7장 단조 시뮬레이션 결과에 영향을 미치는 주요 요소

7강 목차

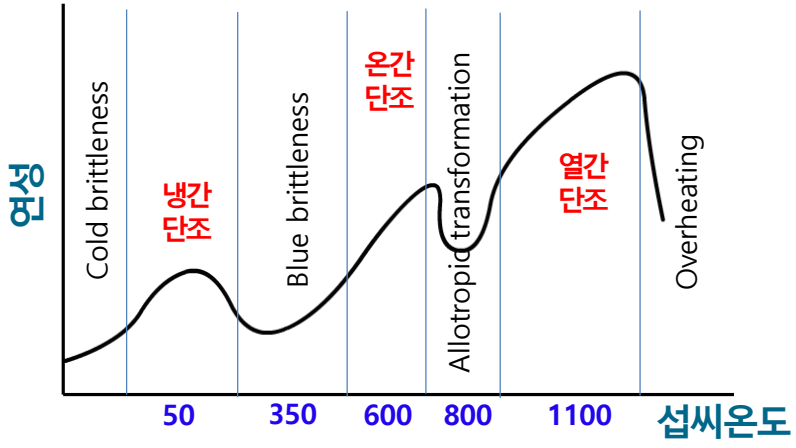
7.1 이론적 및 수치적 인자

7.2 차원과 단위

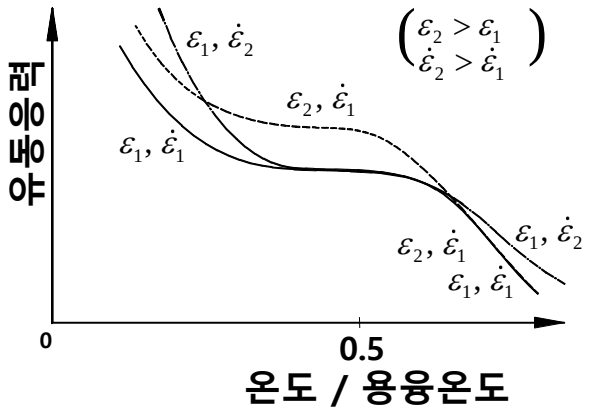
1. 이론적 및 수치적 인자

유동응력 및 온도-연성의 관계

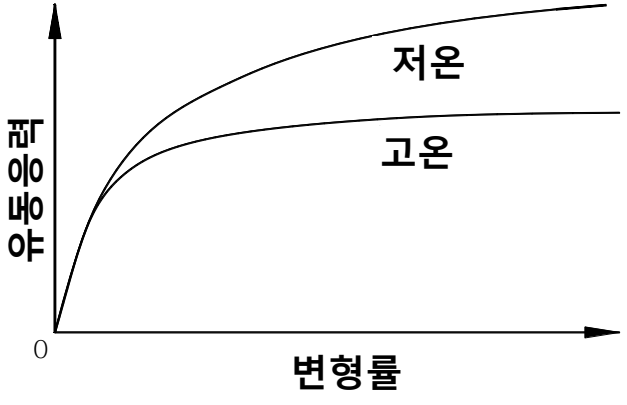
온도-연성의 관계



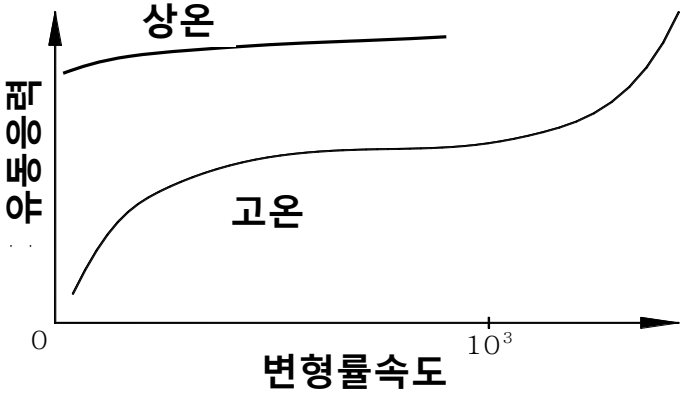
온도, 변형률, 변형률속도의 영향



변형률의 영향



변형률속도의 영향

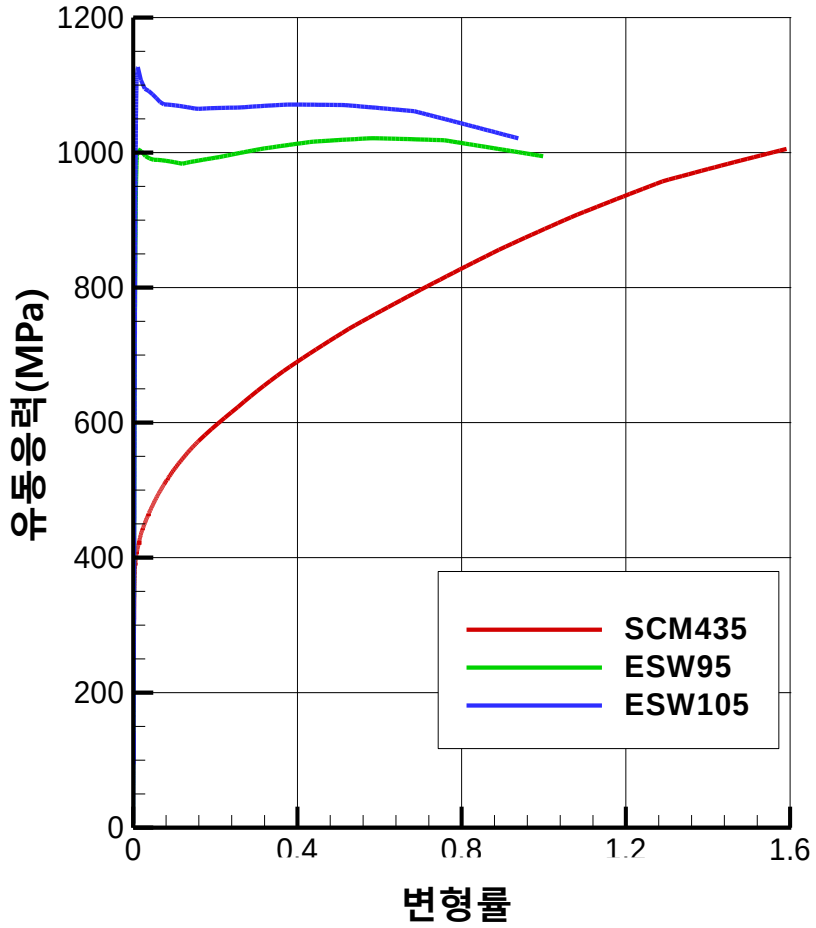


유동응력

- $\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T, D)$

상온 유동응력

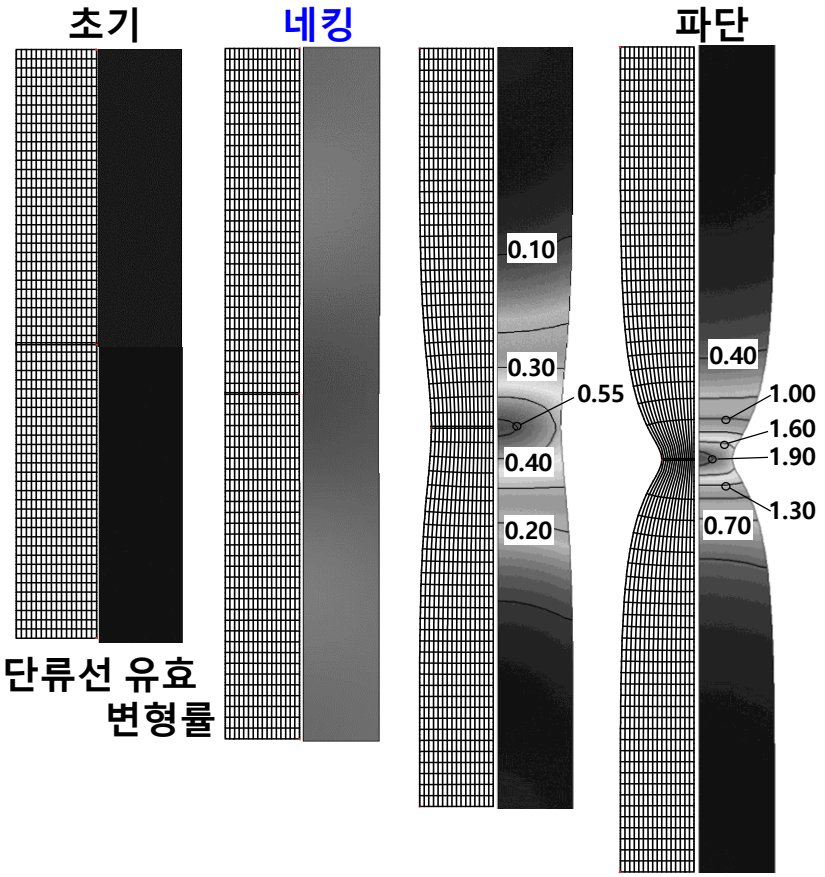
- **Hollomon-Ludwik 모델:** $\bar{\sigma} = Y_0 + K\,\bar{\varepsilon}^n$
  - $K = K(\bar{\varepsilon})$



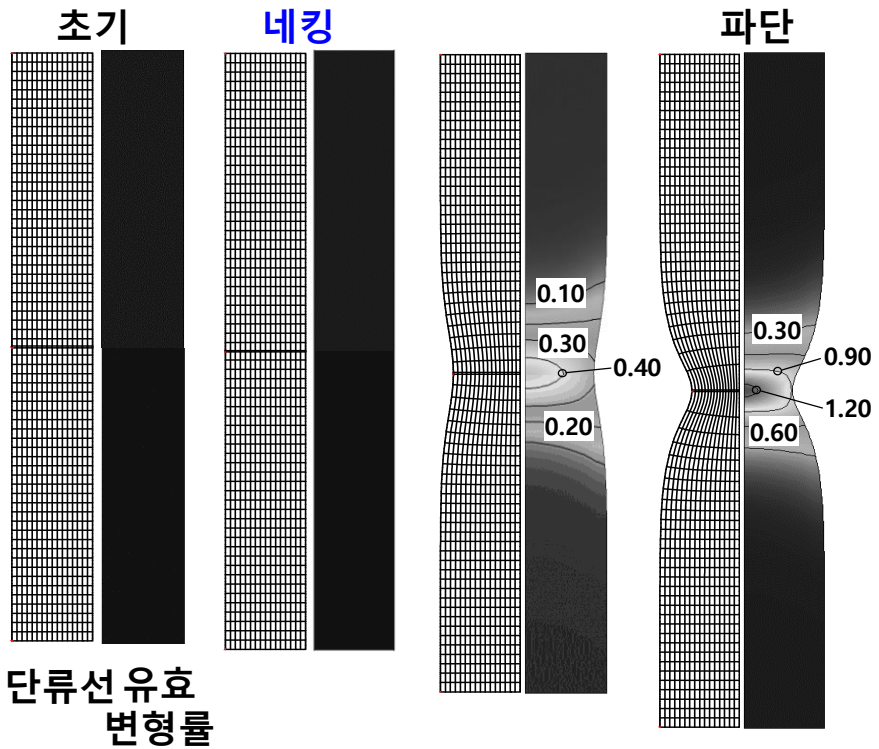
변형경화지수 또는 변형경화능

- **변형경화가 큰 소재는 변형을 비교적 넓게 전파하려는 특성이 있음**
- **저변형률경화 소재는 주변형구간에서 소성변형이 중첩되는 경향이 있음**

변형경화능에 따른 인장시험의 차이



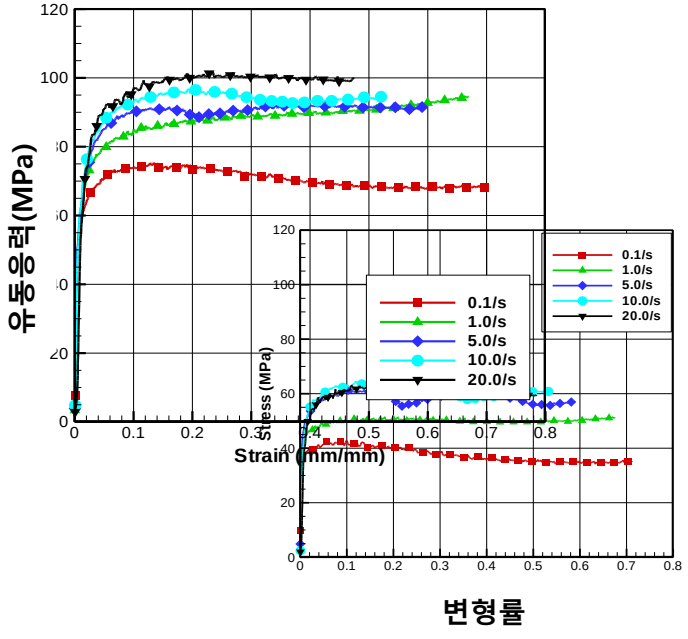
SCM435

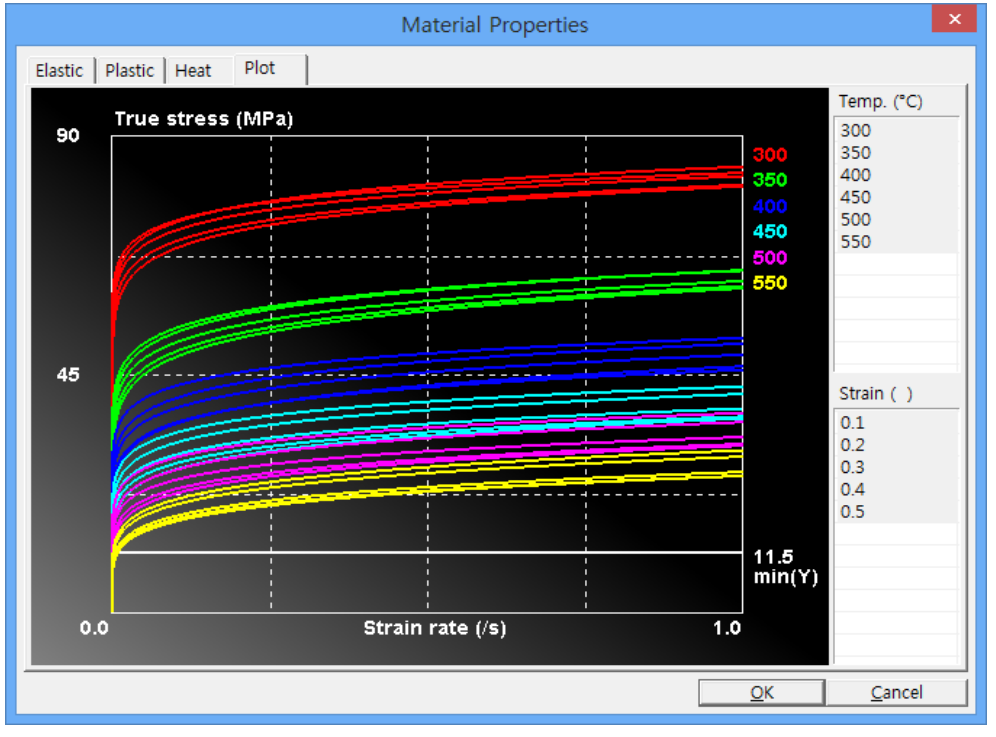


ESW105

고온 유동응력

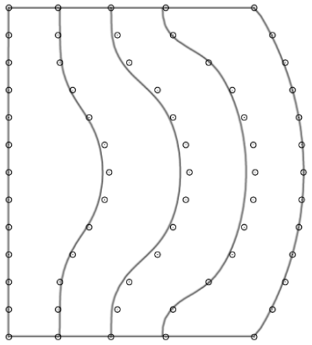
- $\bar{\sigma} = Y_0 + C\,\dot{\bar{\varepsilon}}^{m}$
  - $C = C(\bar{\varepsilon}, T)$
  - $m = m(\bar{\varepsilon}, T)$



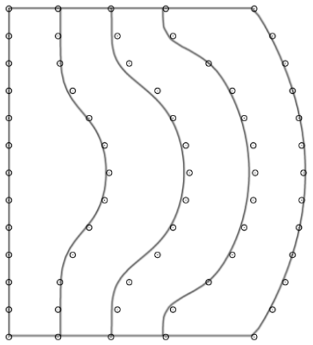


고온 초기항복응력/온도의 영향

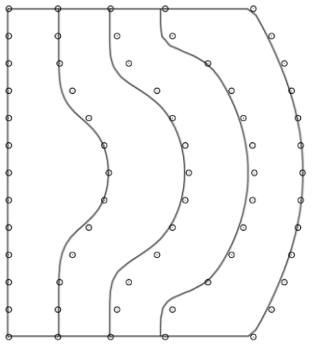
$$\bar{\sigma} = Y_0 + C\,\dot{\bar{\varepsilon}}^{m}$$



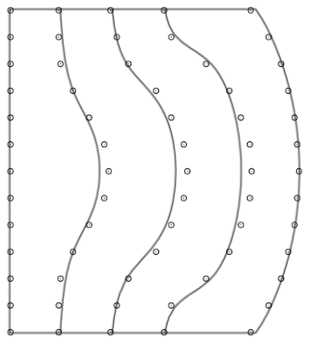
70 MPa limit



80 MPa limit



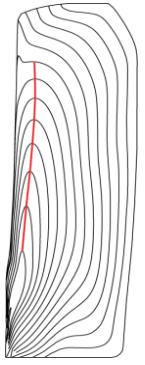
90 MPa limit



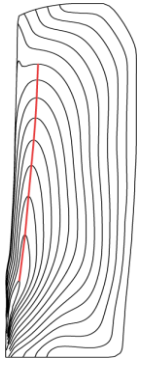
No lower limit

※Maximum flow stress for all cases = about 100 MPa

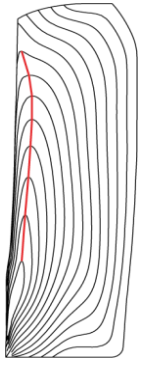
Experiments



80 MPa limit.
Isothermal



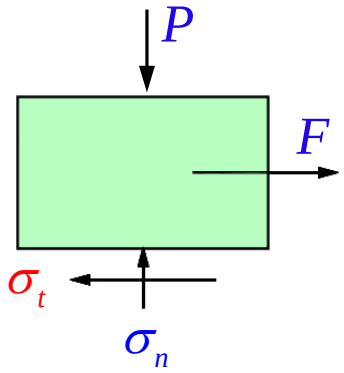
80 MPa limit.
Non-isothermal

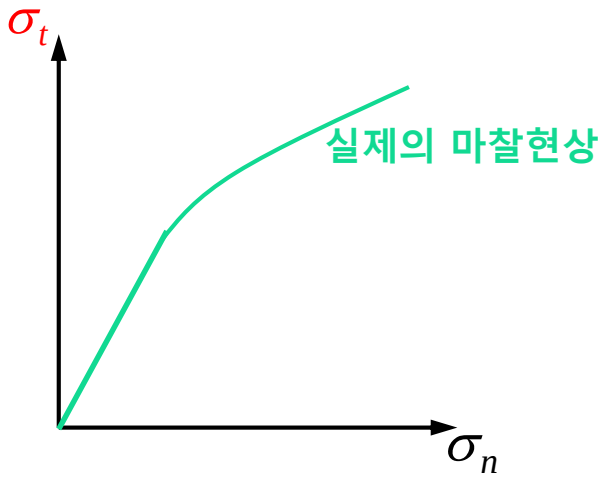


No lower limit.
Isothermal

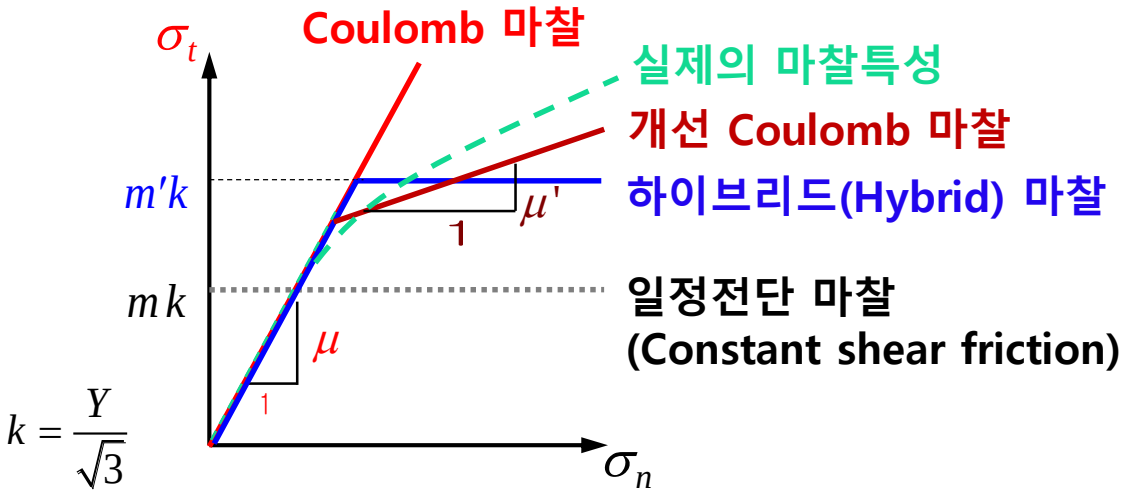
Experiments

마찰





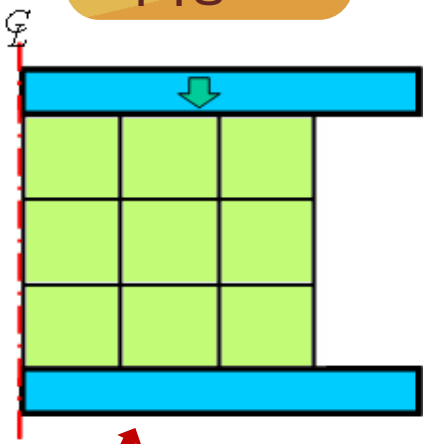
마찰법칙



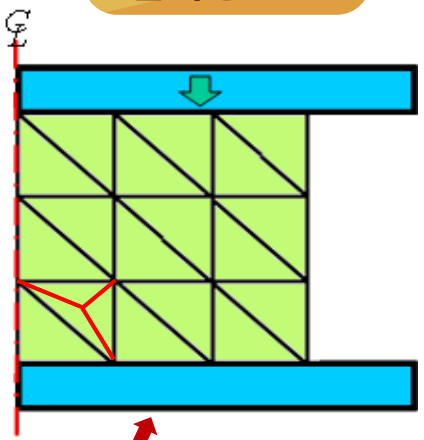
- μ : (저압)마찰계수
- μ' : 고압 마찰계수
- m : 마찰상수
- m' : 한계마찰상수

요소의 형태

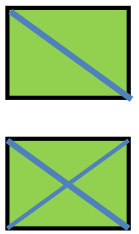
사각형 요소

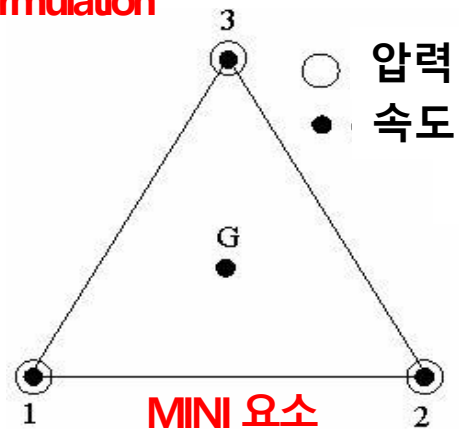


삼각형 요소



Mixed formulation
Locking



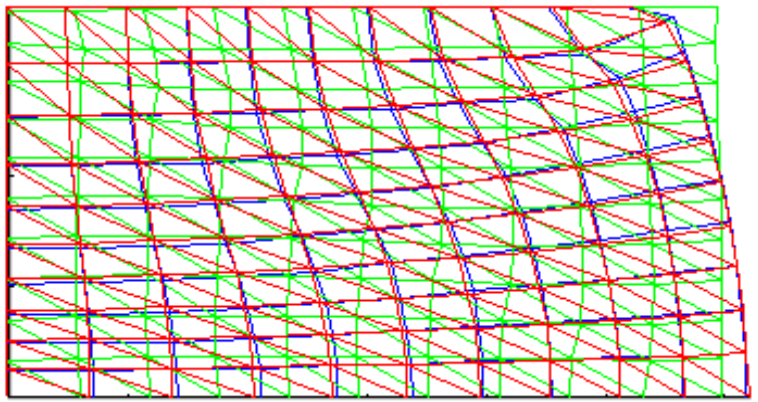


압력 자유도
속도 자유도

MINI 요소

결과의 비교

16	절점 수	16
32	전체 자유도	32
12	경계조건으로 구속된 자유도 수	12
9	비압축성 조건 수	18
11	총 미지수 수	3

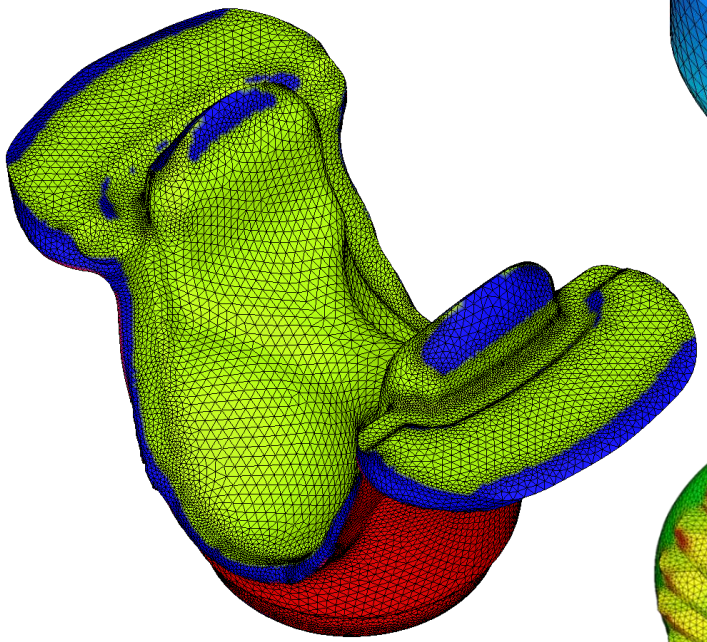


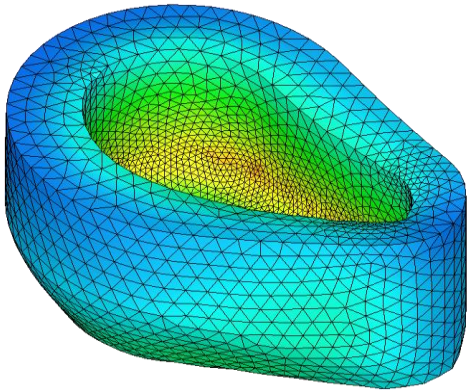
사각형

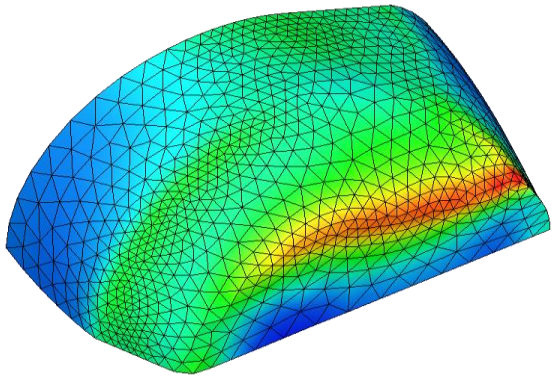
삼각형

MINI-요소

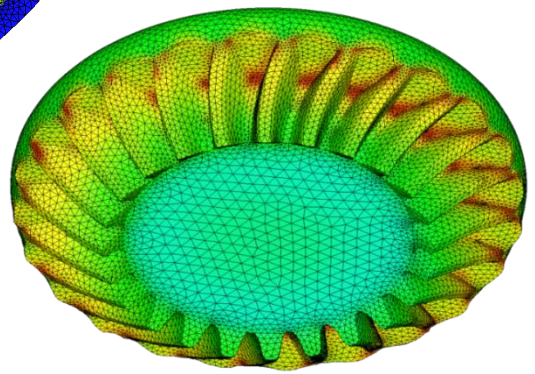
요소 품질

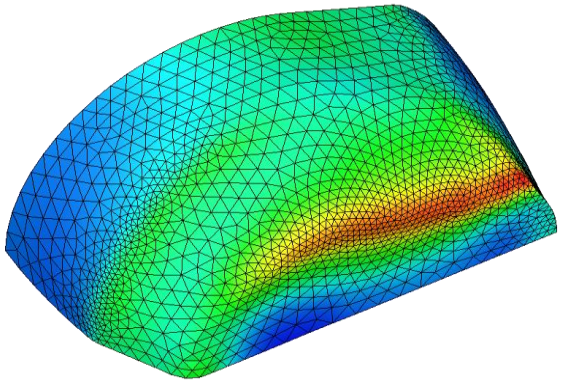






요소망재구성 이전

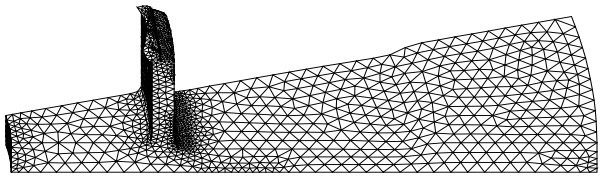


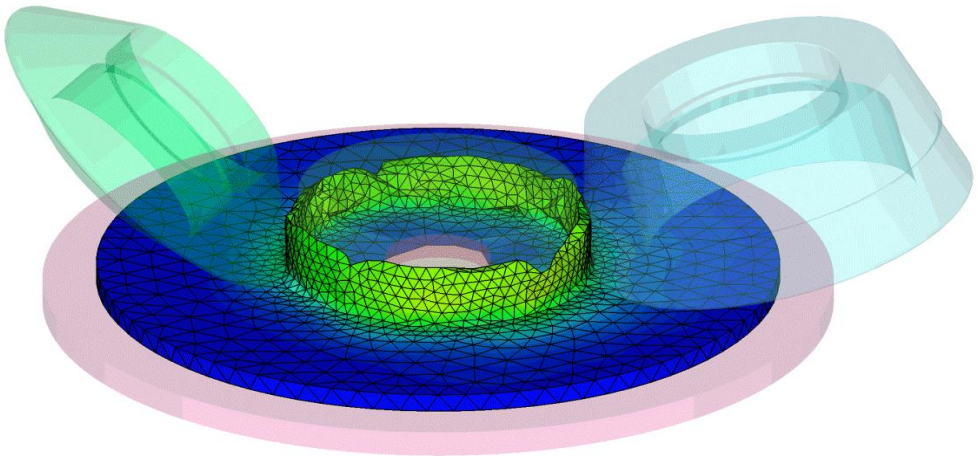


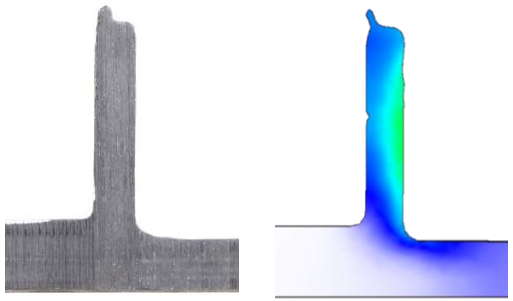
요소망재구성 이후

요소(절점) 수

- 절점 수의 증가는 일반적으로는 해의 정도가 높아진다는 것을 의미
- 소망재구성이 필요한 변형이 큰 공정에서는 오히려 잦은 요소망재구성으로 인하여 해의 정확도를 떨어뜨리는 작용도 할 수 있음

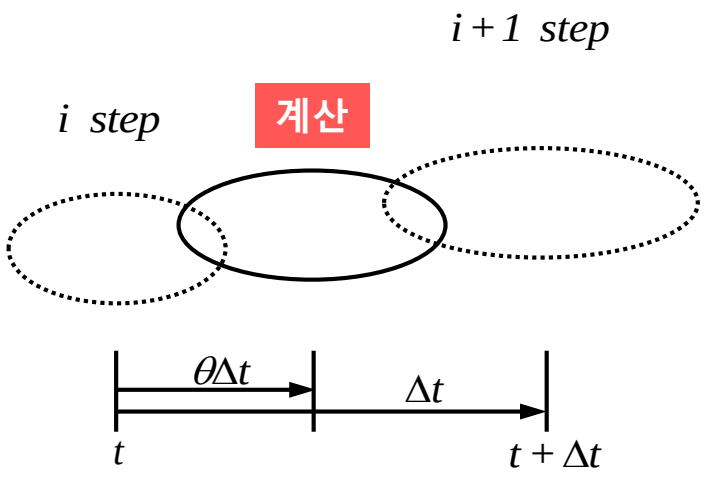


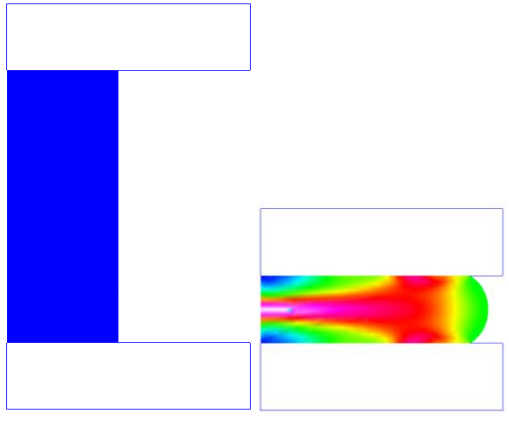




시간증분과 해석스텝 수

- 소프트웨어가 입력정보로부터 계산하는 평균적인 시간증분이 타당하게 결정되어야 하고, 적절한 크기의 소재의 금형 침투 한계 및 소재의 금형 분리 한계가 입력되어야 함
- 해석스텝 수와 최소 금형침범 깊이는 다소 수치적 부피변화에 영향을 미침. 따라서 수치적 부피변화는 시뮬레이션의 신뢰성의 바로미터가 될 수 있음



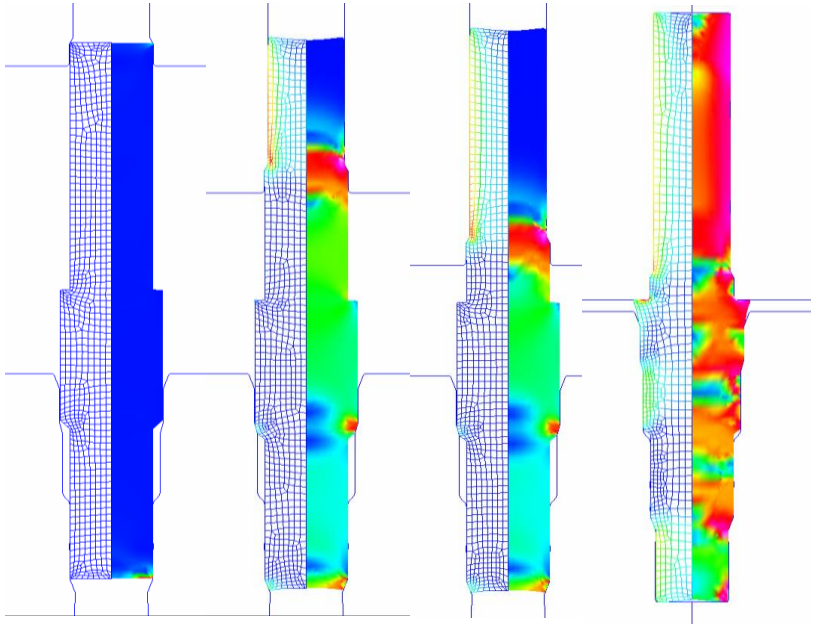


해석스텝 수	부피 변화율(%)
19	1.18
24	0.84
31	0.74
52	0.28
68	0.28
86	0.02

von Mises 항복이론과 관련 소성유동법칙 - 최소허용유효변형률속도

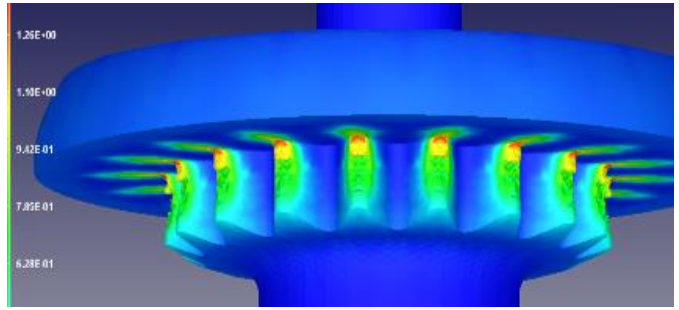
- $\sigma'_{ij} = (2\bar{\sigma}/3\dot{\bar{\varepsilon}})\dot{\varepsilon}_{ij}$ 에서 $\dot{\bar{\varepsilon}}$ 가 0에 가깝게 되면, 수치적으로 계산이 불가능함
- 유효변형률속도 $\dot{\bar{\varepsilon}}$의 하한치, 즉 최소허용유효변형률속도를 설정해 두어야 함

- $\sigma'_{ij} = \dfrac{2}{3}\dfrac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij} \quad if \quad \dot{\bar{\varepsilon}} > \dot{\bar{\varepsilon}}_{\min}$
- $\sigma'_{ij} = \dfrac{2}{3}\dfrac{\bar{\sigma}}{\dot{\bar{\varepsilon}}_{\min}}\dot{\varepsilon}_{ij} \quad if \quad \dot{\bar{\varepsilon}} < \dot{\bar{\varepsilon}}_{\min}$



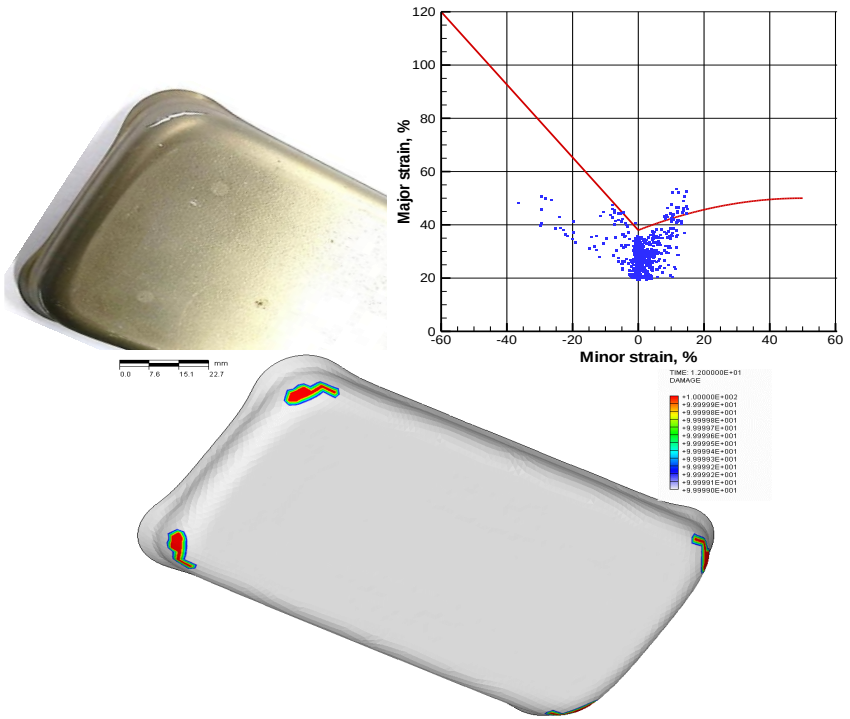
손상도

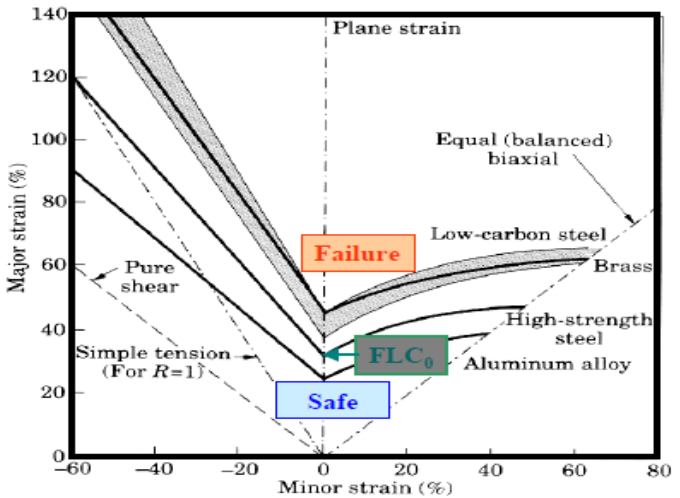
- 연성파괴 이론에서는 재료에 축적된 손상도가 임계치에 이르면 파단이 발생
- 취성파괴는 최대주응력이 일정 크기에 도달하면 최대주응력축과 수직한 면에서 발생
- 냉간단조의 초기소재는 연성재료에 속하지만, 재료가 변형을 받으면서 유효변형률이 축적되어 취성화되는 경향이 있으므로 파단면의 예측에 있어서는 연성파괴를 중심으로 검토하되 취성파괴도 동시에 고려해야 함
- 손상도는 유동응력에도 다소 영향을 미치지만 유동응력에 미치는 영향은 정상적인 공정에서는 무시가능



FLD(Formability Limit Diagram)

- FLD(Formability limit diagram) : 임계성형한계곡선과 함께 최대 및 최소 변형률을 표시한 도형임
- 대개 판재성형 공정의 건전성 평가 목적으로 사용

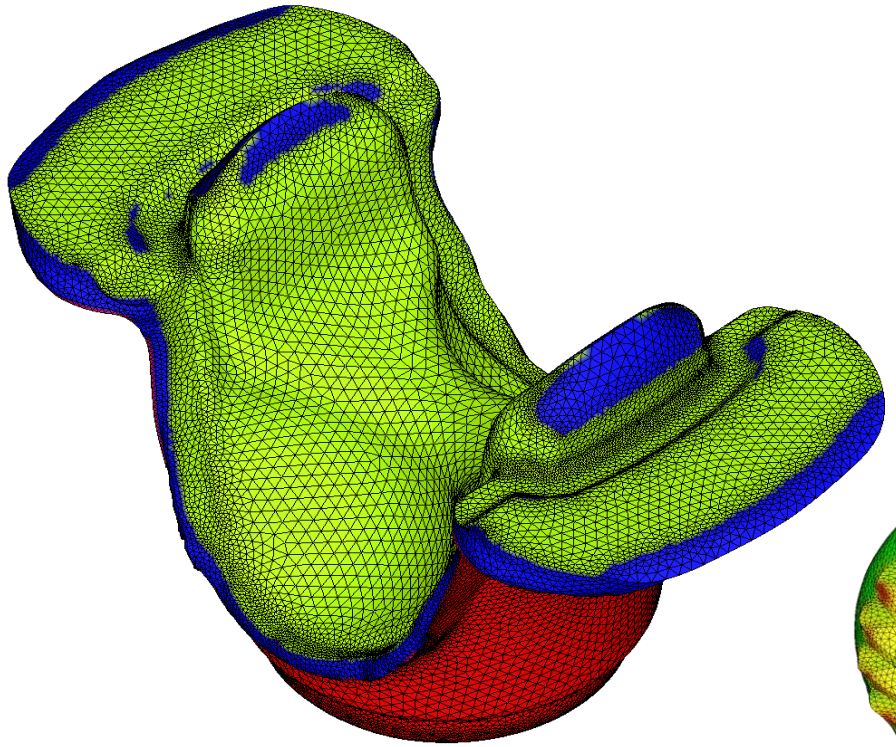


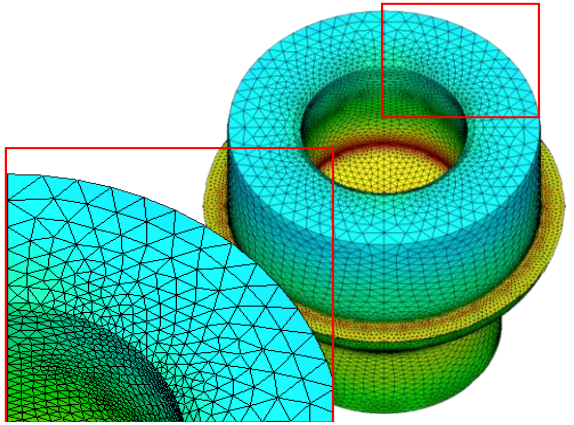


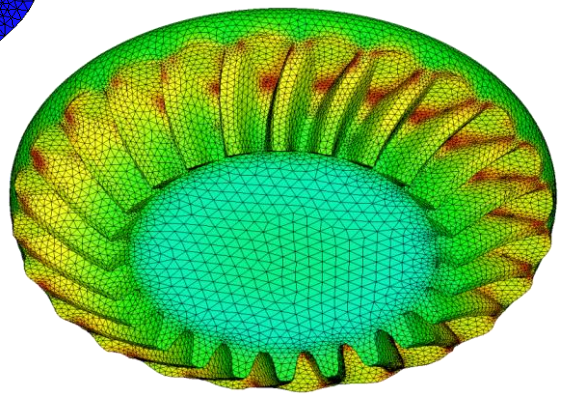
요소망재구성 - 경계조건 및 특성경계의 유지

요소망재구성 시 경계조건 유지는 **결과의 정확도**와 직결

작은 수의 요소 수로 **형상을 정확하게 표현**하는 것이 모든 면에서 유리

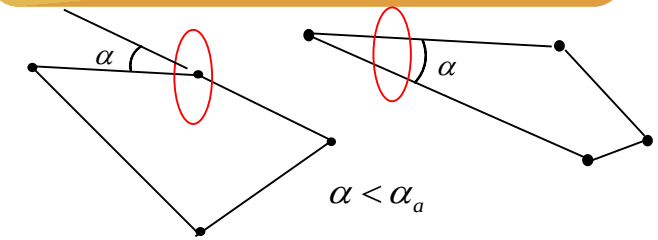




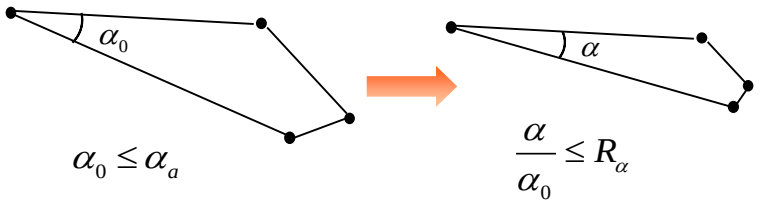


요소망재구성 기준

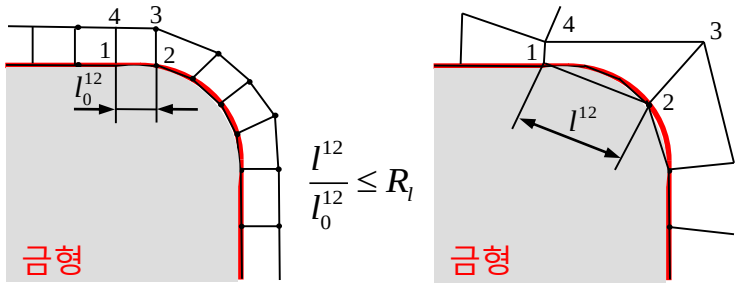
기준 1 – 요소의 각도



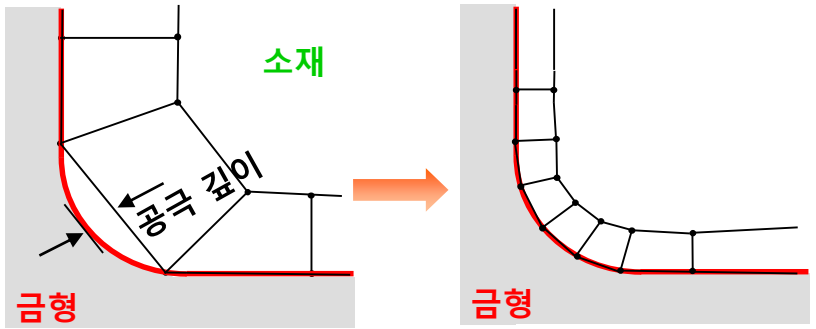
기준 2 – 요소의 상대각도 변화율

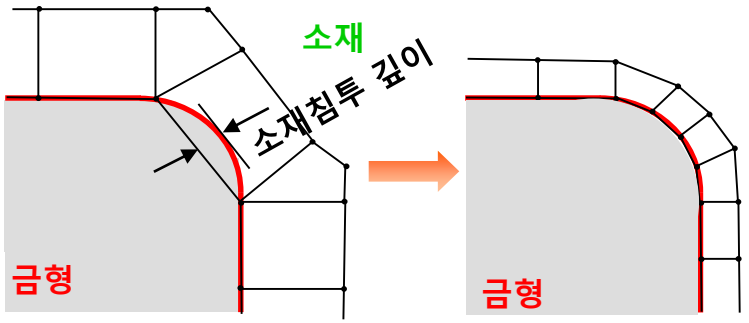


기준 3 – 표면의 최대 길이 변형률

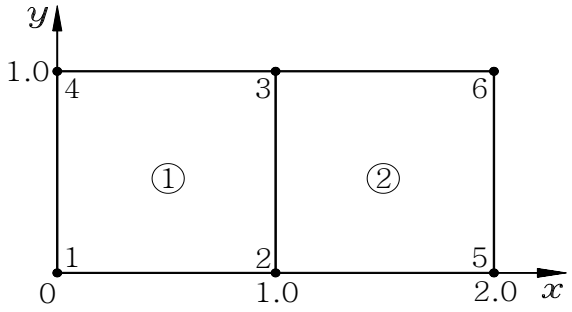


기준 5 – 공극 및 소재침투 깊이

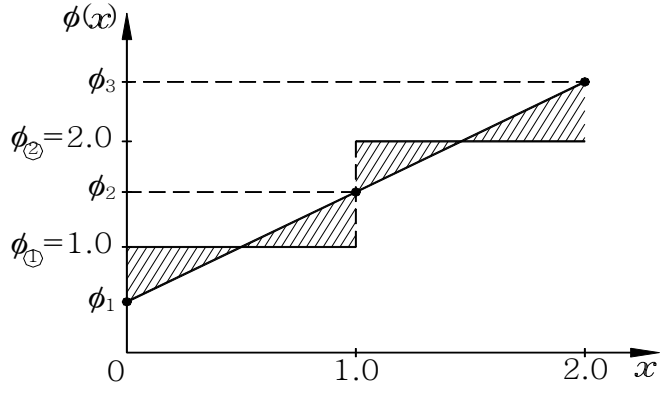


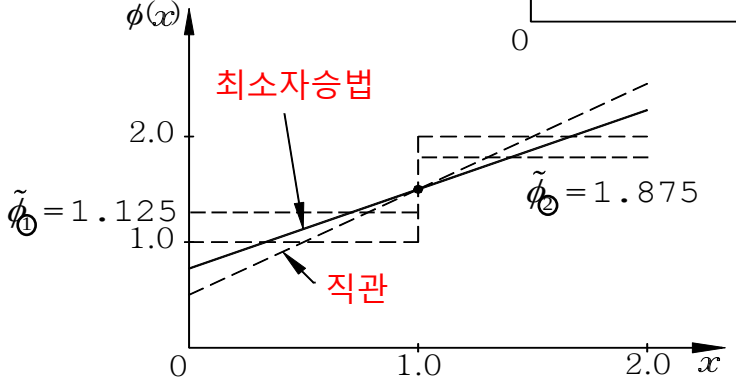


요소망재구성과 수치적 순화



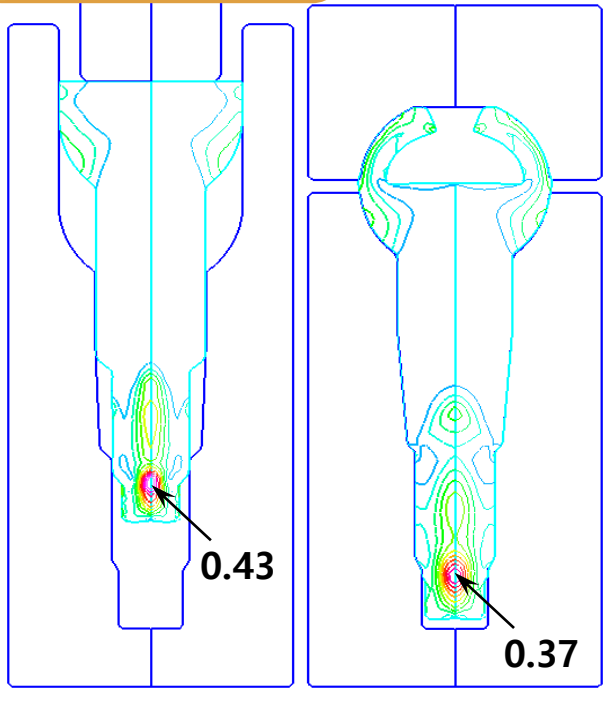
요소 경계에서 응력, 변형률, 변형률속도 등은 불연속임. 변형률, 손상도 등과 같은 이력변수는 요소망재구성으로 수치적 순화 불가피함





국부요소망재구성 및 전체요소망재구성 균형 필요

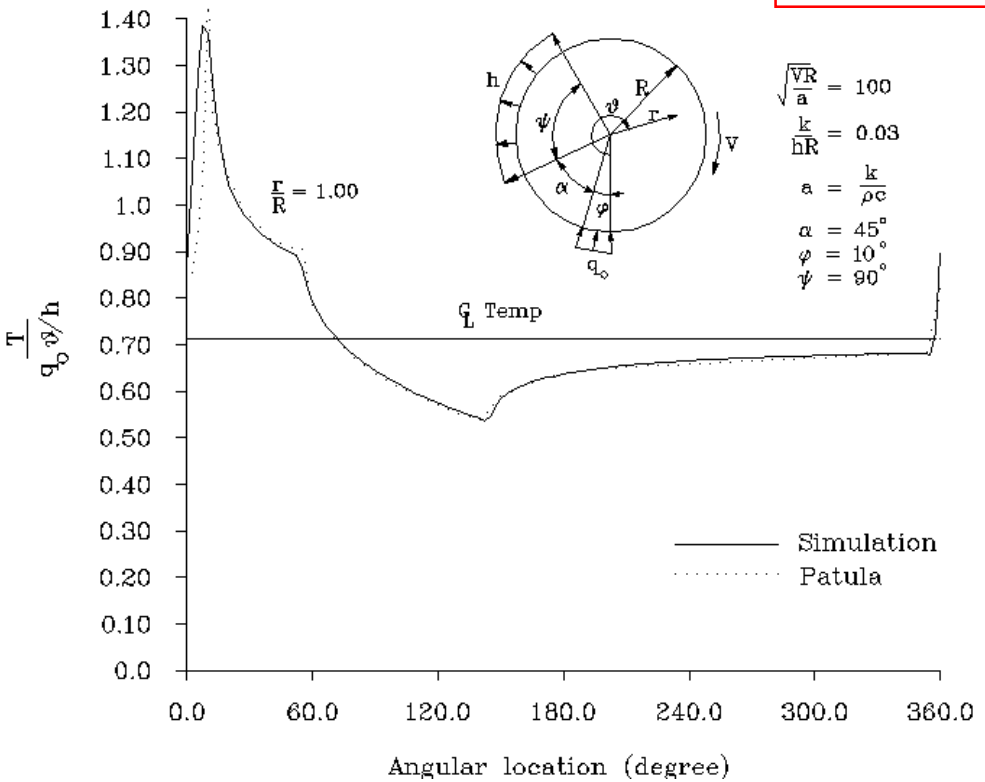
손상도 순화의 예



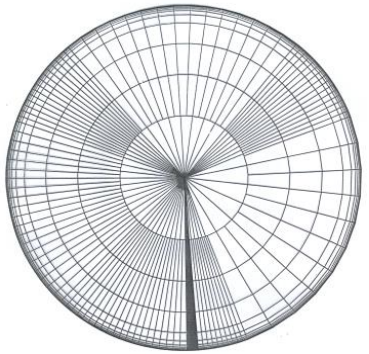
온도해석 시의 표면요소 밀도

이론해와 유한요소해의 비교

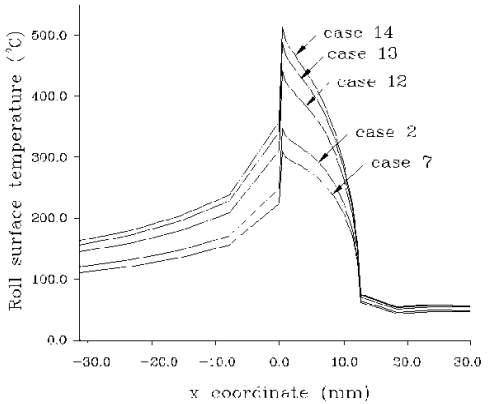
$$-k\frac{\partial T}{\partial n} = h\Delta T$$



유한요소 해석모델

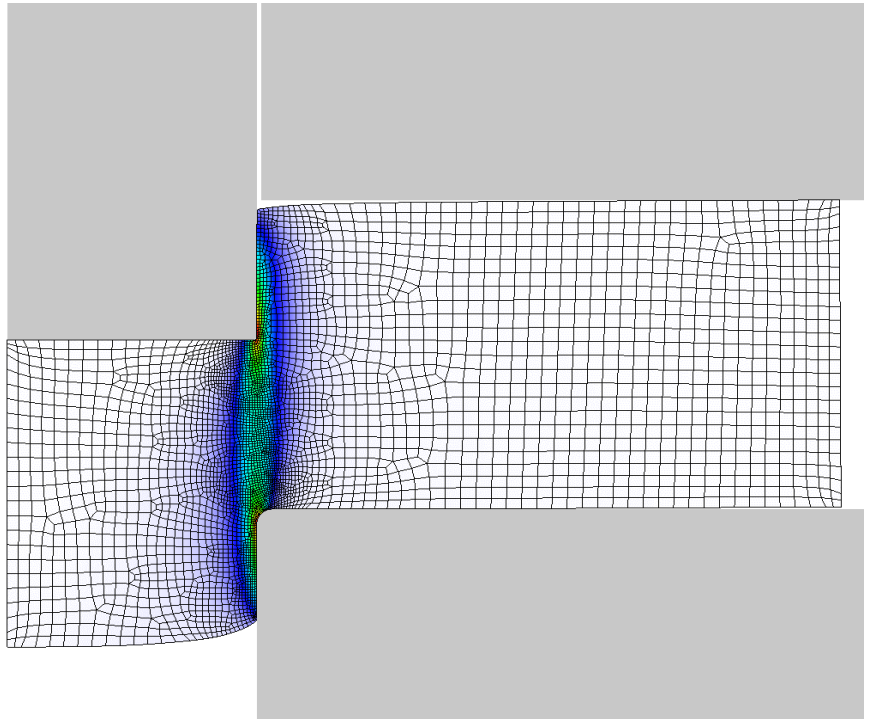


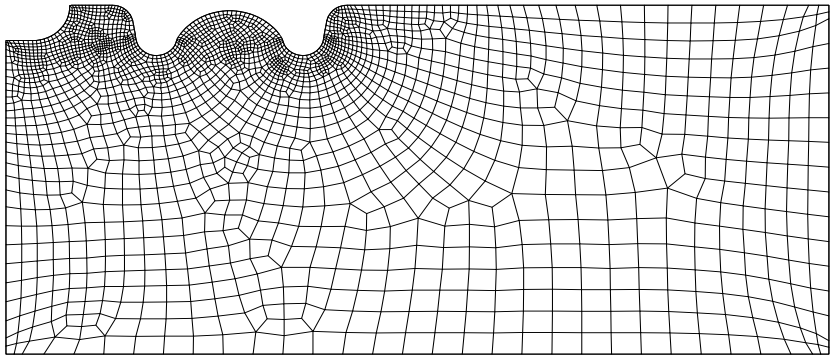
박판압연중 롤의 온도분포

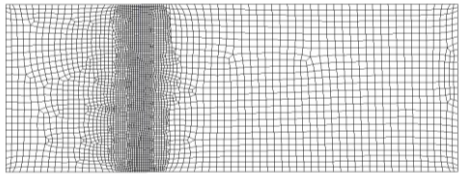


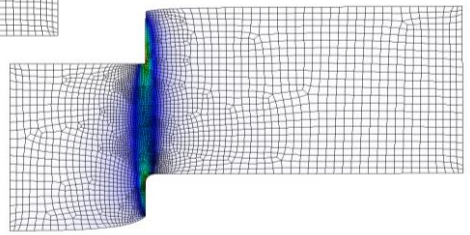
"일반적인 요소로 소재 표면 주위의 온도 분포를 정확하게 예측하는 것은 불가능"

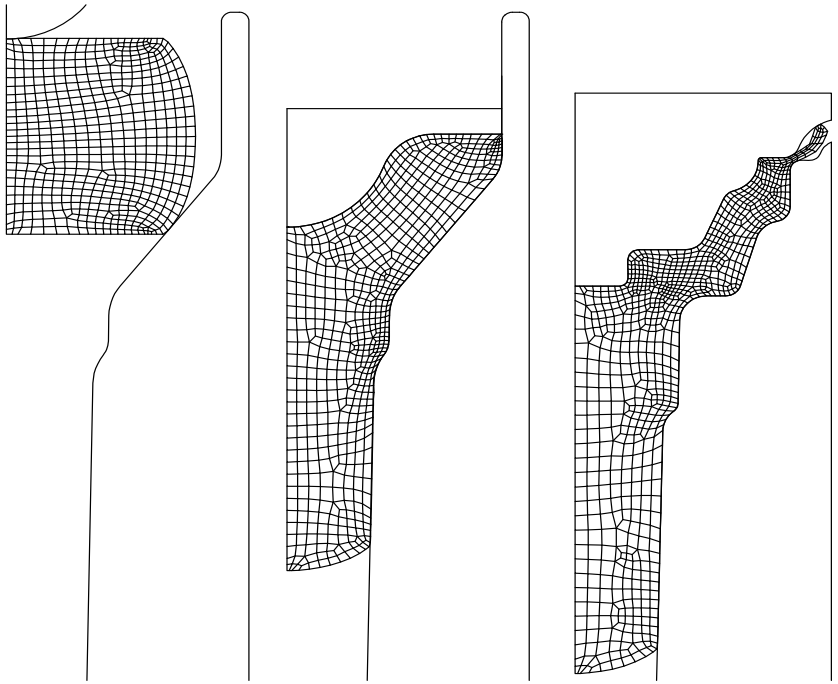
지능적 요소망 사례 - 1. 2D, 사각형요소



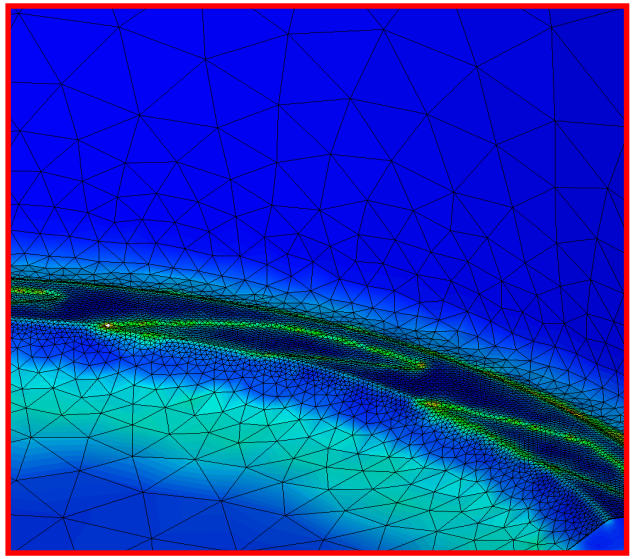




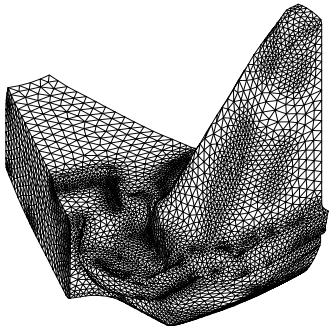


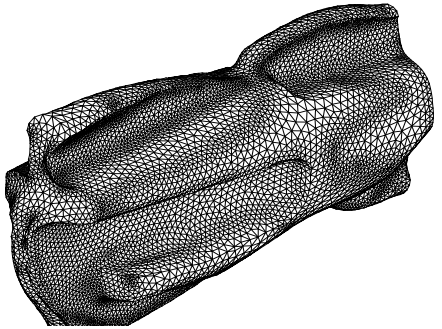


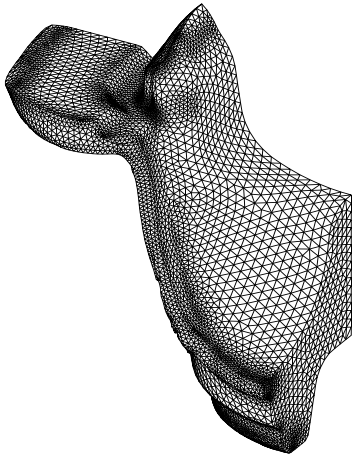
지능적 요소망 사례 – 2. 3D, 사면체요소

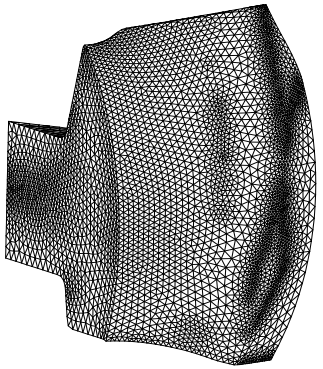


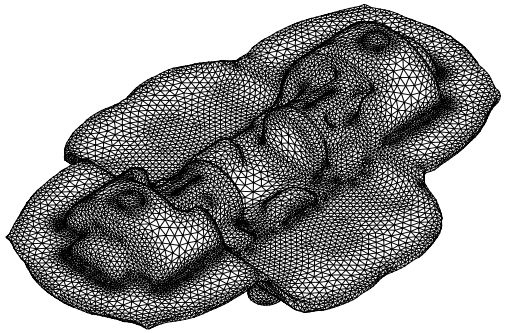
“보기에 좋은, 보기에 자연스러운 요소가
답에도 유리”



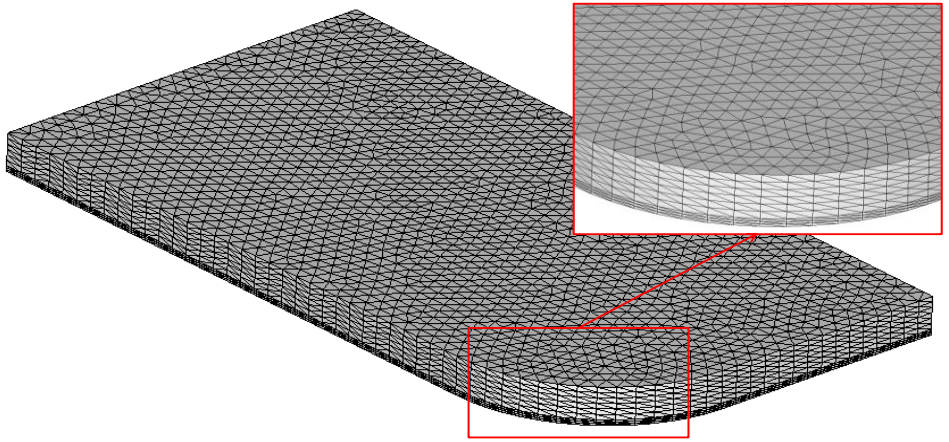


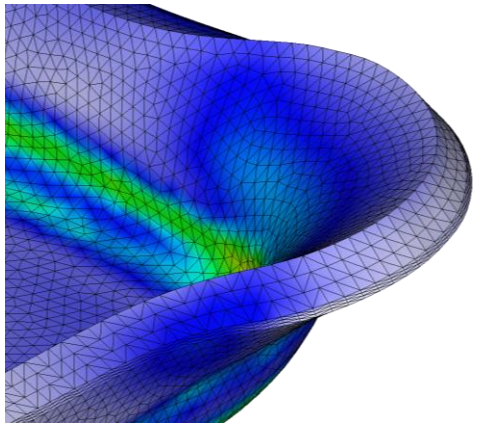


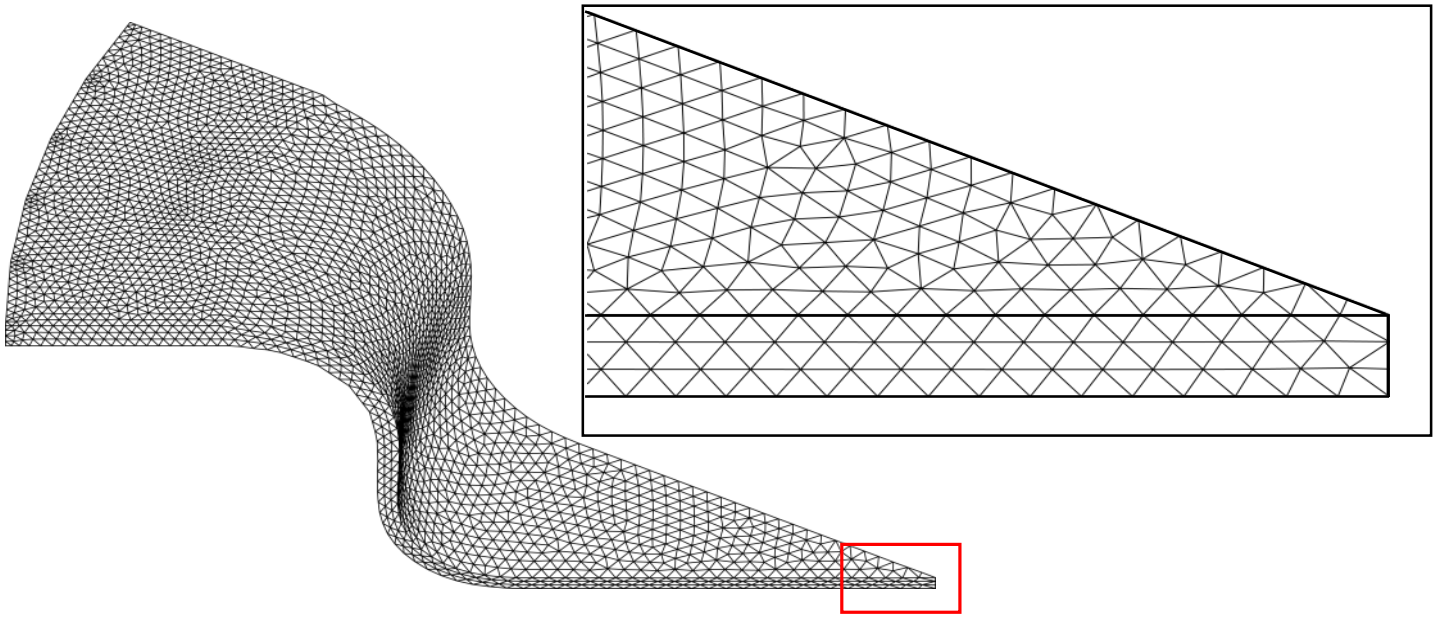




지능적 요소망 사례 - 3. 판재의 요소망 생성 - 적층요소







2.
차원과 단위

차원

- 기본차원 : [Length] ≡ [L], [Mass] ≡ [M] 또는 [Weight] ≡ [F] , [Time] ≡ [T]

단위계

- 과학단위계 : [L], [M], [T]
- 전통단위계 : [L], [F], [T]

영국단위

- 기초단위: ft, lb, sec
- 전통단위의 대표 주자. lb는 기본적으로 lbf(pound force)를 의미함
  질량의 단위: slug = lb $\cdot \sec^2$/ft

SI 단위(The International System of Units)

- 기초단위 : m, kg, s
- kg은기본적으로 kg_m(kilogram mass)를 표현하기 위하여 정의됨

단위

기초단위

- Length : m, ft
- Mass : kg, slug
- Time : s, sec
- Current : A
- Temperature : K
- Voltage : V

보조단위

- rad

조립단위

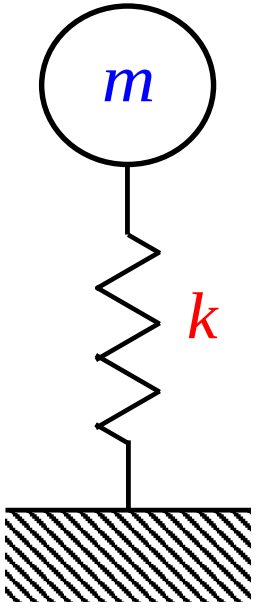
- 속도 : m/s, ft/sec
- 압력 : 1Pa = 1N/m^2, psi = lb/in^2, kg/mm^2
- 동력 : 1W = 1J/s, lb · ft/sec, kg · m/s, hp
- 힘 : 1N = 1kg · m/s^2, lb, kg
- 일 : 1J = 1N · m, lb · ft, kg · m
- 모멘트 : N · m, kg · m

단위계수

- T(10^{12}), G(10^9), M(10^6), k(10^3), c(10^{-2}), m(10^{-3}),(10^{-6}), n(10^{-9}), p(10^{-12})

"모든 단위는 **로만체**로 쓰여져야 함. 반면, 변수는 **이탤릭체**(실수변수) 또는 **굵은 글씨체**(벡터, 행렬)로 쓰여져야 함"

사례 - 1. 왜 규칙을 지켜야 하는가?



$$\omega_n = \sqrt{\frac{k}{m}}, \quad k = 1\text{kg}/\text{mm}, \quad m = 1\text{kg}$$

$$\omega_n = \sqrt{\frac{1\text{kg}_\text{f}/\text{mm}}{1\text{kg}_\text{m}}} = \sqrt{\frac{1\text{kg}_\text{m}\ g}{1\text{kg}_\text{m}\ \text{mm}}}$$

$$= \sqrt{\frac{1\cancel{\text{kg}_\text{m}} \times 10^4\ \cancel{\text{mm}}}{1\cancel{\text{kg}_\text{m}}\ \cancel{\text{mm}} \cdot \text{s}^2}} = 100\ \frac{1}{\text{s}} = \frac{50}{\pi}\text{Hz}$$

사례 - 2. 공학단위와 과학단위의 혼용으로 인한 실수

지구중력가속도 단면적

질량 압력 거리

$E = (m \times g + p \times A)H$

$E = (35200kg \times 9.8 + 7kg/㎠ \times 8532.3㎠)0.62m$

$= (344960kg + 59936kg)0.62$

$E = 251{,}035kg.m = 2{,}460{,}143\ N\text{-}m$

$E = (mg + pA)H$

$E = (35200kg \times 9.8m/s^2 + 7kgf/㎠ \times 8532.3㎠) \times 0.62m$

$= (344960N + 59726kgf \times 9.8N/kgf) \times 0.62m$

$= 576770\ Nm = 577000\ Nm$

사례 - 3. 인터넷에 떠돌고 있는 잘못된 강의노트에서

원래의 자료

$$\cancel{F} = m\cancel{a} \quad \Rightarrow \quad \cancel{N} = \cancel{kg} \cdot \cancel{m} / \cancel{\sec}^2$$

$$W(weight) = m(\cancel{kg}) \times g(\cancel{m} / \cancel{\sec}^2), \quad g = 9.806.\cancel{m} / \cancel{\sec}^2$$

정정된 자료

$$\mathbf{F} = m\mathbf{a} \quad \Rightarrow \quad \mathrm{N} = \mathrm{kg} \cdot \mathrm{m} / \mathrm{s}^2$$

$$W(\mathrm{weight}) = m(\mathrm{kg}) \times g(\mathrm{m} / \mathrm{s}^2), \quad g = 9.806 \mathrm{m} / \mathrm{s}^2$$