statistics in Design and the Implications for Deterministic Computer Experiments," *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, p. V003T30A008.

[35] Sobieszczanski-Sobieski, J., and Haftka, R. T., 1997, "Multidisciplinary Aerospace Design Optimization: Survey of Recent Developments," Structural optimization, **14**, pp. 1–23.

[36] Pareto, V., 1964, *Cours d'économie Politique*.

[37] Fonseca, C. M., and Fleming, P. J., 1995, "An Overview of Evolutionary Algorithms in Multiobjective Optimization," Evol Comput, **3**(1), pp. 1–16.

[38] Zeleny, Milan., 1982, "Multiple Criteria Decision Making," p. 563. [Online]. Available: https://books.google.com/books/about/Multiple_Criteria_Decision_Making.html?id=vTayAAAAIAAJ. [Accessed: 28-Nov-2024].

[39] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T., 2002, "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II," IEEE Transactions on Evolutionary Computation, **6**(2), pp. 182–197. https://doi.org/10.1109/4235.996017.

[40] Zitzler, E., 2001, "SPEA2: Improving the Strength Pareto Evolutionary Algorithm."

[41] Liu, Q., Li, X., Liu, H., and Guo, Z., 2020, "Multi-Objective Metaheuristics for Discrete Optimization Problems: A Review of the State-of-the-Art," Applied Soft Computing Journal, **93**. https://doi.org/10.1016/J.ASOC.2020.106382.

[42] Martins, J. R. R. A., and Lambe, A. B., 2013, "Multidisciplinary Design Optimization: A Survey of Architectures," AIAA journal, **51**(9), pp. 2049–2075.

[43] Kim, S., and Lee, S., 2021, "Simplified Model of a High Burnup Spent Nuclear Fuel Rod under Lateral Impact Considering a Stress-Based Failure Criterion," Metals (Basel), **11**(10), p. 1631.

[44] Serra, J., 1988, "Image Analysis and Mathematical Morphology, Vol. 1(1982) & Vol. 2 (1988)." [Online]. Available: citeulike-article-id:7544267. [Accessed: 05-Jul-2023].

[45] Fogel, E., and Halperin, D., 2007, "Exact and Efficient Construction of Minkowski Sums of Convex Polyhedra with Applications," Computer-Aided Design, **39**(11), pp. 929–940.

[46] Gardner, R., 2002, "The Brunn-Minkowski Inequality," Bulletin of the American mathematical society, **39**(3), pp. 355–405.

[47] Van Den Boomgaard, R., and Van Balen, R., 1992, "Methods for Fast Morphological Image Transforms Using Bitmapped Binary Images," CVGIP: Graphical Models and Image Processing, **54**(3), pp. 252–258.

[48] Dougherty, E. R., 1992, "An Introduction to Morphological Image Processing," *SPIE*, Optical Engineering Press.

[49] Ghosh, P. K., 1993, "A Unified Computational Framework for Minkowski Operations," Comput Graph, **17**(4), pp. 357–378.

[50] Deruntz, J. A., and Hodge, P. G., 1960, "Crushing of a Tube between Rigid Plates," Journal of Applied Mechanics, Transactions ASME, **30**(3), pp. 391–395. https://doi.org/10.1115/1.3636567.

[51] Reid, S. R., and Reddy, T. Y., 1978, "Effect of Strain Hardening on the Lateral Compression of Tubes between Rigid Plates," Int J Solids Struct, **14**(3), pp. 213–225. https://doi.org/10.1016/0020-7683(78)90026-4.

[52] Yella Reddy, T., and Reid, S. R., 1979, "On Obtaining Material Properties from the Ring Compression Test," Nuclear Engineering and Design, **52**(2), pp. 257–263. https://doi.org/10.1016/0029-5493(79)90055-4.

[53] Nemat-Alla, M., 2003, "Reproducing Hoop Stress–Strain Behavior for Tubular Material Using Lateral Compression Test," Int J Mech Sci, **45**(4), pp. 605–621. https://doi.org/10.1016/S0020-7403(03)00115-2.

[54] Garrison, B., Yan, Y., and TerMaath, S., 2021, "Determining Failure Properties of As-Received and Hydrided Unirradiated Zircaloy-4 from Ring Compression Tests," Eng Fail Anal, **125**, p. 105362. https://doi.org/10.1016/J.ENGFAILANAL.2021.105362.

[55] Puls, M. P., Shi, S.-Q., and Rabier, J., 2005, "Experimental Studies of Mechanical Properties of Solid Zirconium Hydrides," Journal of nuclear materials, **336**(1), pp. 73–80.

[56] Rico, A., Martin-Rengel, M. A., Ruiz-Hervias, J., Rodriguez, J., and Gomez-Sanchez, F. J., 2014, "Nanoindentation Measurements of the Mechanical Properties of Zirconium Matrix and Hydrides in Unirradiated Pre-Hydrided Nuclear Fuel Cladding," Journal of nuclear materials, **452**(1–3), pp. 69–76.

[57] Yamanaka, S., Yoshioka, K., Uno, M., Katsura, M., Anada, H., Matsuda, T., and Kobayashi, S., 1999, "Thermal and Mechanical Properties of Zirconium Hydride," J Alloys Compd, **293**, pp. 23–29.

[58] Kuroda, M., Yoshioka, K., Yamanaka, S., Anada, H., Nagase, F., and Uetsuka, H., 2000, "Influence of Precipitated Hydride on the Fracture Behavior of Zircaloy Fuel Cladding Tube," J Nucl Sci Technol, **37**(8), pp. 670–675.

[59] Evans, C., 2014, "Micromechanisms and Micromechanics of Zircaloy-4."

[60] Kese, K., Olsson, P. A. T., Holston, A.-M. A., and Broitman, E., 2017, "High Temperature Nanoindentation Hardness and Young's Modulus Measurement in a Neutron-Irradiated Fuel Cladding Material," Journal of Nuclear Materials, **487**, pp. 113–120.

[61] Zhu, W., Wang, R., Shu, G., Wu, P., and Xiao, H., 2010, "First-Principles Study of Different Polymorphs of Crystalline Zirconium Hydride," The Journal of Physical Chemistry C, **114**(50), pp. 22361–22368.

[62] Olsson, P. A. T., Massih, A. R., Blomqvist, J., Holston, A.-M. A., and Bjerkén, C., 2014, "Ab Initio Thermodynamics of Zirconium Hydrides and Deuterides," Comput Mater Sci, **86**, pp. 211–222.

[63] Weck, P. F., Kim, E., Tikare, V., and Mitchell, J. A., 2015, "Mechanical Properties of Zirconium Alloys and Zirconium Hydrides Predicted from Density Functional Perturbation Theory," Dalton Transactions, **44**(43), pp. 18769–18779.

[64] Suman, S., Khan, M. K., Pathak, M., and Singh, R. N., 2017, "Investigation of Elevated-Temperature Mechanical Properties of δ-Hydride Precipitate in Zircaloy-4 Fuel Cladding Tubes Using Nanoindentation," J Alloys Compd, **726**, pp. 107–113.

[65] Lemaitre, J., and Chaboche, J.-L., 1978, "Aspect Phénoménologique de La Rupture Par Endommagement," J Méc Appl, **2**(3).

[66] Murakami, S., 1983, "Notion of Continuum Damage Mechanics and Its Application to Anisotropic Creep Damage Theory."

[67] Hillerborg, A., Modéer, M., and Petersson, P.-E., 1976, "Analysis of Crack Formation and Crack Growth in Concrete by Means of Fracture Mechanics and Finite Elements," Cem Concr Res, **6**(6), pp. 773–781.

[68] Smith, M., 2009, "ABAQUS/Standard User's Manual, Version 6.9."

[69] Woo, D., and Lee, Y., 2023, "Understanding the Mechanical Integrity of Zircaloy Cladding with Various Radial and Circumferential Hydride Morphologies via Image Analysis," Journal of Nuclear Materials, **584**, p. 154560. https://doi.org/10.1016/J.JNUCMAT.2023.154560.

[70] Kim, D., Kim, D., Woo, D., and Lee, Y., 2022, "Development of an Image Analysis Code for Hydrided Zircaloy Using Dijkstra's Algorithm and Sensitivity Analysis of Radial Hydride Continuous Path," Journal of Nuclear Materials, **564**, p. 153647. https://doi.org/10.1016/J.JNUCMAT.2022.153647.

[71] Kõrgesaar, M., 2019, "The Effect of Low Stress Triaxialities and Deformation Paths on Ductile Fracture Simulations of Large Shell Structures," Marine Structures, **63**, pp. 45–64. https://doi.org/10.1016/J.MARSTRUC.2018.08.004.

[72] Arslan, E., and Haskul, M., 2023, "Fracture Behavior Prediction of a High-Strength Aluminum Alloy under Multiaxial Loading," Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering. https://doi.org/10.11159/ICMIE23.143.

[73] Box, G. E. P., and Wilson, K. B., 1992, "On the Experimental Attainment of Optimum Conditions," pp. 270–310. https://doi.org/10.1007/978-1-4612-4380-9_23.

[74] St, L., and Wold, S., 1989, "Analysis of Variance (ANOVA)," Chemometrics and intelligent laboratory systems, **6**(4), pp. 259–272.

[75] Wang, G. G., and Shan, S., 2007, "Review of Metamodeling Techniques in Support of Engineering Design Optimization," Journal of Mechanical Design, **129**(4), pp. 370–380. https://doi.org/10.1115/1.2429697.

[76] Morris, M. D., and Mitchell, T. J., 1995, "Exploratory Designs for Computational Experiments," J Stat Plan Inference, **43**(3), pp. 381–402.

[77] McKay, M. D., Beckman, R. J., and Conover, W. J., 2000, "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," Technometrics, **42**(1), pp. 55–61.

[78] Giunta, A. A., Dudley, J. M., Narducci, R., Grossman, B., Haftka, R. T., Mason, W. H., and Watson, L. T., 1994, "Noisy Aerodynamic Response and Smooth Approximations in HSCT Design," 5th Symposium on Multidisciplinary Analysis and Optimization, 1994, pp. 1117–1128. https://doi.org/10.2514/6.1994-4376.

[79] Kaufman, M., Balabanov, V., Burgee, S. L., Giunta, A. A., Grossman, B., Haftka, R. T., Mason, W. H., and Watson, L. T., 1996, "Variable-Complexity Response Surface Approximations for Wing Structural Weight in HSCT Design," Comput Mech, **18**(2), pp. 112–126. https://doi.org/10.1007/BF00350530.

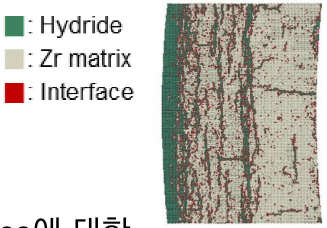
[80] Jin, R., Chen, W., and Simpson, T. W., 2001, "Comparative Studies of Metamodelling Techniques under Multiple Modelling Criteria," Structural and multidisciplinary optimization, **23**, pp. 1–13.

[81] Srinivas, N., and Deb, K., 1994, "Muiltiobjective Optimization Using Nondominated Sorting in Genetic Algorithms," Evol Comput, **2**(3), pp. 221–248. https://doi.org/10.1162/EVCO.1994.2.3.221.

[82] Deb, K., Agrawal, S., Pratap, A., and Meyarivan, T., 2000, "A Fast Elitist Non-Dominated Sorting Genetic Algorithm for Multi-Objective Optimization: NSGA-II," Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), **1917**, pp. 849–858. https://doi.org/10.1007/3-540-45356-3_83.

핀치하중 파괴 저항성 평가를 위한 전산모델 개발

재료 물성



- 다양한 실험적 방법을 통해 제시된 기계적 물성에 대한 문헌 조사[21,55-64]
  - 문헌에서 도출한 Zr matrix와 hydride의 탄성계수와 밀도 및 항복 응력을 적용하였으며, Zr/hydride interface에 대한 기계적 물성은 Chan et al.[21]의 연구자료를 활용함.

Investigator	Young's modulus (GPa)					Methodology
	Zirconium	Zircaloy-2	Zircaloy-4	ZIRLO	δ-hydride	
Puls et al. [55]	-	-	-	-	97.50	Compression test
Rico et al. [56]	-	-	-	83.00	95.00	Nanoindentation test
Yamanaka et al. [57]	95.50	-	-	-	137.80	Ultrasonic pulse-echo
Kuroda et al. [58]	-	-	105.00	-	135.9	Uniaxial tensile test
Evans [59]	-	-	115.00	-	155.00	Nanoindentation test
Kese et al. [60]	-	95.4	-	-	115.00	Nanoindentation test
Zhu et al. [61]	103.04	-	-	-	129.93	Density functional theory
Olsson et al. [62]	-	-	-	-	127.00	Density functional theory
Weck et al. [63]	98.80	-	104.20	91.30	129.90	Density functional theory
Suman et al. [64]	-	-	99.24	-	133.18	Nanoindentation test
Chan et. al. [21]		-	-	80-85	78-82	Microfracture cantilever experiments

Appendix

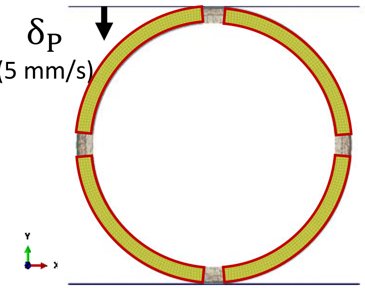
* RCT: Ring Compression Test

핀치하중 파괴 저항성 평가를 위한 전산모델 개발

○ 재료 물성

- Zr matrix, hydride, Zr/hydride interface로 재구성된 이미지를 통해 **픽셀 기반 FE 모델을 생성**
- 계산의 효율성을 위해 주요 균열 영역에 픽셀 기반 FE 모델 적용

  **이를 제외한 영역은 RCT의 힘-변위 데이터를 활용하여 단일 재료 연속체 모델로 단순화됨. [50–54]



- **Elastic modulus** of RCT load-displacement curve [50]

$$E = \frac{12P_eR^3(1-\upsilon^2)}{\delta_e t_0^2 l}\left(\frac{\pi}{4}-\frac{2}{\pi}\right) \quad \dots(1)$$

- **Yield strength** of RCT load-displacement curve [51, 52]

$$\sigma_{yield} = \frac{\alpha P_c R}{t_0^2 l} \quad \dots(2)$$

- **Plastic zone** of RCT load-displacement curve [53]

$$\sigma = K(\varepsilon_0 + \varepsilon_p)^n \quad \dots(3)$$

t_0: Ring tube thickness
l: Ring tube length
R: Mean radius of ring
P_c: Collapse load, a starting point of large scale plastic flow
P_e: Maximum elastic load
δ_e: Maximum elastic defection
υ: Poisson's ratio
α: Geometric constant (0.866)

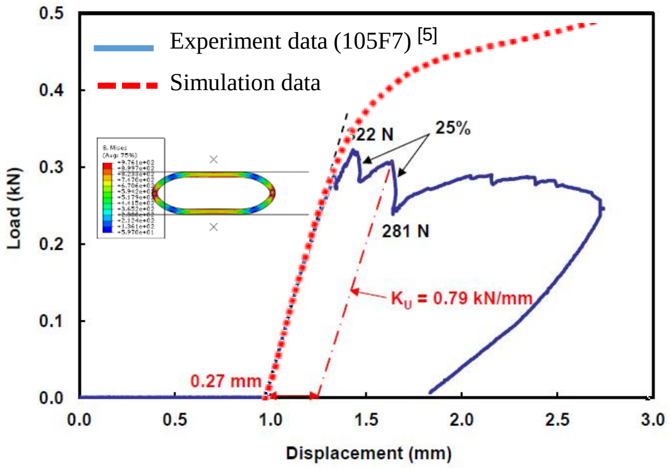
K: Strength coefficient
n: Strain-hardening exponent
ε_0: Elastic-limit strain
ε_p: Plastic strain

<Empirical fitting values of K and n> [53, 54]

	2D			
	Calculated		Empirical fit	
H content (wppm)	E (GPa)	σ_{ys} (MPa)	K	n
As-received	89	790	1100	0.09
105	90	800	1125	0.09
130	92	780	1100	0.09
210	90	780	1100	0.09
370	92	790	1125	0.09
414	92	790	1125	0.09
442	87	790	1090	0.09
443	87	780	1090	0.09
610	87	790	1090	0.09

<Material properties of the ring specimen>

R	t_0	l	δ_e	P_e	P_c	E	σ_y
4.78 mm	0.55 mm	8.00 mm	0.26	200 MPa	322 MPa	101.0 GPa	635.4 MPa



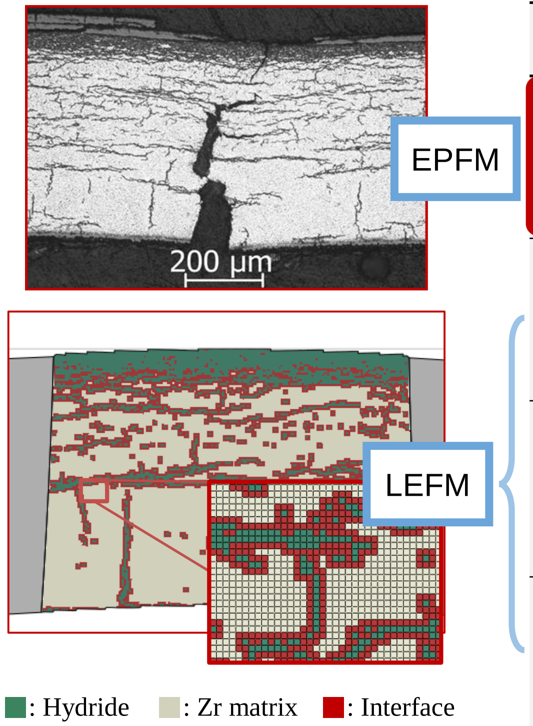
<Load-displacement curves for simplified region models>

- CZM: Cohesive Zone Model
- TSL : Traction Separation Law
- LEFM : Linear Elastic Fracture Mechanics
- EPFM : Elastic Plastic Fracture Mechanics

핀치하중 파괴 저항성 평가를 위한 전산모델 개발

○ 손상역학 전산기법 선정

- 수소화물을 포함한 피복관의 균열을 모사하기 위해 손상역학 전산기법 선정
  - ▶ 수소화물을 포함한 피복관은 복잡한 파괴 거동을 가지며 이를 모사할 수 있는 전산기법 필요
  - ▶ 균열 모사에 사용되는 손상모델 비교 분석 및 한계점 파악



모델	주요 메커니즘	적용 범위	장점	한계
Ductile damage	: 재료 변형에 의한 손상 축적 기반	: 연성, 취성 재료 손상	: 계면과 내부를 하나의 손상 모델로 통합 처리	: 취성거동 모사 시 파라미터 조정 필요 : 높은 비선형성으로 수렴 어려움
XFEM	: Fracture toughens 기반	: 취성 재료 손상 : 복잡한 균열 경로	: 손상 거동 일관성 있게 처리 가능	: 계면과 내부 손상 동시 모사 어려움 : 메쉬 품질 의존성 큼
CZM	: 계면이 접착 강도와 분리 에너지 기반	: 취성 계면 손상	: 계면 특성 정밀히 정의 가능 : 손상 거동 일관성 있게 처리 가능	: 내부 손상 거동 모사 불가 : 메쉬 품질 의존성 큼 : 복잡한 상호작용에서 수렴 어려움
TSL	: 계면의 응력-변위관계	: 취성 계면 손상 : 계면 균열 초기 손상	: 간단한 설정 : 계면 초기 손상 상세히 분석 가능	: 내부 손상 거동 모사 불가 : 복잡한 손상 거동 모사 한계

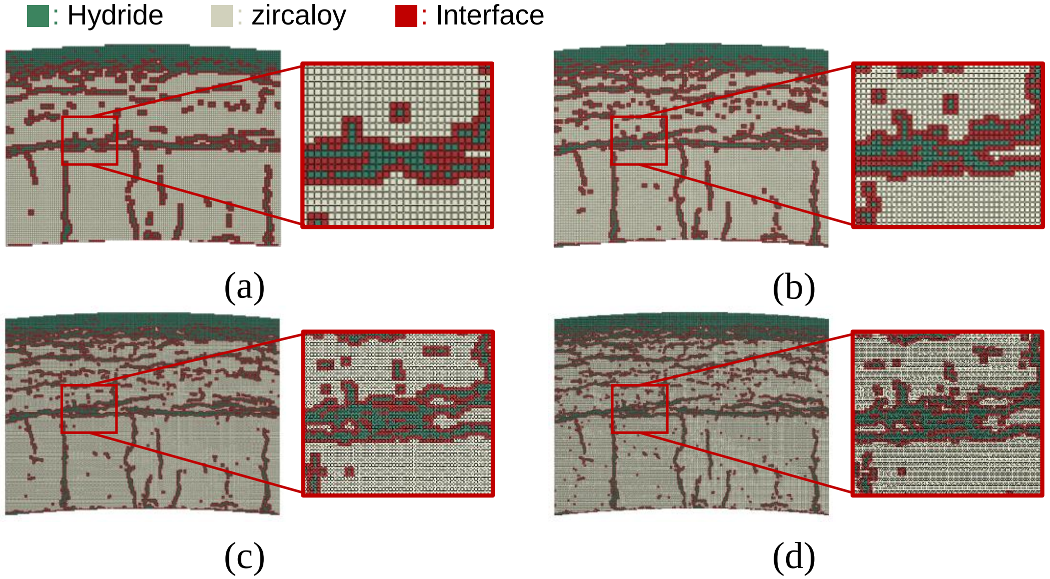
핀치하중 파괴 저항성 평가를 위한 전산모델 개발

Element 크기 선정

- Ductile damage model을 적용한 손상 거동을 모사하기 위해서는 적절한 요소 크기 사용이 중요
  - ▶ 균열 전파 분석에서 너무 작은 요소 크기는 과도한 분석 시간을 요구하며, 너무 큰 요소 크기는 균열 발생 및 전파를 정확히 모사하기 어려움

▪ **4가지 해상도에 대한 유한요소모델**

: 해석의 효율성을 위해 12시 영역이 포함된 1/2 링 모델 사용



〈Pixel-based finite element models for the four resolutions 〉

〈Element characteristics for four resolutions〉

Resolution	(a) 138×102	(b) 184×136	(c) 277×204	(d) 370×273
Element size	5.82 μm	4.34 μm	2.89 μm	2.16 μm
Total number of elements	13,056	23.478	53,156	94,794

* RCT: Ring Compression Test

핀치하중 파괴 저항성 평가를 위한 전산모델 개발

Element 크기 선정

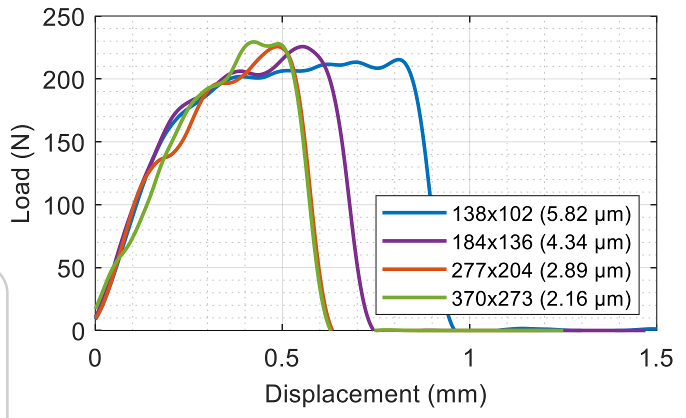
– 해석 결과와 문헌조사를 바탕으로 요소 크기 선정

- ✓ 요소 크기가 작아질수록 파괴 저항 감소, 3 ㎛ 이하인 경우 유의미한 차이 없음.
- ✓ 요소 크기가 작아질수록 해석시간 기하급수적 증가
- ✓ 반경방향 수소화물 간격이 5 ㎛ 이하인 경우 연속적인 수소화물로 간주

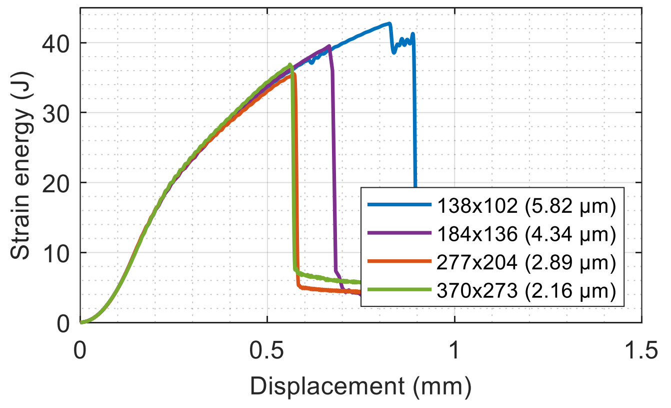
▪ 4가지 요소크기 별 해석결과

Resolution	(a) 138×102	(b) 184×136	(c) 277×204	(d) 370×273
Element size	5.82 μm	4.34 μm	2.89 μm	2.16 μm
Total number of elements	13,056	23,478	53,156	94,794
Maximum RCT load	214.29 N	225.68 N	225.65 N	229.40 N
Total Strain energy	6.20 J	4.52 J	2.85 J	3.08 J
Modulus of Toughness	0.64 N/mm^3	0.38 N/mm^3	0.24 N/mm^3	0.27 N/mm^3
Analysis Time	3 $hour$	5 $hour$	15 $hour$	24 $hour$

[The load-displacement curve]



[Strain energy-time curve]



** Billone, M. C . et al. "Radial hydrides separated by a gap of ≤5 ㎛ are considered to be continuous." 29)

** Wang S. et al. "Determine both the habit plane and morphology of hydrides in fine-grained (grain sizes < 10 ㎛), 2 phase (α-β) zirconium alloys." 67)

Metamodeling using RCT simulation data

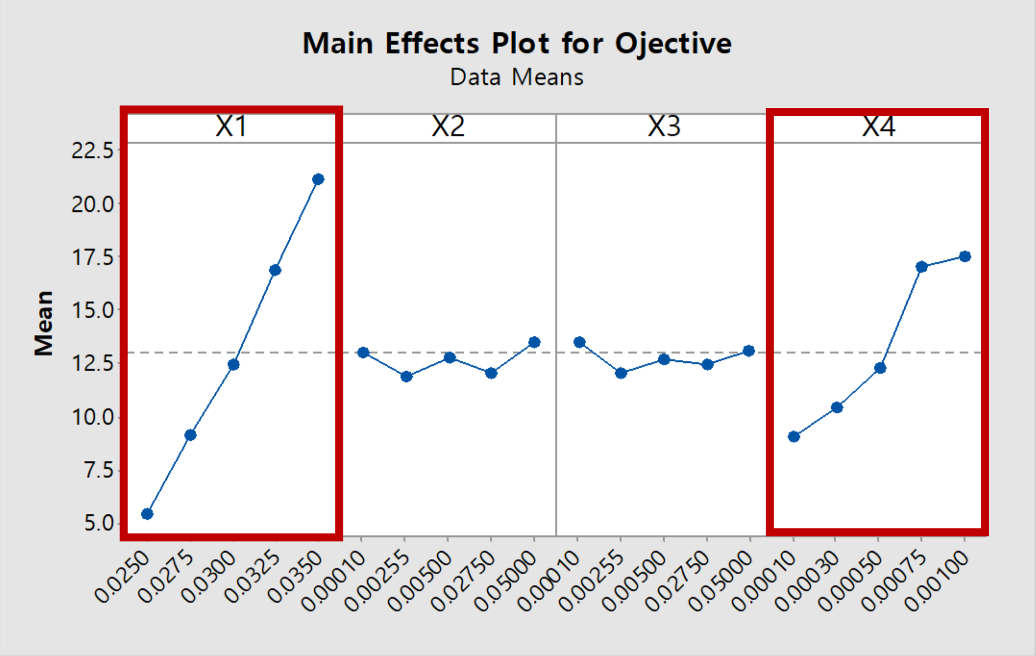
Parametric study

- Central Composite Design (CCD)을 활용하여 ANOVA 수행
  - ▶ 선정한 parameters가 objective function에 미치는 영향 평가

X1	G_f	Fracture Energy
X2	$\bar{\varepsilon}^{pl}_{0,\ \eta:0}$	Equivalent plastic strain at damage initiation ($\eta = 0$, pure shear)
X3	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$	Equivalent plastic strain at damage initiation ($\eta = 0.33$, uniaxial tension)
X4	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$	Equivalent plastic strain at damage initiation ($\eta = 0.58$, plane strain)

<Analysis of Variance>

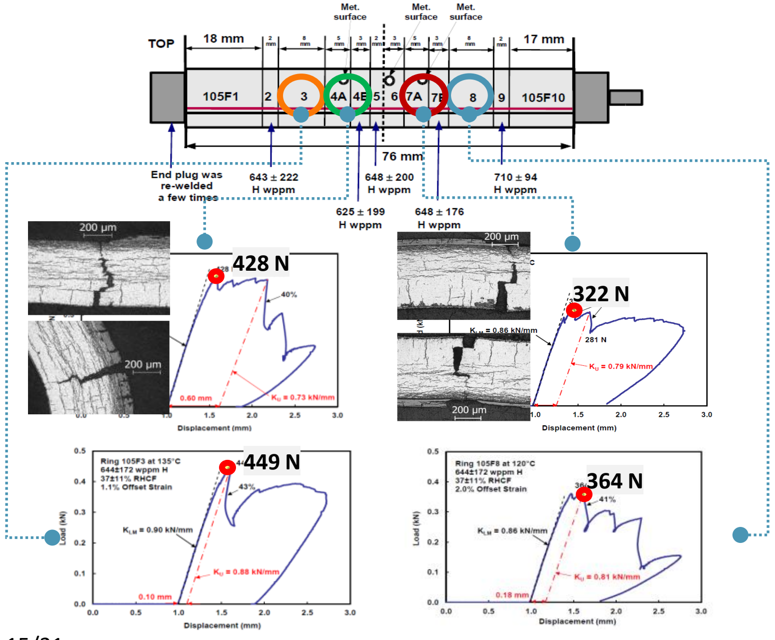
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	1117.9	79.847	3.47	0.027
Linear	4	1105.8	276.46	12.03	0.001
X1	1	832.46	832.46	36.22	0
X2	1	0.66	0.662	0.03	0.869
X3	1	0.3	0.303	0.01	0.911
X4	1	272.4	272.4	11.85	0.006
Square	4	6.82	1.705	0.07	0.988
X1*X1	1	2.82	2.817	0.12	0.734
X2*X2	1	0.69	0.686	0.03	0.866
X3*X3	1	1.08	1.083	0.05	0.833
X4*X4	1	5.41	5.409	0.24	0.638
2-WayInteraction	6	5.21	0.869	0.04	1
X1*X2	1	0.4	0.403	0.02	0.897
X1*X3	1	2.15	2.152	0.09	0.766
X1*X4	1	0.06	0.063	0	0.959
X2*X3	1	1	1.004	0.04	0.839
X2*X4	1	0.79	0.788	0.03	0.857
X3*X4	1	0.8	0.803	0.03	0.855
Error	10	229.82	22.982		
Total	24	1347.7			



▶ This parameter are critical in predicting crack initiation.

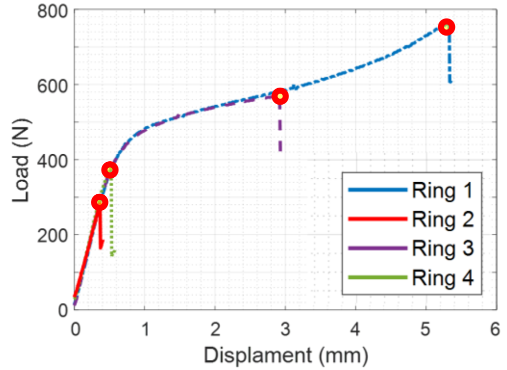
Appendix

HBU ZIRLO™ 1-cycle rodlet

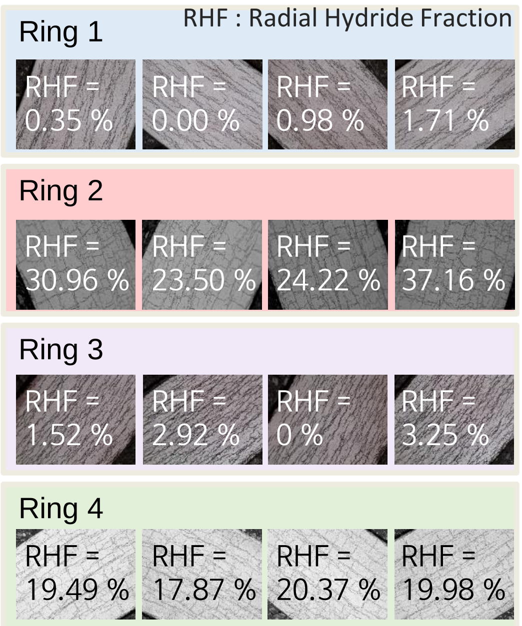


* Credit: ANL-15/21

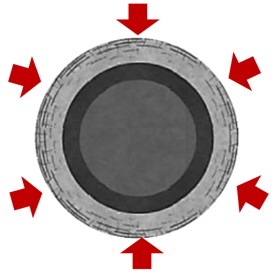
수소장입 피복관 시편



Ring No.	Hydrogen Content (wppm)	Hydride Reorientation	Ave. RHF (%)	Max. Force (N)
1	228.7	X	135	765
2	243.3	O	150	282
3	668.2	X	150	569
4	674.4	O	120	341



* Credit: Nuclear Fuel Materials and Safety Lab at SNU



- ▶ 핀치하중 작용 방향 불확실성
- ▶ 다양한 RHF 분포 변화

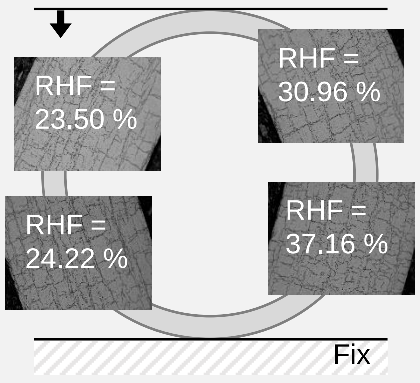
핀치하중 방향 불확실성 + 수소화물 분포 불확실성
→ 다양한 형태의 수소화물로 인한 균열개시하중 변동성 반영

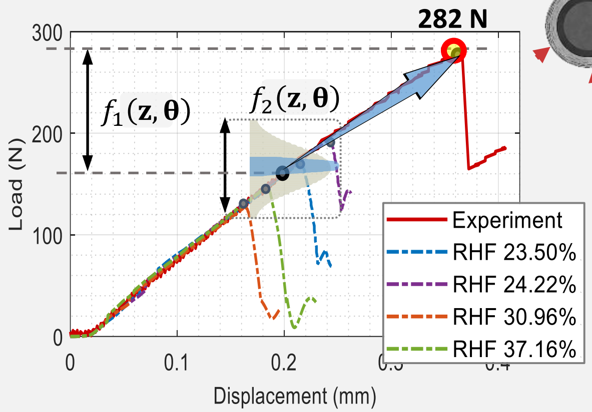
- RHF : Radial Hydride Fraction

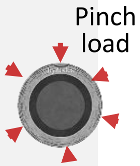
균열개시하중 예측 문제정의

Factor	Fracture parameters
$X1$	G_f
$X2$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0}$
$X3$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$
$X4$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$

수소장입 피복관 실험 및 수소화물 형태 별 해석 데이터







▶ 다양한 RHF 분포 변화

Hydrogen Concentration	Applied Hoop Stress	Ave. RHF	Length	Outer Radius	Thickness
243.3 wppm	140 MPa	28.95 %	7.50 mm	4.28 mm	0.56 mm

- $f_1(\mathbf{z},\boldsymbol{\theta}) = \left|y_{exp} - \mu_{y_{sim}}(\mathbf{z},\boldsymbol{\theta})\right|$
- $f_2(\mathbf{z},\boldsymbol{\theta}) = \sigma_{y_{sim}}(\mathbf{z},\boldsymbol{\theta})$

$f_1(\mathbf{z},\boldsymbol{\theta})$	: 균열 개시 하중에 대한 실험과 해석 평균 간 오차
$f_2(\mathbf{z},\boldsymbol{\theta})$	: 수소화물 분포 불확실성에 따른 균열 개시 하중 예측 변동성
$\boldsymbol{\theta}$	: 파괴변수 벡터 ($X1$~$X4$)
$\mathbf{z}$	: 수소화물 형태 가변성을 나타내는 불확실성 인자 벡터(RHF)
y	: 균열 개시 하중
$\mu_{y_{sim}}$	: 전산모델의 균열 개시 하중 평균
$\sigma_{y_{sim}}$	: 전산모델의 균열 개시 하중 표준 편차
exp	: 실험 데이터
sim	: 해석 데이터

- $\mu_{y_{sim}}(\mathbf{z},\boldsymbol{\theta}) = \frac{1}{N}\sum_{i=1}^{N} y_{sim}(\mathrm{z}_i,\boldsymbol{\theta})$
- $\sigma_{y_{sim}}(\mathbf{z},\boldsymbol{\theta}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_{sim}(\mathrm{z}_i,\boldsymbol{\theta}) - \mu_{y_{sim}}(\mathbf{z},\boldsymbol{\theta})\right)^2}$

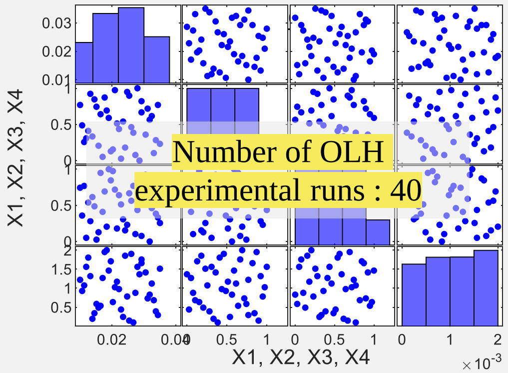
N	N : 다양한 RHF 금속조직 이미지에 대한 전산 모델의 수
i	i : RHF 별 전산모델 인덱스

- OLH : Optimal Latin Hyper Cube sampling
- CCD : Central Composite Design

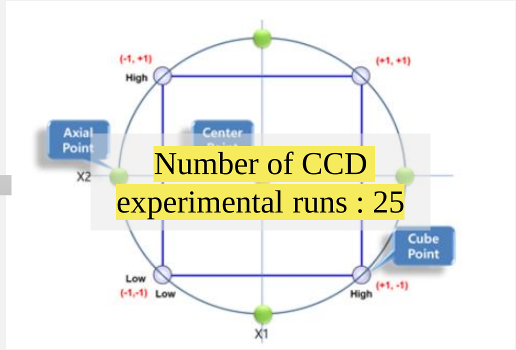
파괴변수 추정을 위한 메타모델 구축

수치해석적 실험 데이터 수집

Data scatter plot of 4



* OLH : Optimal Latin Hyper Cube sampling

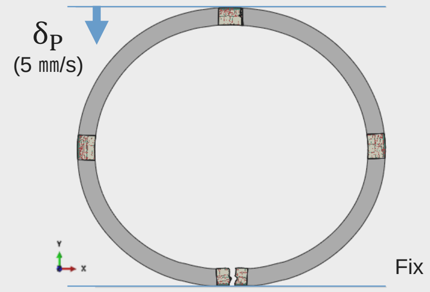


Value	*X1*	*X2*	*X3*	*X4*
Lower	0.0100	0.0001	0.0001	0.0001
Upper	0.0350	1.0000	1.0000	0.0020

Total of 260 (65x4) dataset

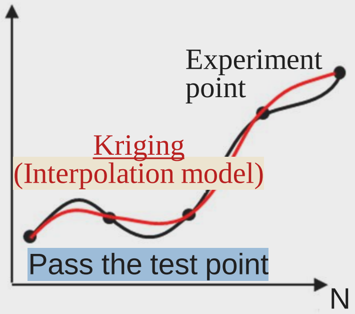
Training dataset	: 200 (77 %)
Test dataset	: 60 (23 %)

Simulation model ↔ Kriging metamodel



- 해석 시 시간/비용 많이 소요
- 설계영역 탐색에 많은 횟수의 해석 요구

$\hat{f}_1(\mathbf{z}, \boldsymbol{\theta}), \hat{f}_2(\mathbf{z}, \boldsymbol{\theta})$



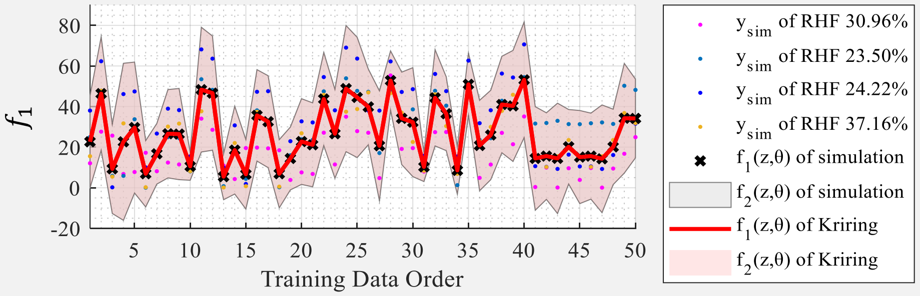
- 특성치 계산 수치적 부담 x
- 설계영역 탐색, 최적설계 적합

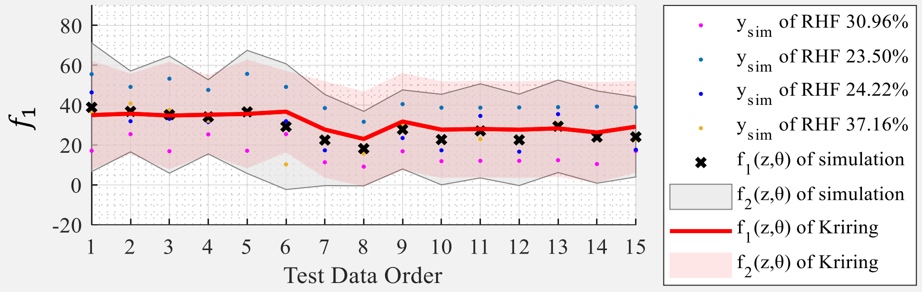
▶ 복잡한 Full Simulation을 근사하여 높은 계산 비용을 줄일 수 있는 Kriging metamodel 구축

파괴변수 추정을 위한 메타모델 구축

실험점에 대한 메타모델 예측 성능

$95\%\ Credible\ Intervals = \hat{f}_1 \pm 1.96\hat{f}_2$





- 파괴변수와 균열개시하중 예측 및 예측 변동성 함수 간의 관계를 정확하게 포착
- 다양한 수소화물 형태에 따른 균열 개시하중의 불확실성 효고적으로 통합

$f_1(\mathbf{z},\boldsymbol{\theta})$: 균열개시 하중에 대한 실험과 해석 평균 간 오차
$f_2(\mathbf{z},\boldsymbol{\theta})$: 수소화물 분포 불확실성에 따른 균열개시하중 예측 변동성

Factor	Fracture parameters
$X1$	G_f
$X2$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0}$
$X3$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$
$X4$	$\bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$

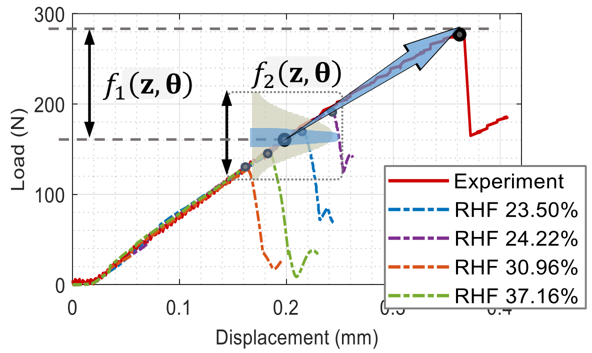
- Kriging metamodel $\hat{f}_1(\mathbf{z},\boldsymbol{\theta}), \hat{f}_2(\mathbf{z},\boldsymbol{\theta})$
- Multi-objective optimization formulation

Find $\boldsymbol{\theta} = [X1, X2, X3, X4]$ such that

Minimize $\boldsymbol{F}(\mathbf{z},\boldsymbol{\theta}) = \left[\hat{f}_1(\mathbf{z},\boldsymbol{\theta}), \hat{f}_2(\mathbf{z},\boldsymbol{\theta})\right]^T$

Subject to $\boldsymbol{\theta}_{lower} \leq \boldsymbol{\theta} \leq \boldsymbol{\theta}_{upper}$,

$\mathbf{z} \in \{z_1, z_2, \cdots, z_N\}$,



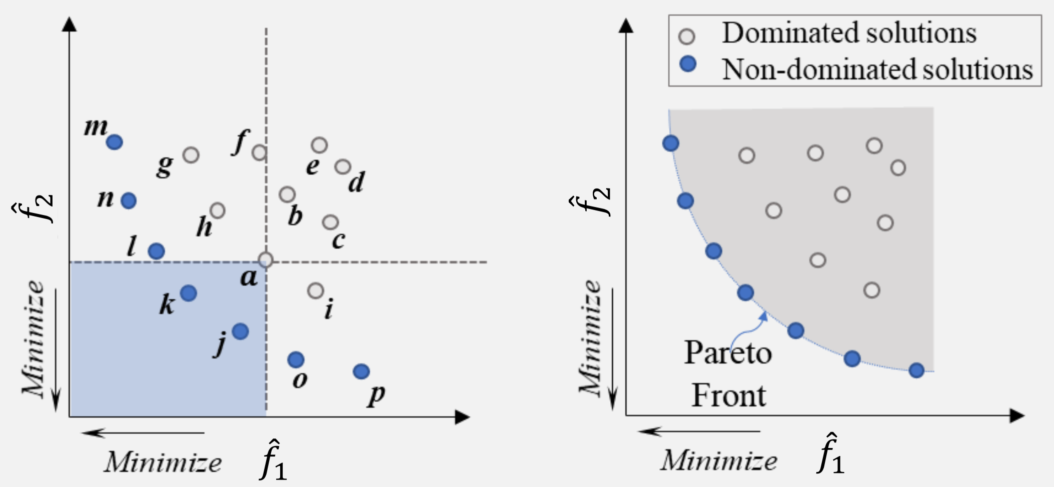
메타모델을 활용하여 효율적인 파괴변수 추정가능

• NSGA : Non-dominated Sorting Genetic Algorithm

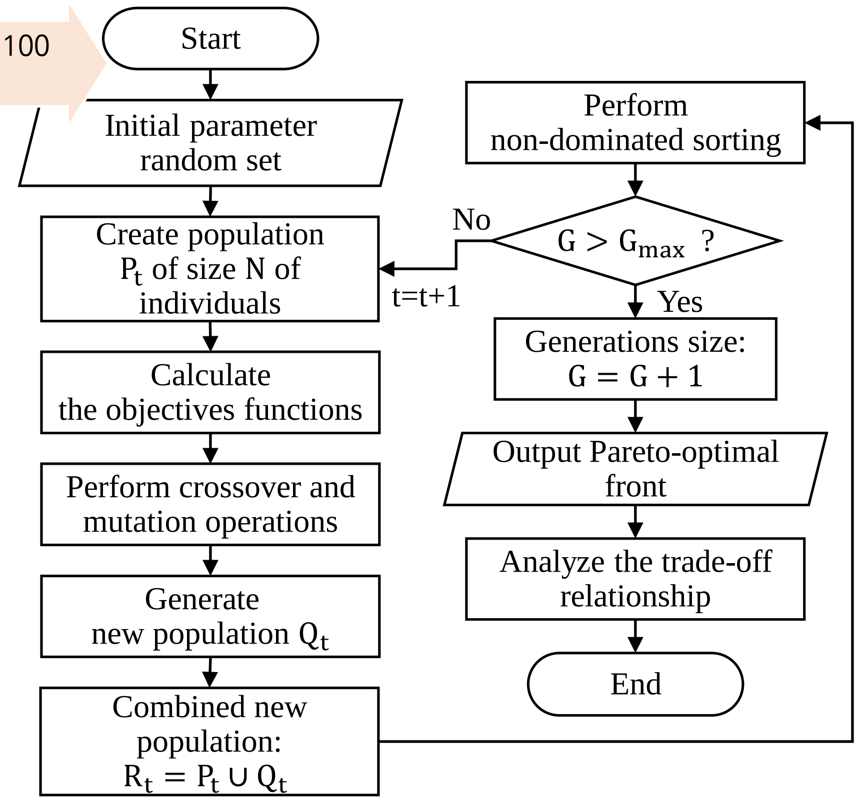
다목적 최적화를 통한 파괴변수 추정

상충관계를 고려한 NSGA-Ⅱ 최적화

- ✓ 모집단 개체 크기 N = 100
- ✓ 세대수 G = 200



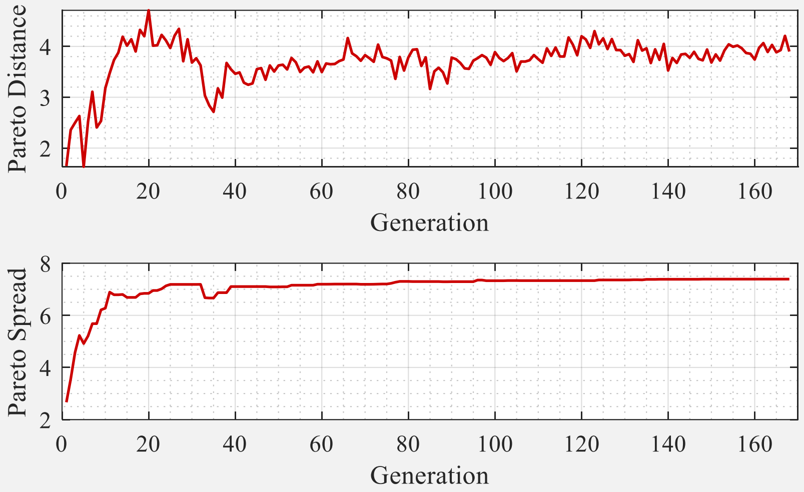
<Flowchart of NSGA-II algorithm>

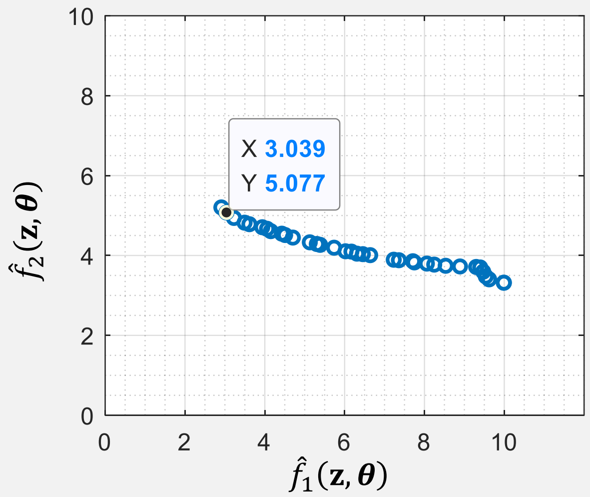


- NSGA : Non-dominated Sorting Genetic Algorithm

다목적 최적화를 통한 파괴변수 추정

NSGA-Ⅱ Evolution	Pareto front solutions





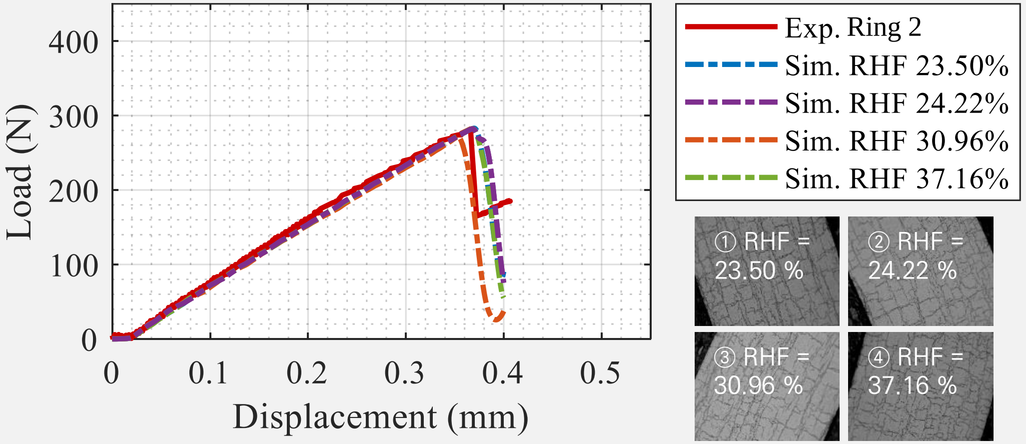
<Optimized fracture parameters and objective function values.>

Method	$X1 : G_f$	$X2 : \bar{\varepsilon}^{pl}_{0,\ \eta:0}$	$X3 : \bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$	$X4 : \bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$	$\hat{f}_1(\mathbf{z}, \boldsymbol{\theta})$	$\hat{f}_2(\mathbf{z}, \boldsymbol{\theta})$
Distance to ideal point	0.0102	0. 7074	0. 7214	0.0010	3.5298	4.8131
Weighted Sum (0.5, 0.5)	0.0103	0.7074	0.7079	0.0010	3.0387	5.0767

추정 파괴변수 검증

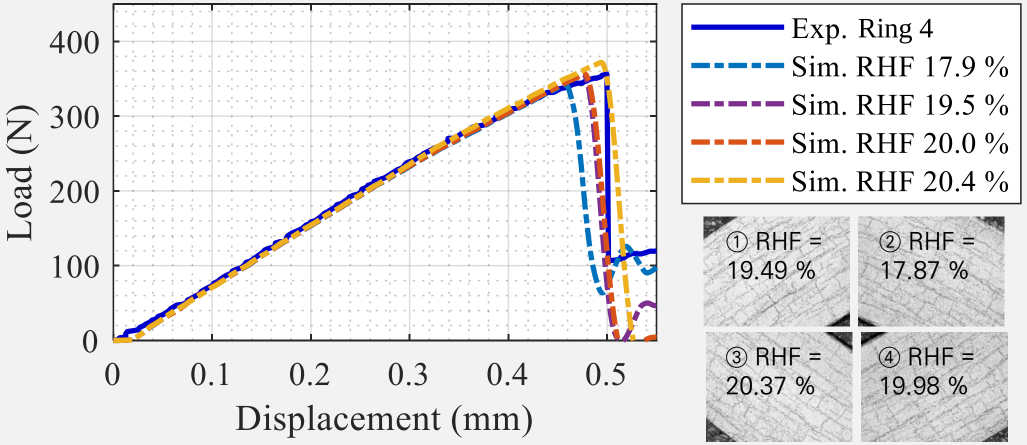
$X1 : G_f$	$X2 : \bar{\varepsilon}^{pl}_{0,\ \eta:0}$	$X3 : \bar{\varepsilon}^{pl}_{0,\ \eta:0.33}$	$X4 : \bar{\varepsilon}^{pl}_{0,\ \eta:0.58}$
0.0103	0.7074	0.7079	0.0010

Hydrogen Content (243 wppm), Ave. RHF (28.95 %)



Data		y	μ_y	$f_1(z,\theta)$	$f_2(z,\theta)$
Exp.		282.00 N	282.00 N	-	-
Sim. (RHF)	(23.5 %)	282.98 N	279.73 N	3.024	4.850
	(24.2 %)	282.26 N			
	(31.0 %)	271.34 N			
	(37.2 %)	282.34 N			
Kriging		-	-	3.039	5.077
Error		-	0.81 %	0.47 %	4.46 %

Hydrogen Content (674 wppm), Ave. RHF (19.40 %)



Data		y	μ_y	$f_1(z,\theta)$	$f_2(z,\theta)$
Exp.		356.09 N	356.09 N	-	-
Sim. (RHF)	(17.9 %)	341.87 N	356.52 N	0.435	10.607
	(19.5 %)	355.85 N			
	(20.0 %)	356.51 N			
	(20.4 %)	371.85 N			
Kriging		-	-	-	-
Error		-	0.12 %	-	-