Topology Optimization

Computational Design Laboratory
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    compliance minimization problem
    volume minimization problem
    eigenvalue maximization problem

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    volume minimization problem

- 해석 프로세스

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  - 재료 물성 및 특성 입력
  - 요소망 생성
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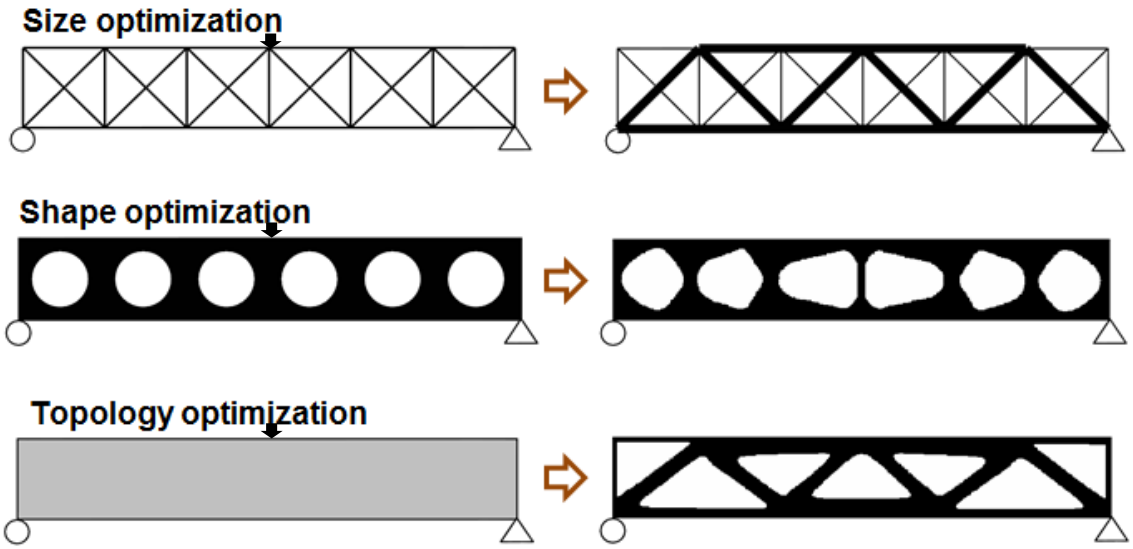
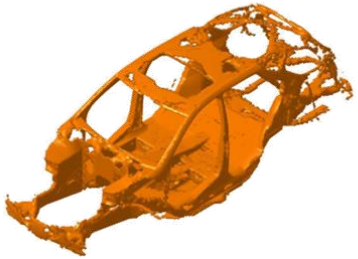
  - 최적설계 문제 정식화 및 최적설계 실행
  - 후처리

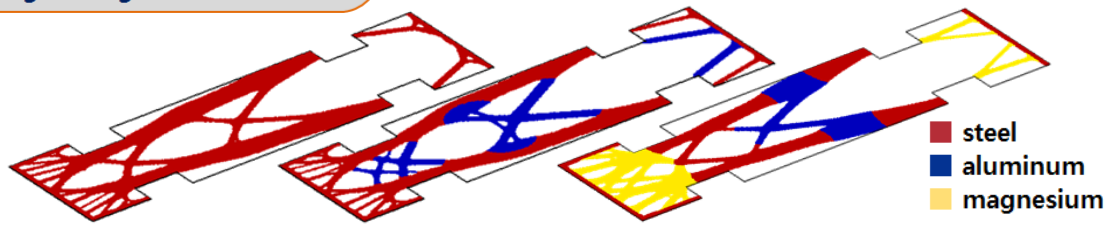
TOPOLOGY OPTIMIZATION



BIW design for weight reduction



Underbody design using light-weight material



TOPOLOGY OPTIMIZATION: NFX

표 5.11.1 목적함수에 따른 문제구성 종류

목적함수	설계 제약조건	관련 해석	제조조건(공통)
정적 컴플라이언스(최소)	부피비	· 선형 정적 해석	
동적 컴플라이언스(최소)	부피비	· 주파수 응답 해석	
부피비(최소)	변위/응력	· 선형 정적 해석 · 주파수 응답 해석 (변위제약)	· 성형 방향 · 대칭 조건 (1~3축 대칭)
평균 고유치(최대)	부피비	· 모드 해석	
부피비(최소)	모드	· 모드 해석	

표 5.11.2 재료 보간 방법

	SIMP solid isotropic material with penalization	RAMP[12] rational approximation of material properties
보간식	$k_e(x_e) = x_e^p k_{e0}$	$k_e(x_e) = \frac{x_e}{1+q(1-x_e)} k_{e0}$
미분식	$\frac{\partial k_e}{\partial x_e} = p x_e^{p-1} k_{e0}$	$\frac{\partial k_e}{\partial x_e} = \frac{1+q}{\left[1+q(1-x_e)\right]^2} k_{e0}$
관련해석	선형 정적	모달, 주파수 응답
벌칙계수	$p = 3.0 \sim 4.0$	$q = 5.0 \sim 6.0$

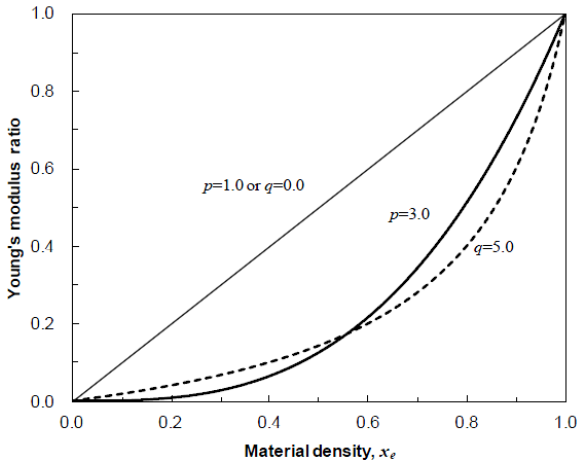


그림 5.11.1 재료보간모델별 밀도에 따른 강성비

TOPOLOGY OPTIMIZATION: NFX

최적화 문제 구성

최적화 문제 구성 예

목적함수	부피 최소화
구속조건	변위제한 0.05mm
설계변수	요소 형상 밀도

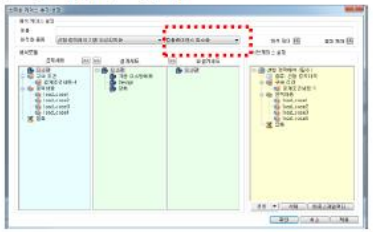
➢ 위상최적화란?

최적설계를 하고자 하는 설계영역의 구속조건과 설계변수를 설정하고 목적함수를 만족하는 최적모델을 생성하는 해석입니다

➢ 최적화 문제 구성

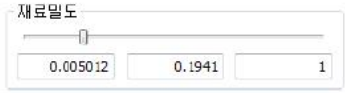
- 목적함수는 부피나 질량과 같이 줄이거나 키우고 싶은 값을 의미합니다.
- 구속조건은 변위나 응력처럼 만족해야 하는 설계조건을 의미합니다.
- 설계변수는 치수나 재료 특성처럼 결정해야 할 설계인자들입니다.

① 목적함수 정의



② 구속조건 정의

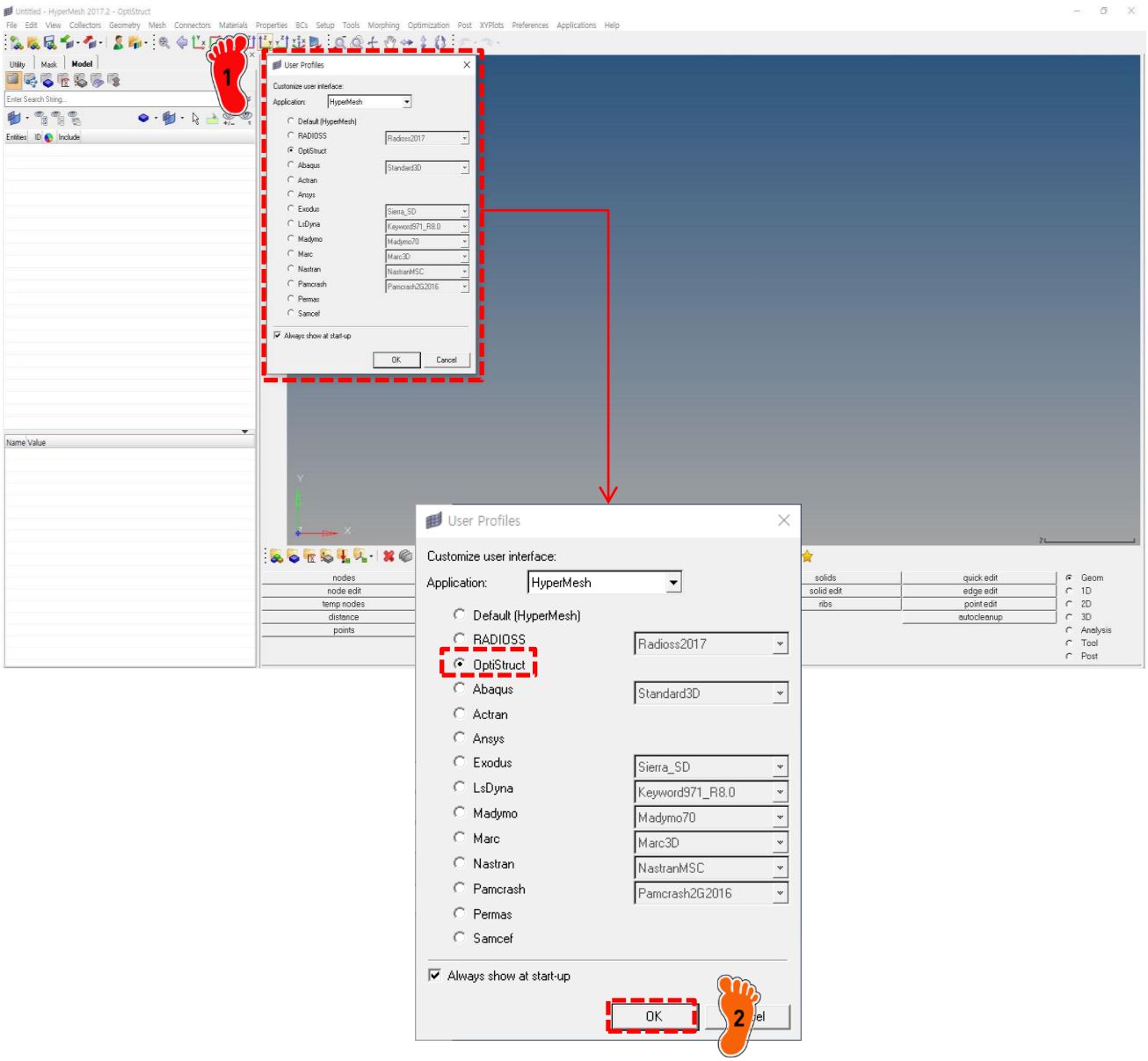
③ 설계변수 정의



2D STRUCTURE

목적함수: 컴플라이언스 최소화
구속조건: 부피율

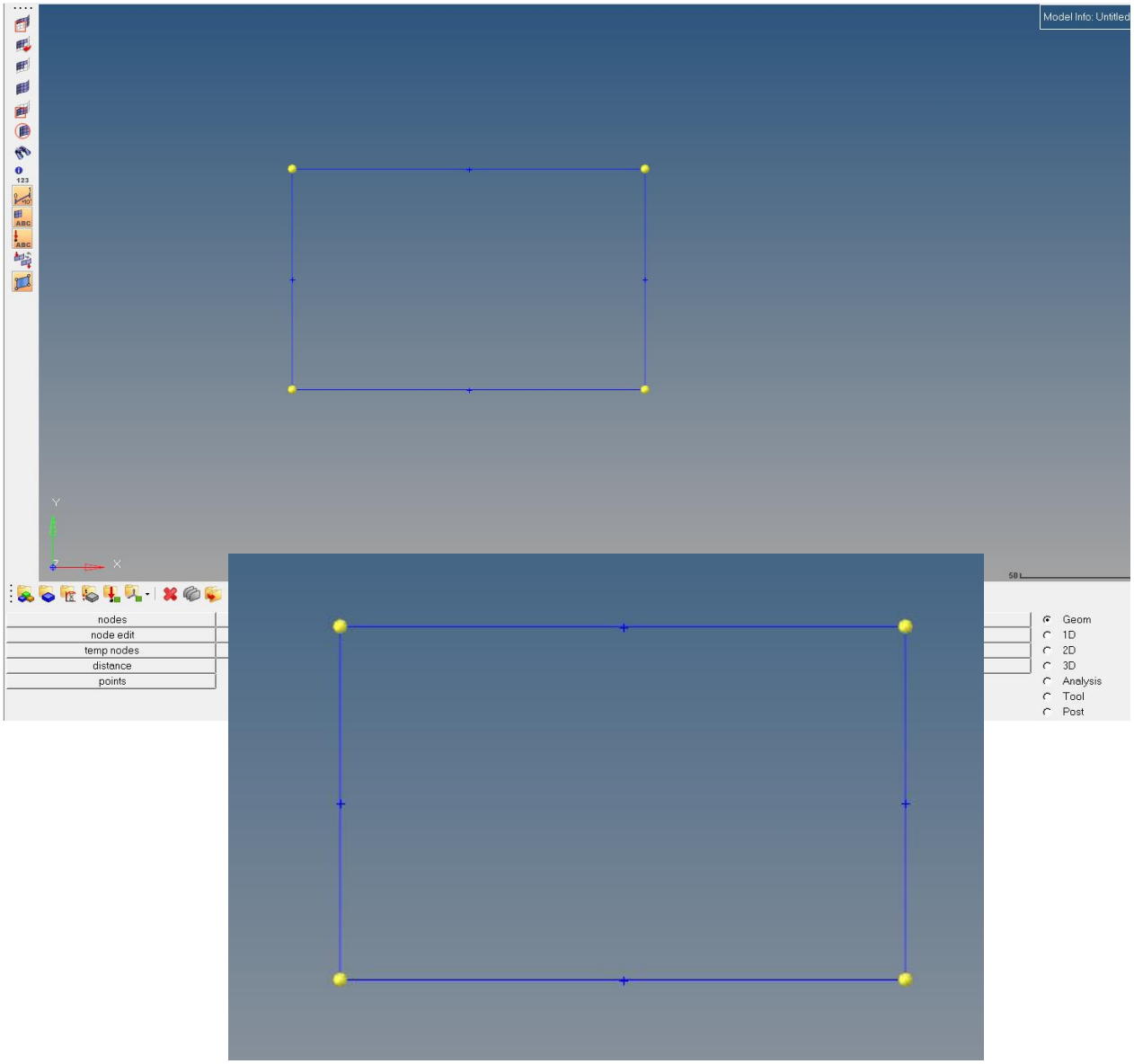
기하형상 생성 (1)



1 OptiStruct 선택

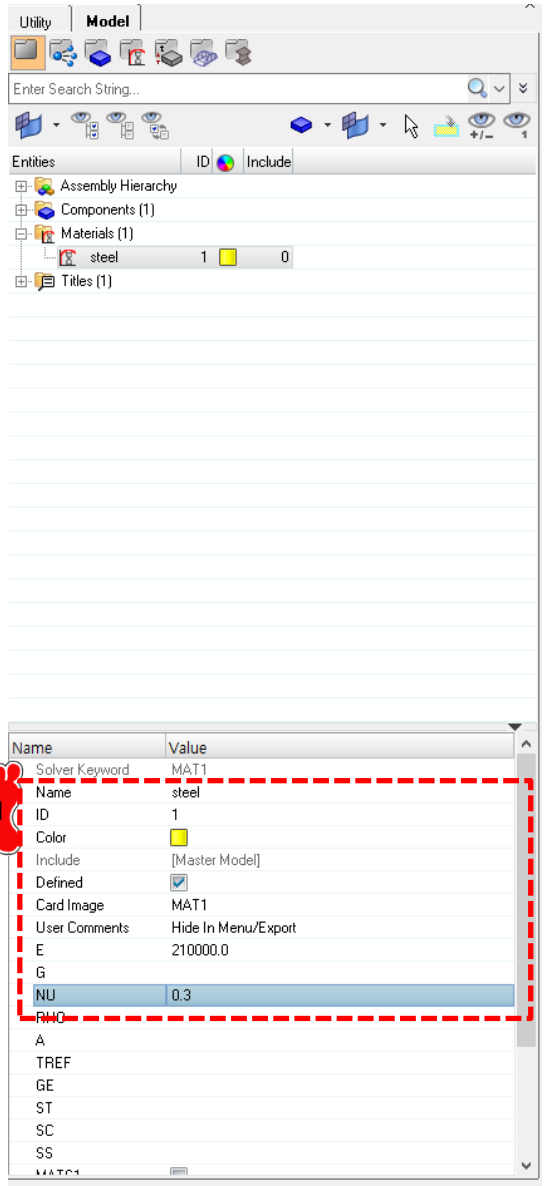
2 OK

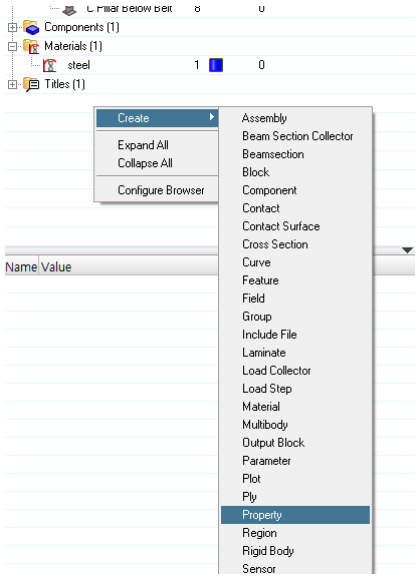
기하형상 생성 [2]

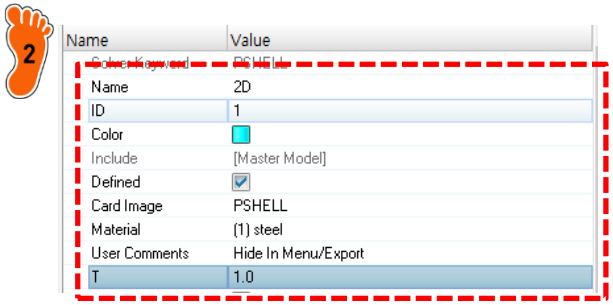


1 (0,0,0),(160,0,0),(160,100,0), (0,100,0) 노드 생성
라인 생성

재료 물성 및 특성 입력



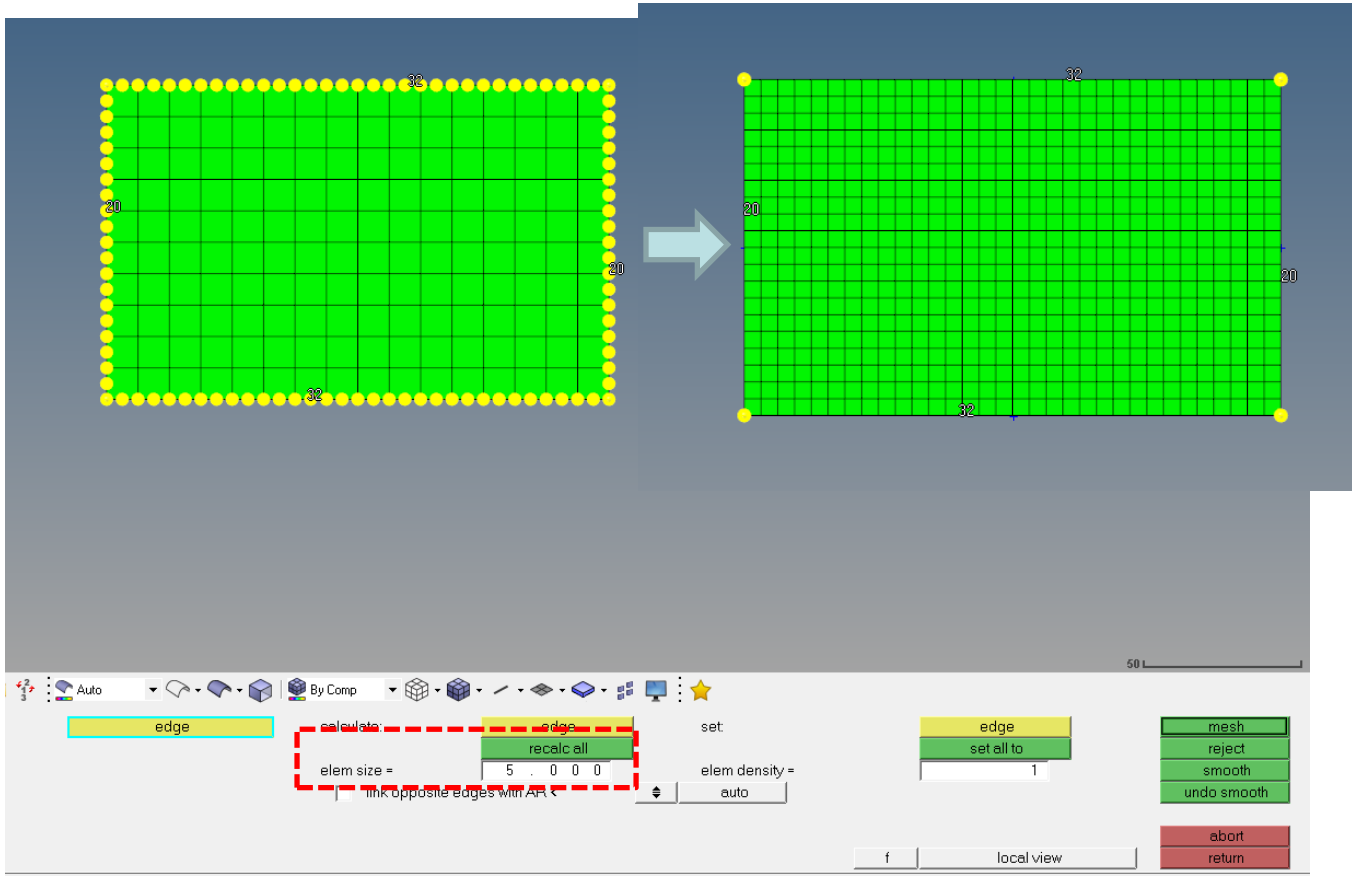




1 우클릭, Create > Material
Name > steel
탄성계수(E)
>210 Gpa (210000 N/mm^2)
푸아송비(NU) > 0.3
재료 생성

2 Create > Property
Card Image > PSHELL
Material > steel
T > 1mm
Name > 2D

요소망 생성

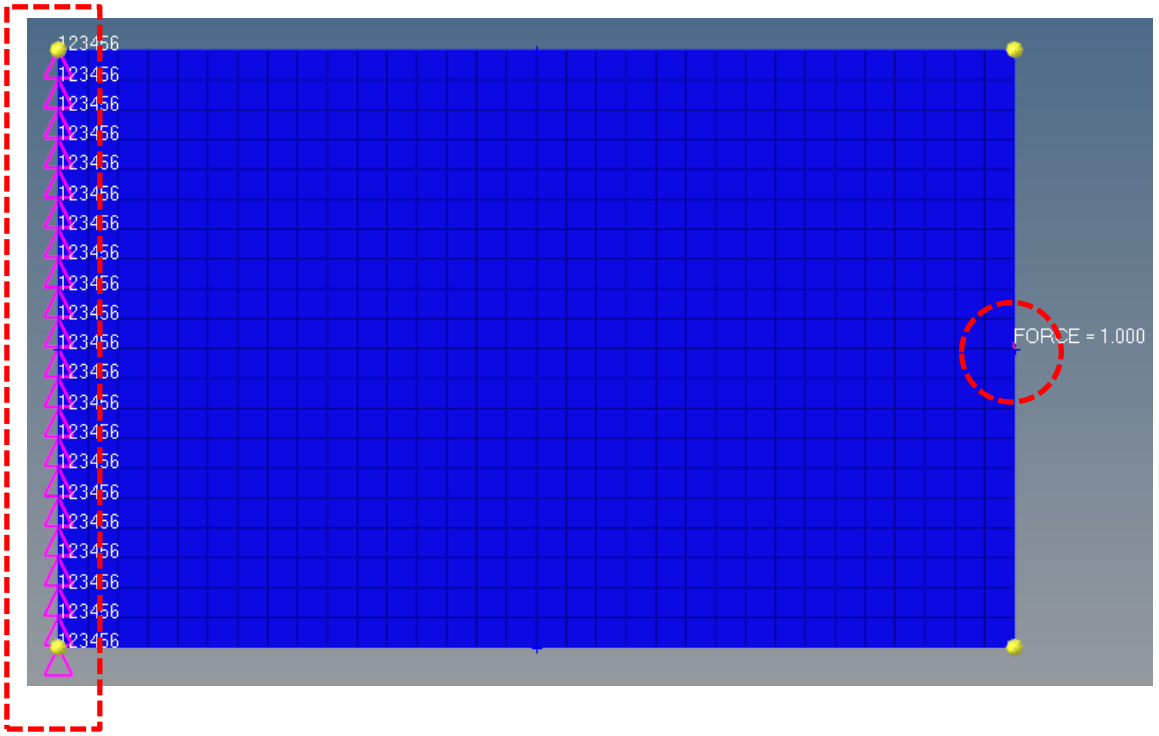


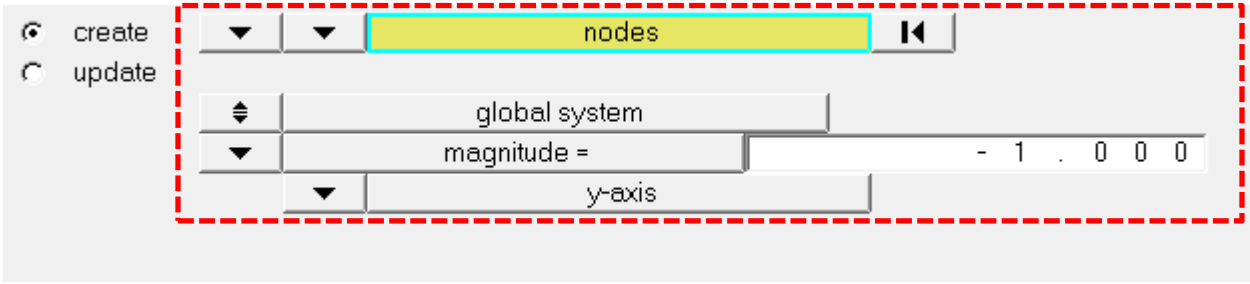
1 크기 5인 2차원 요소망 생성

2D > planes > 4개 line 선택 > create

Elem size > 5 > recalc all > mesh > return

구속조건 및 하중조건 설정





1 Load Collectors
Name > SPC
BCS > Creates > Constraints
고정구속

2 Load Collectors
Name > load
BCS > Creates > Forces
가운데 절점에 Y방향 단위 하중 (-1N) 입력

Load steps
Analysis type
> Linear Static
SPC > SPC
LOAD > load

DESIGN VARIABLE SETTING

1 Analysis > optimization > topology

create

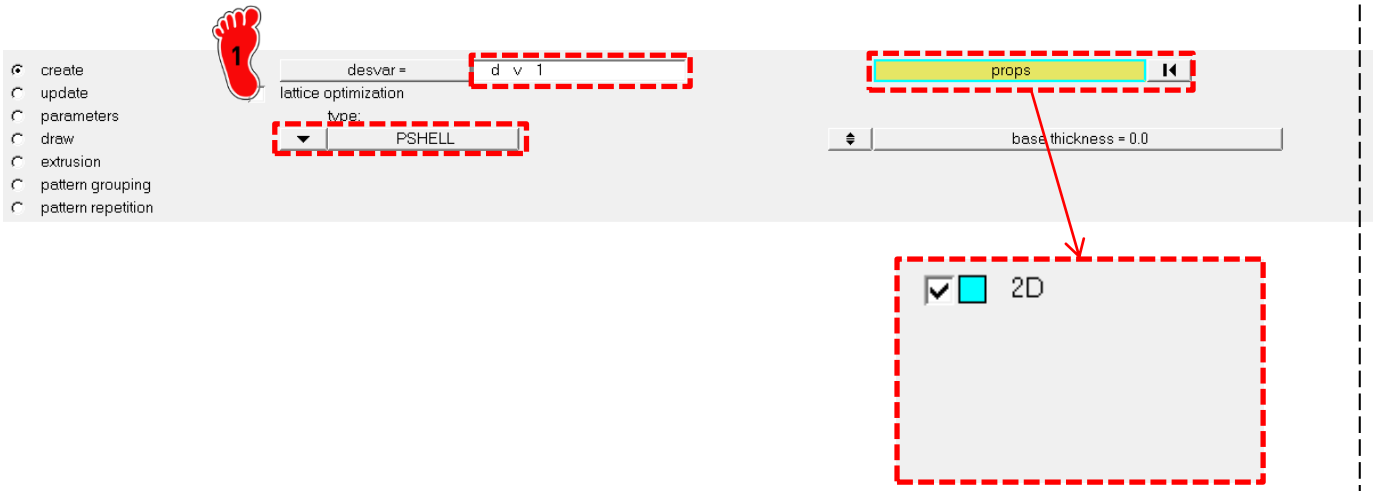
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



RESPONSE SETTING (1)

1 Analysis > optimization > Responses

create

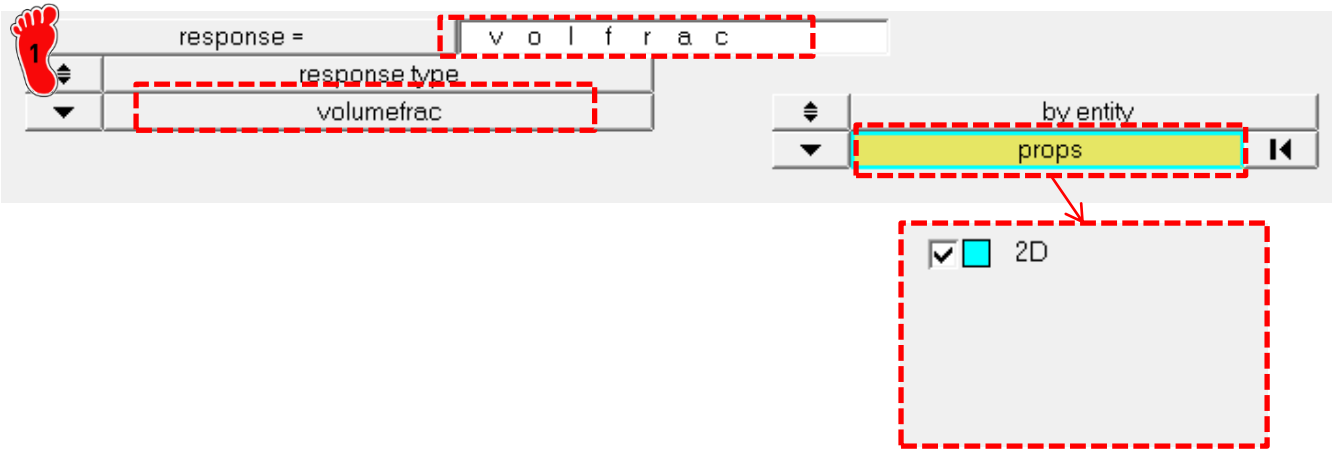
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



RESPONSE SETTING (2)

→ **Design variable**

→ **Responses**

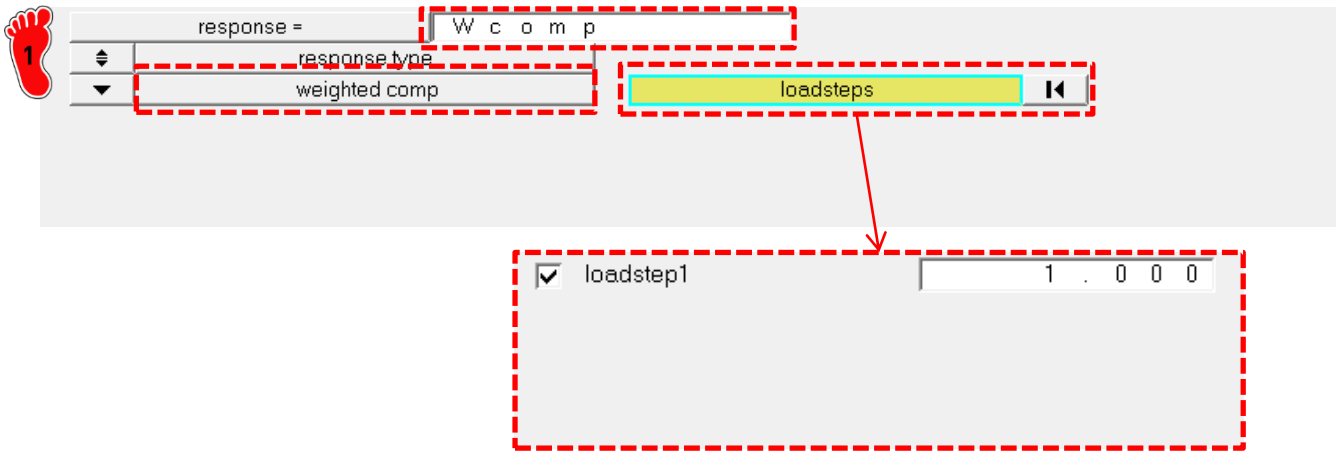
→ **Objective**

→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Responses

create



OBJECTIVE SETTING

→ **Design variable**

→ **Responses**

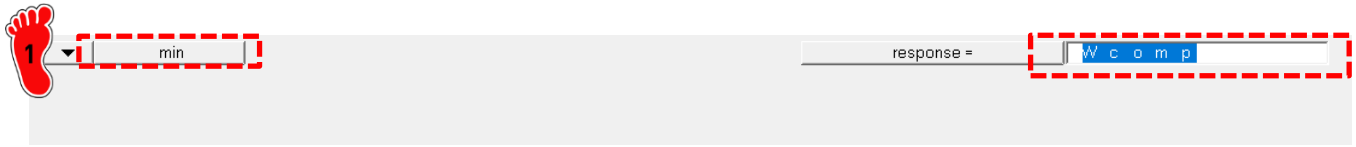
→ **Objective**

→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Objective

create



CONSTRAINTS SETTING

→ **Design variable**

→ **Responses**

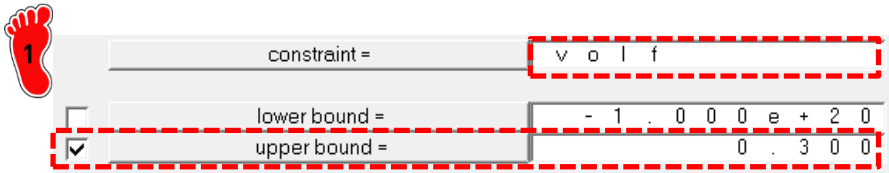
→ **Objective**

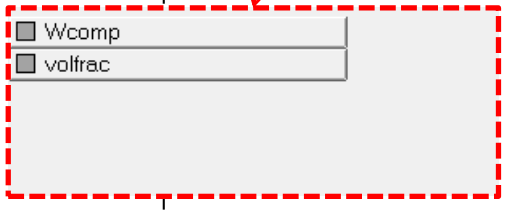
→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Dconstraints

create





CONTROL SETTING

1 Analysis > optimization > Dconstraints

create

→ **Design variable**

→ **Responses**

→ **Objective**

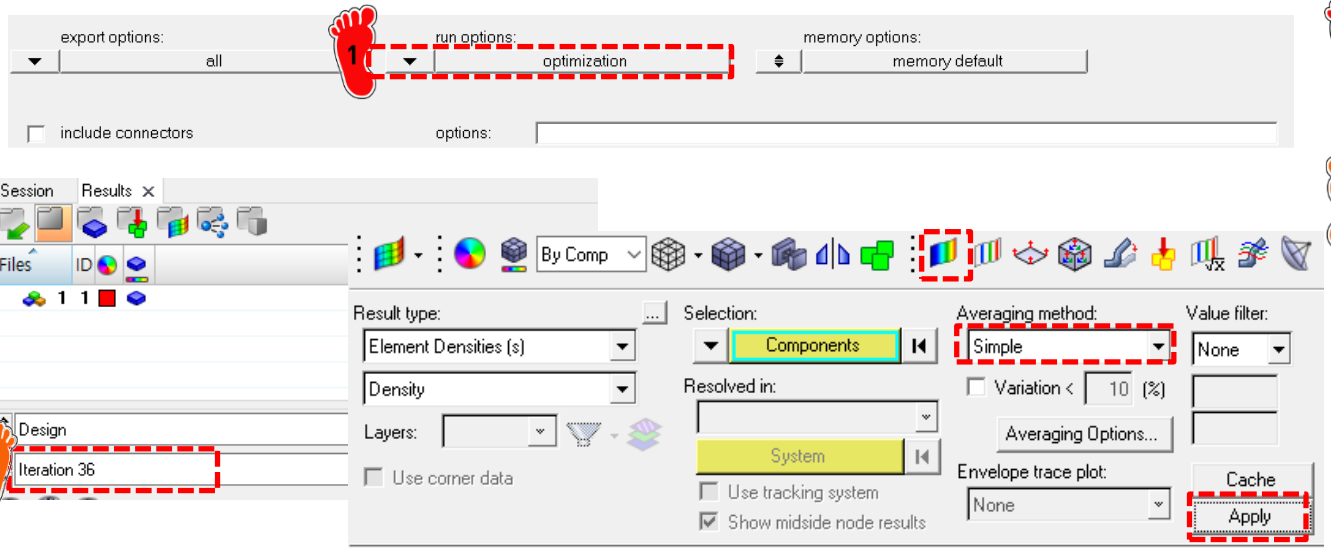
→ **Dconstraints**

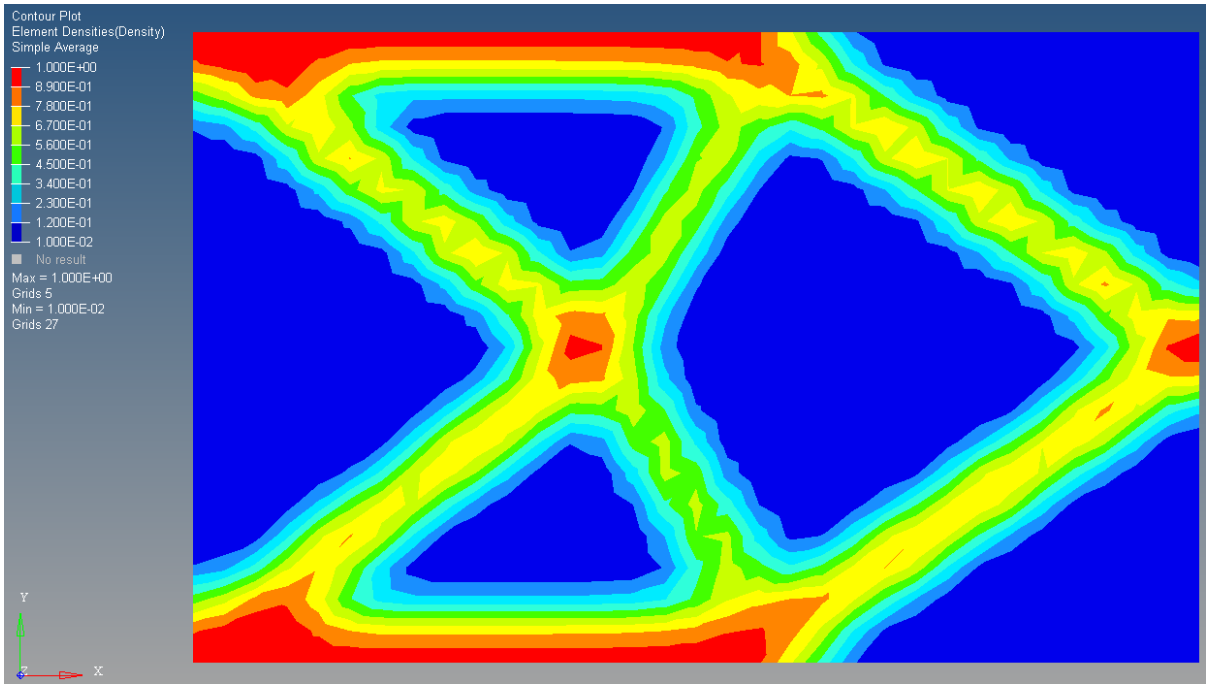
→ **Opti control**

1

☑	DESMAX=	50	☑	OBJTOL=	0.005
☐	MINDIM=	0.000	☐	DELSIZ=	0.500
☐	MATINIT=	0.600	☐	DELSHP=	0.200
☐	MINDENS=	0.010	☐	DELTOP=	0.500
☑	DISCRETE=	3.000	☐	GBUCK=	0
☑	CHECKER=	1	☐	MAXBUCK=	10
☐	MMCHECK=	0	☐	DISCRT1D=	1.000

후처리 [1]



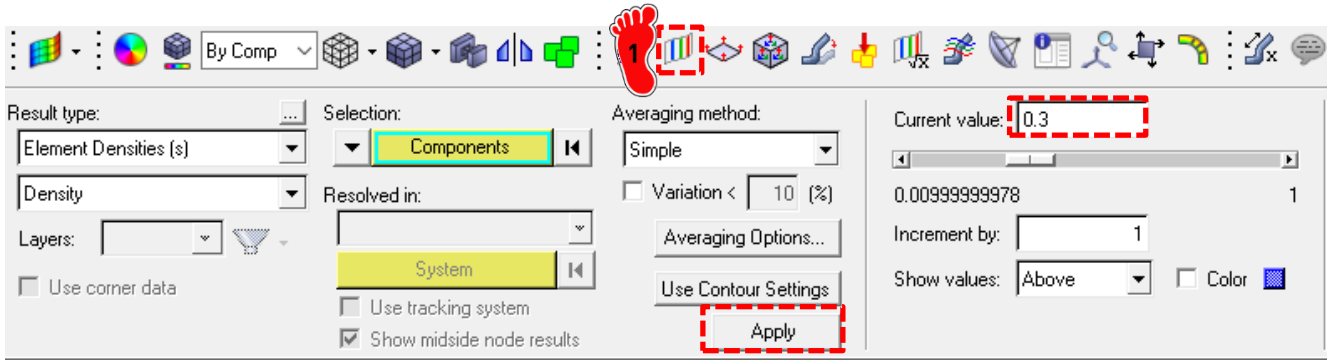


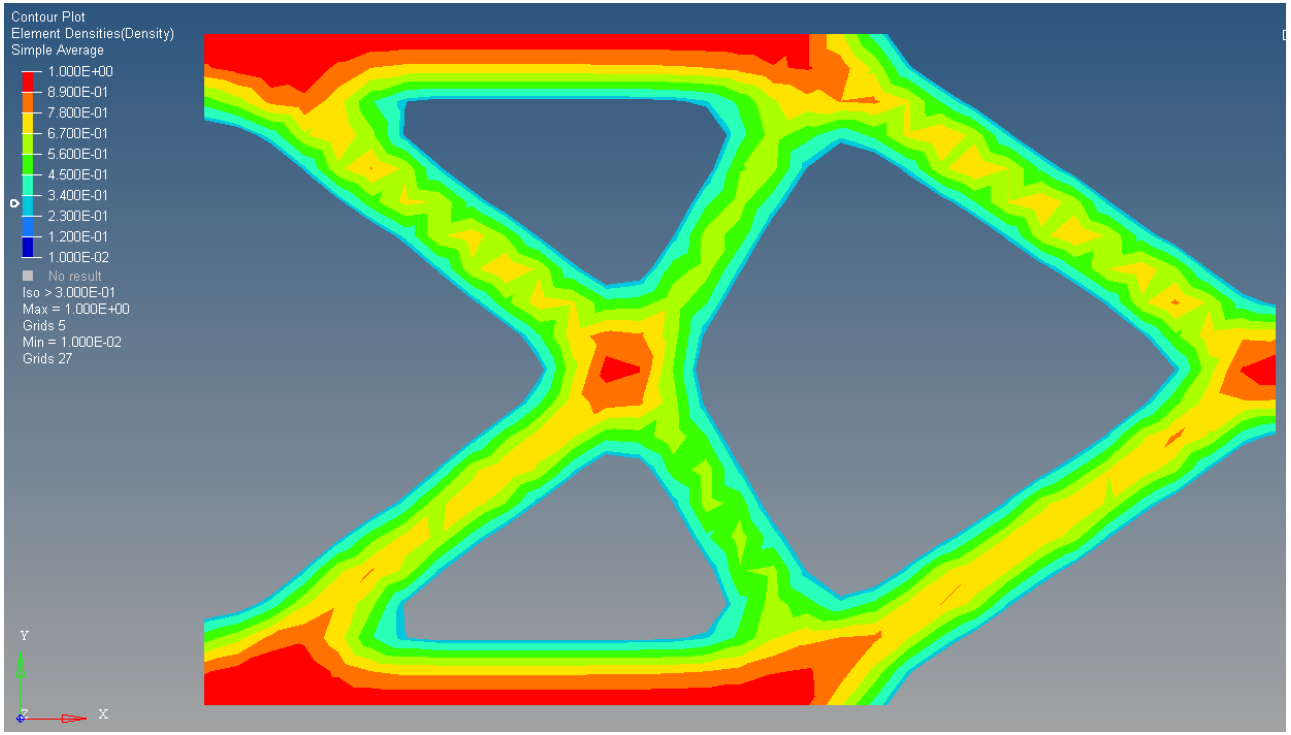
1 Analysis > optistruct

2 Iteration > 마지막 Iteration 선택

재료 밀도가 1에 가까울수록 중요한 파트라고 볼 수 있음

후처리 [2]





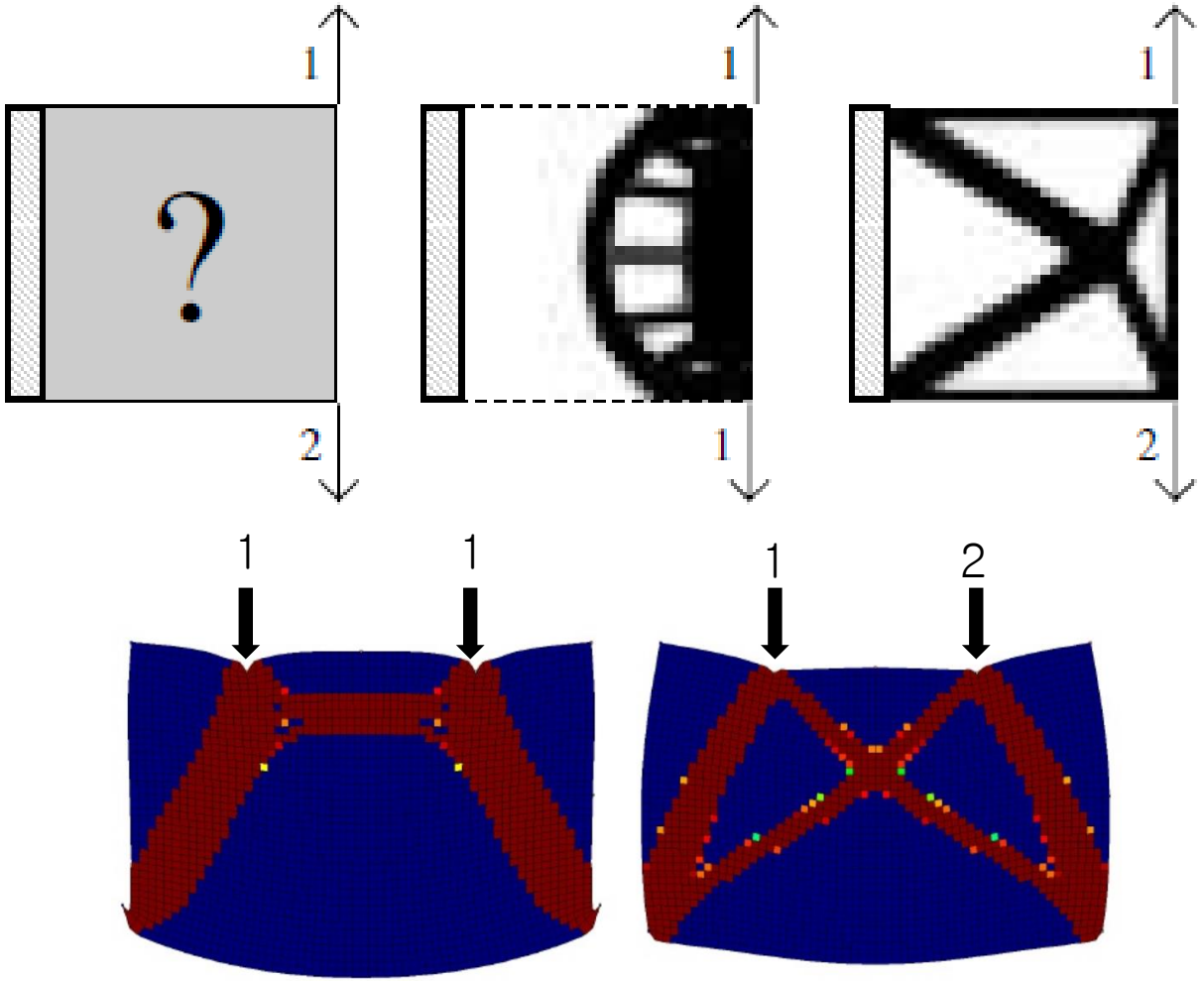
1 Iso
Current value > 0.3
Apply

2D STRUCTURE (다중 하중)

목적함수: 컴플라이언스 최소화
구속조건: 부피율

다중 하중 조건

- Combined load vs. Multiple loads

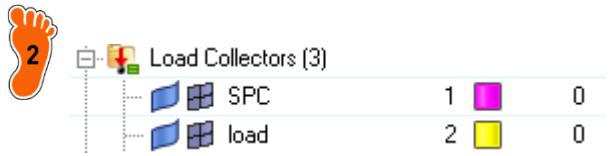


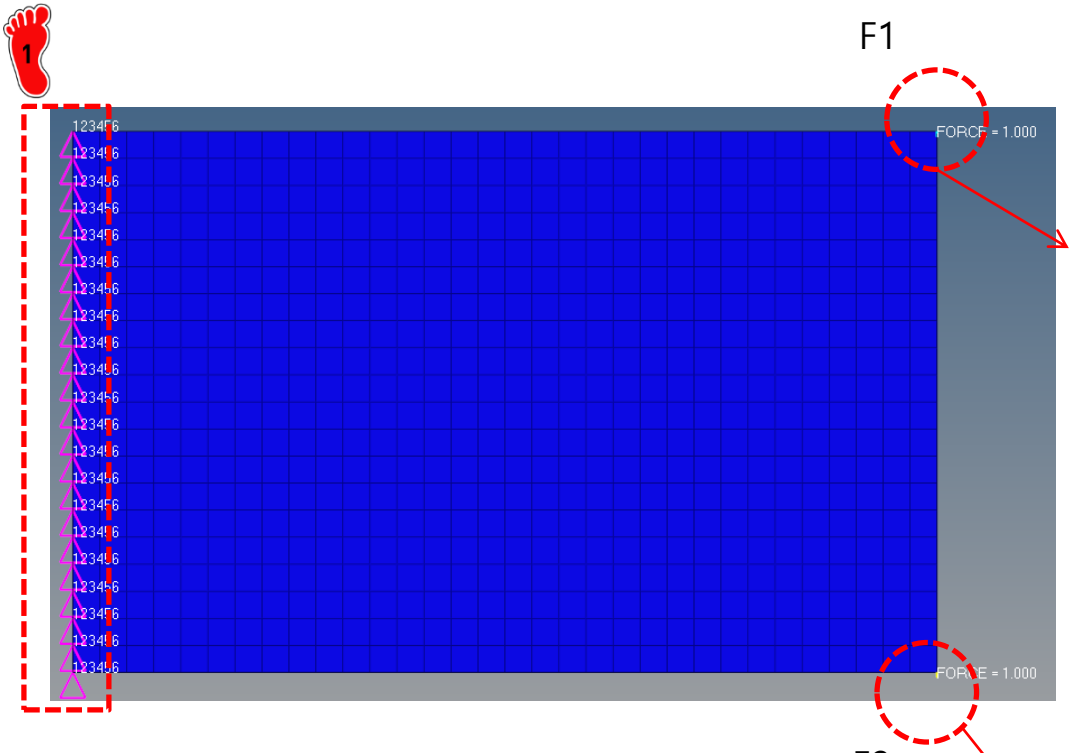
2001, O. Sigmund, “A 99 line topology optimization code written in Matlab”, *Struct. Multidisc. Optim.*, Vol. 21
2008, F. Wein, “Topolgy Optimization Using the SIMP Method”, Presentation at LSE

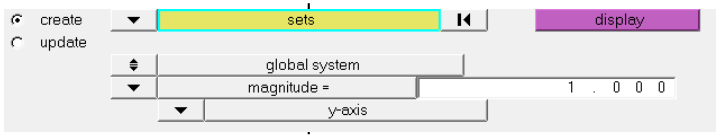
구속조건 및 하중조건 설정

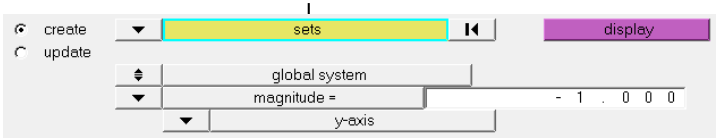
1 고정구속

2 load collectors 생성

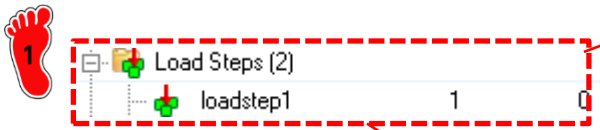








구속조건 및 하중조건 설정



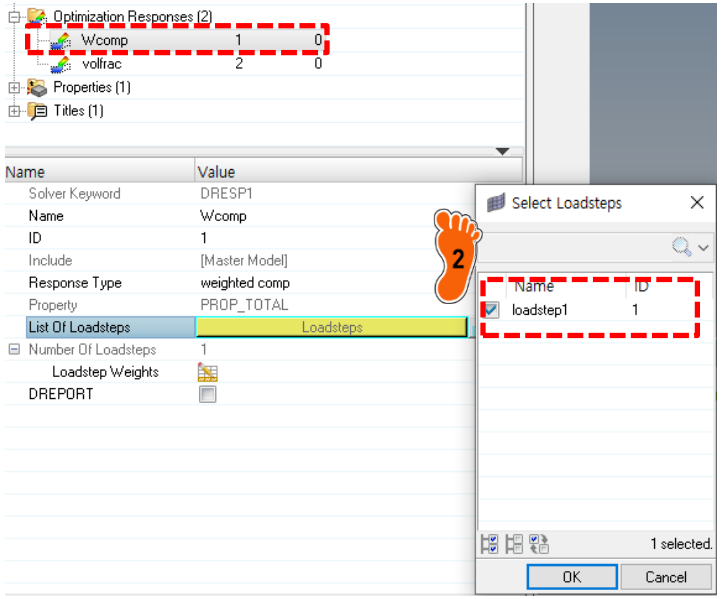
Analysis type	Linear Static
SPC	(1) SPC
LOAD	(2) load

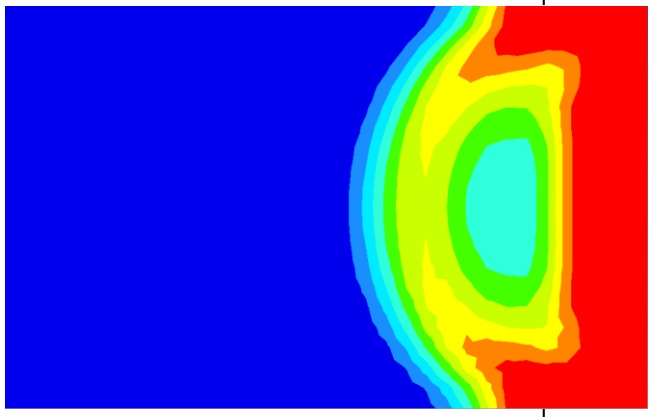
1 load step 생성

Analysis type	Linear Static
SPC	(1) SPC
LOAD	(3) load2

2 Loadstep1 check

optimization

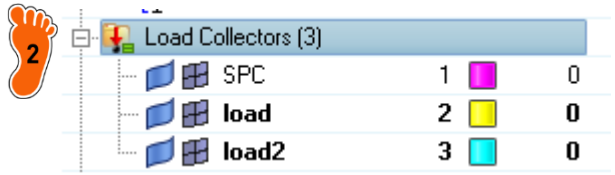


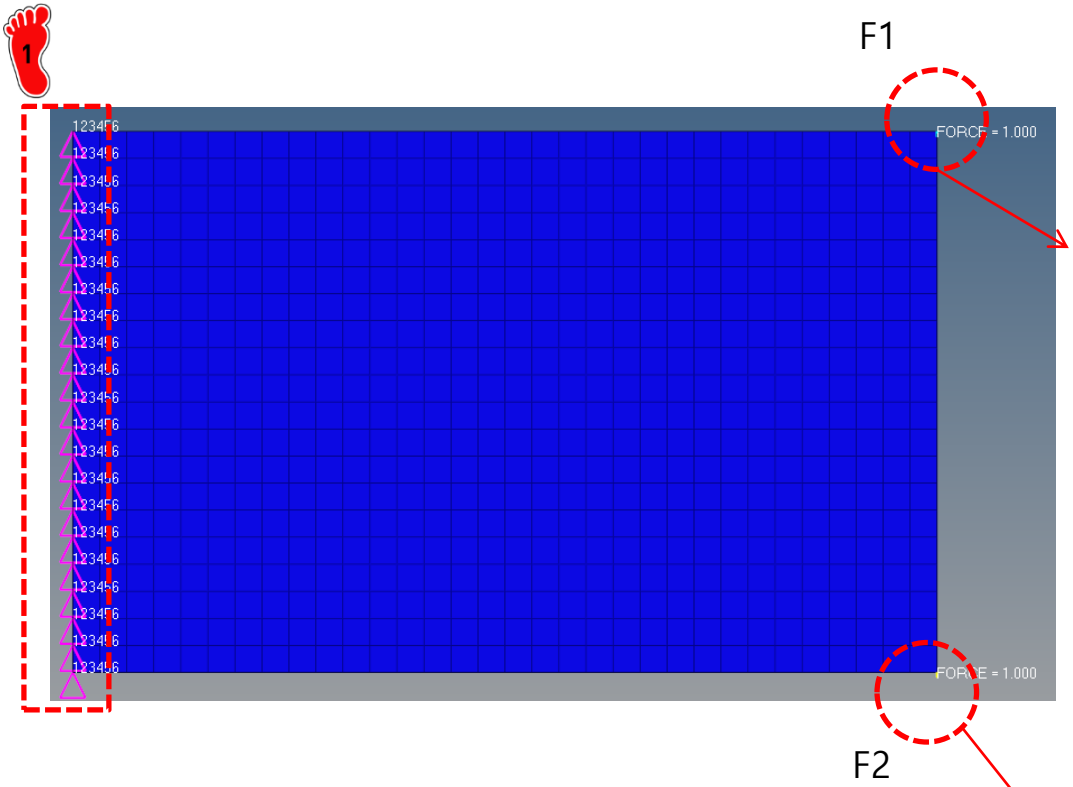


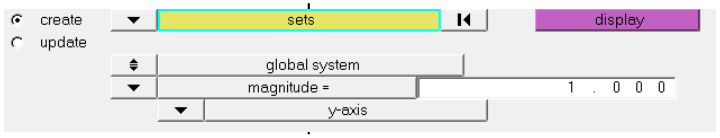
구속조건 및 하중조건 설정

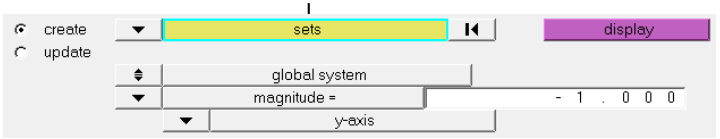
1 고정구속

2 두개의 load collectors 생성
각 각 forces 생성

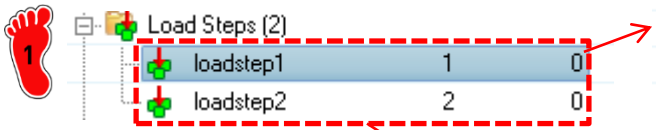


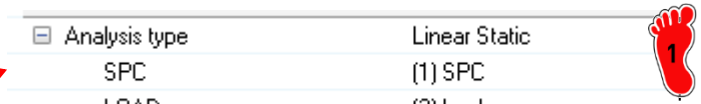




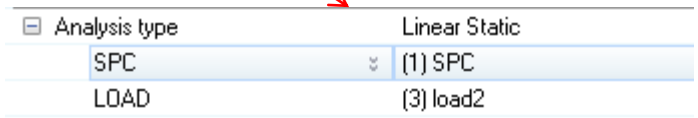


구속조건 및 하중조건 설정

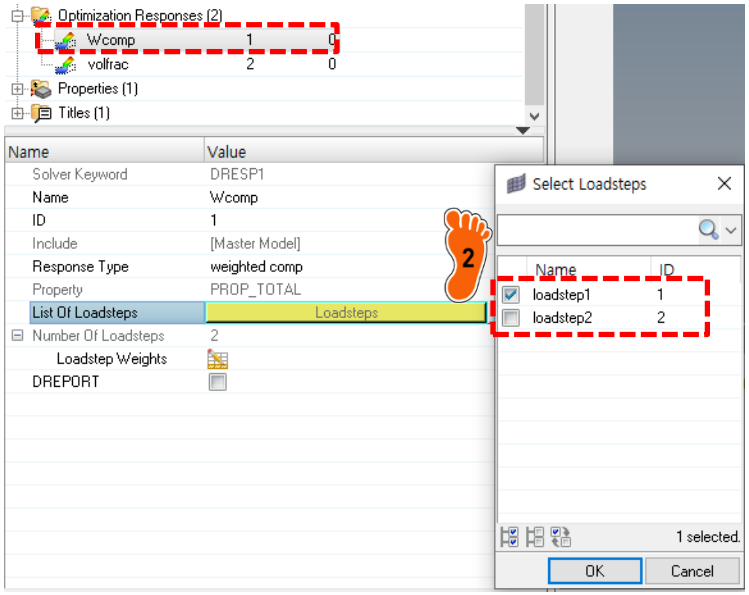


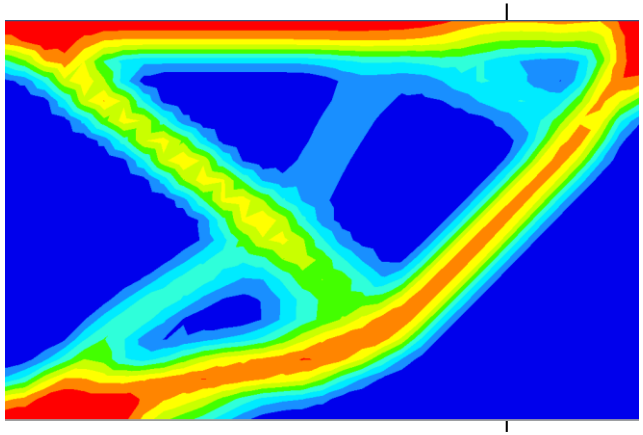


1 두개의 load step 생성

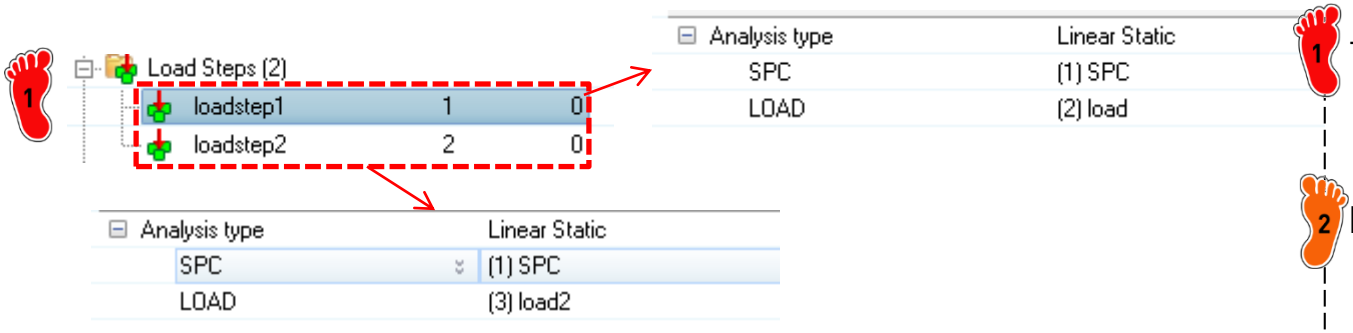


2 Loadstep1 check



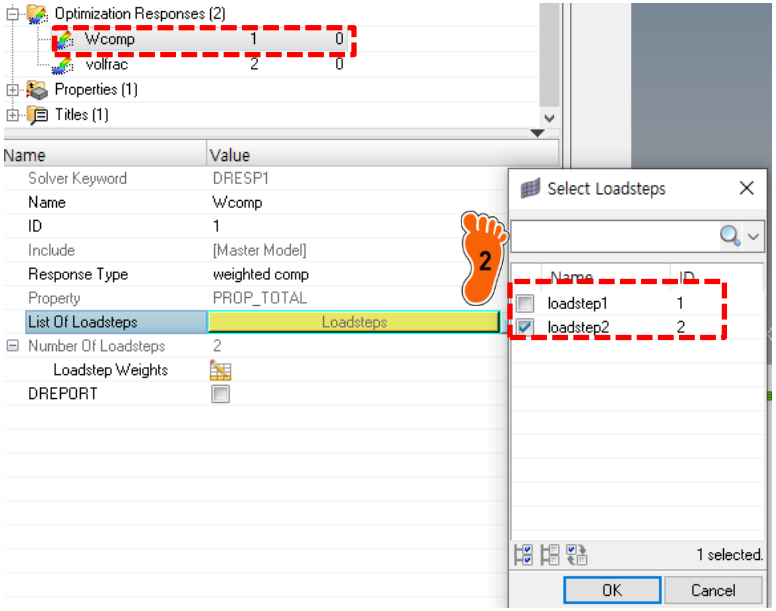


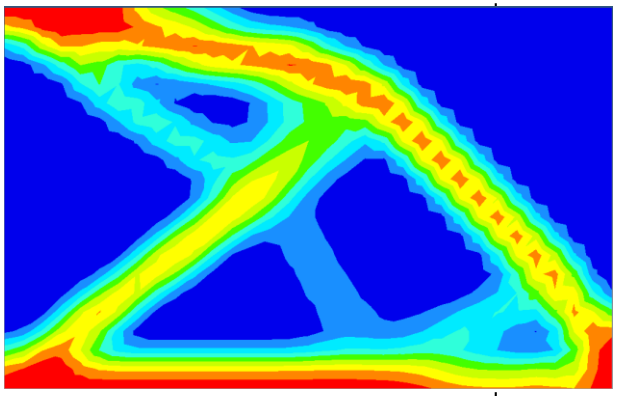
구속조건 및 하중조건 설정



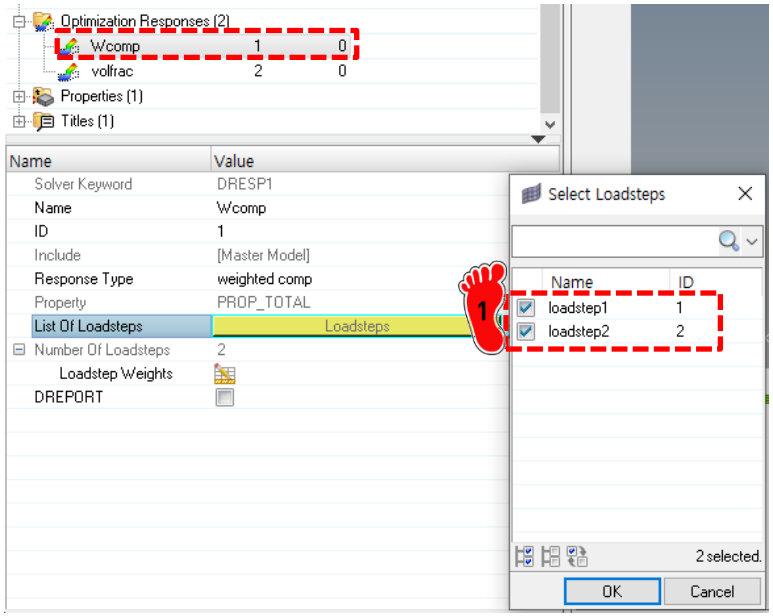
1 두개의 load step 생성

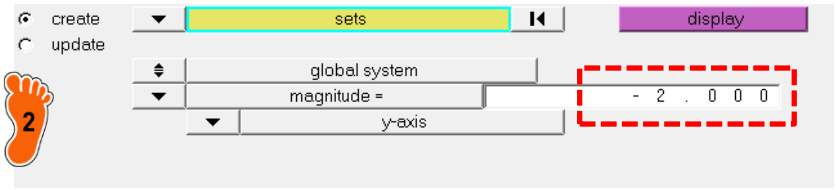
2 Loadstep2 check





구속조건 및 하중조건 설정

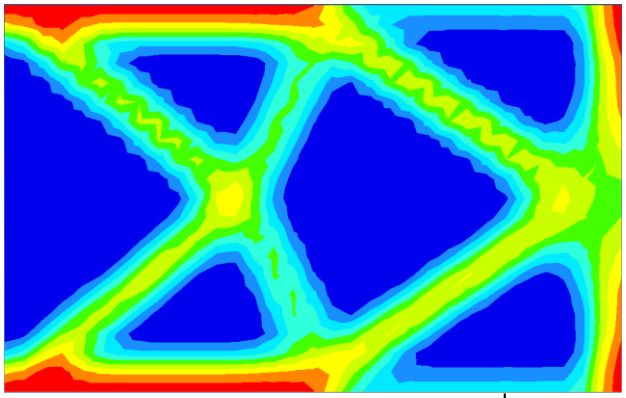




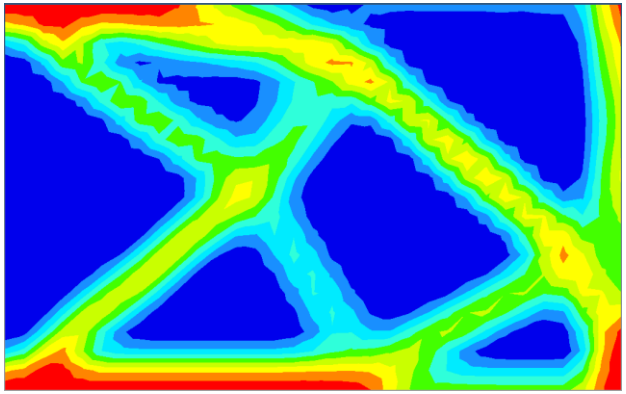
1 Loadstep1,2 check
> optistruct

2 아래쪽 load 크기 2로 변경
> optistruct

Multiple loads (F1:F2=1:1)

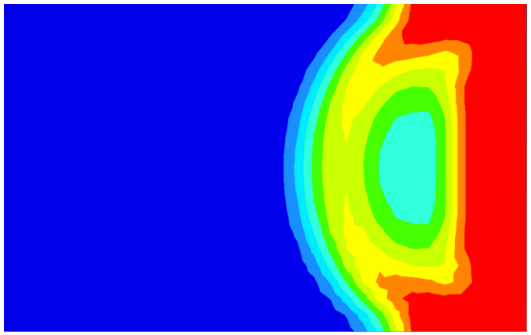


Multiple loads (F1:F2=1:2)

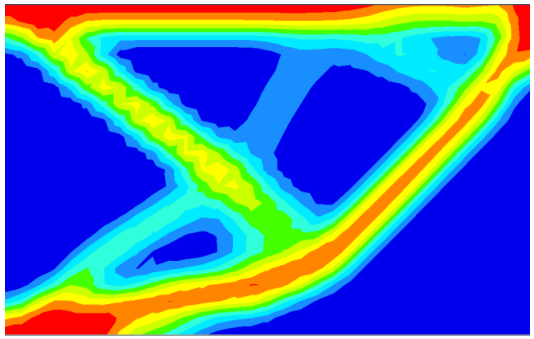


최적화 결과

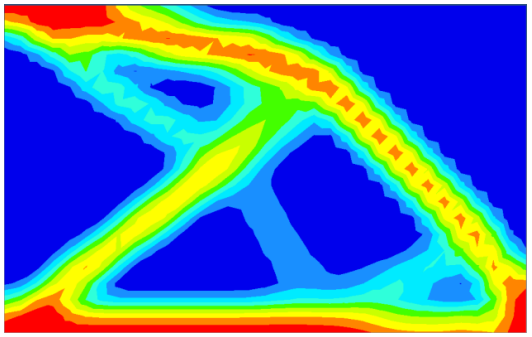
Combined load



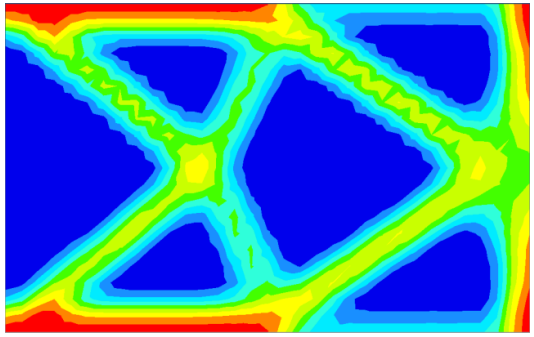
Single load 1



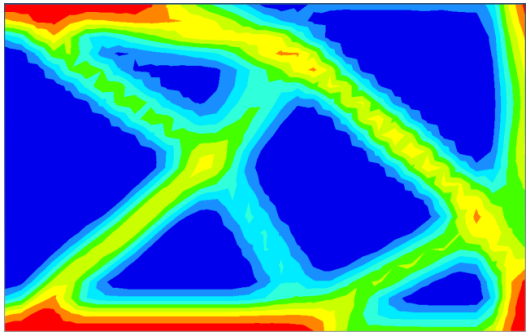
Single load 2



Multiple loads (F1:F2=1:1)



Multiple loads (F1:F2=1:2)



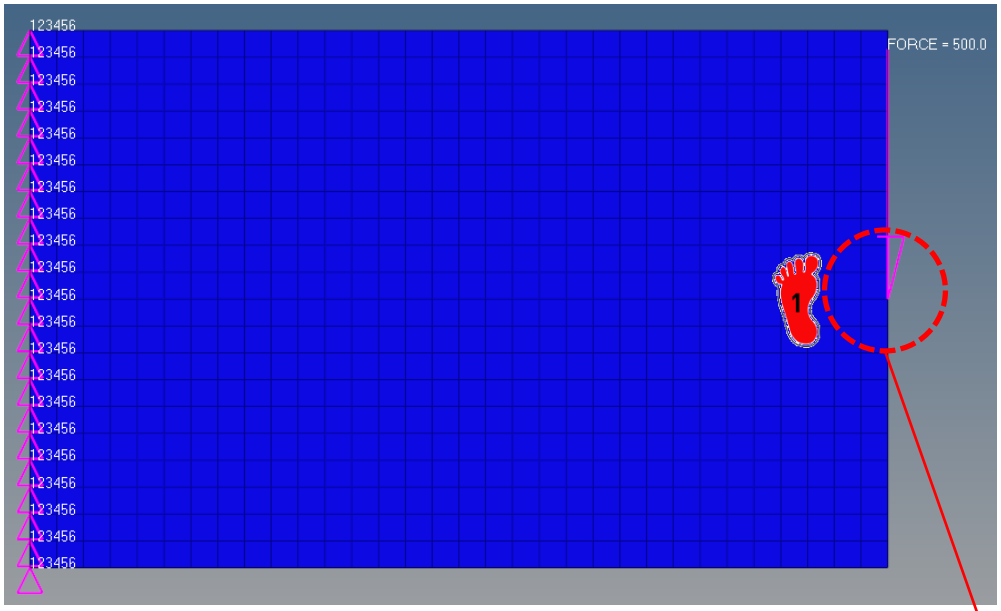
1 Combined load의 경우 하중을 동시에 적용한 경우에 대해, Multiple loads의 경우 각각의 하중 모두에 대한 최적화 결과가 나타나게 됨

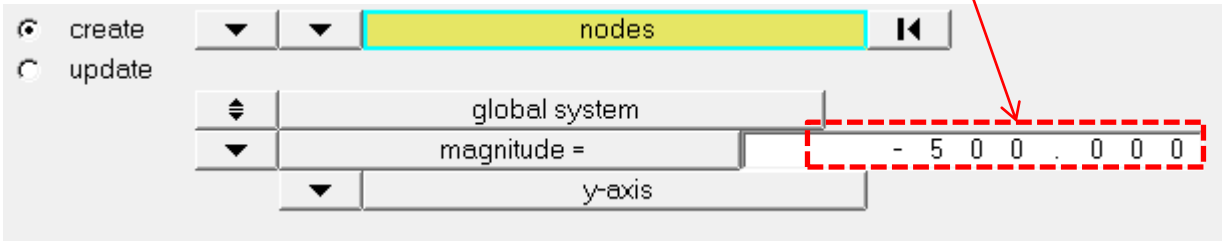
2D STRUCTURE

목적함수: 부피 최소화
구속조건: 변위

하중조건 변경

하중 크기를 -500 N 으로 변경





DESIGN VARIABLE SETTING

1 Analysis > optimization > topology

create

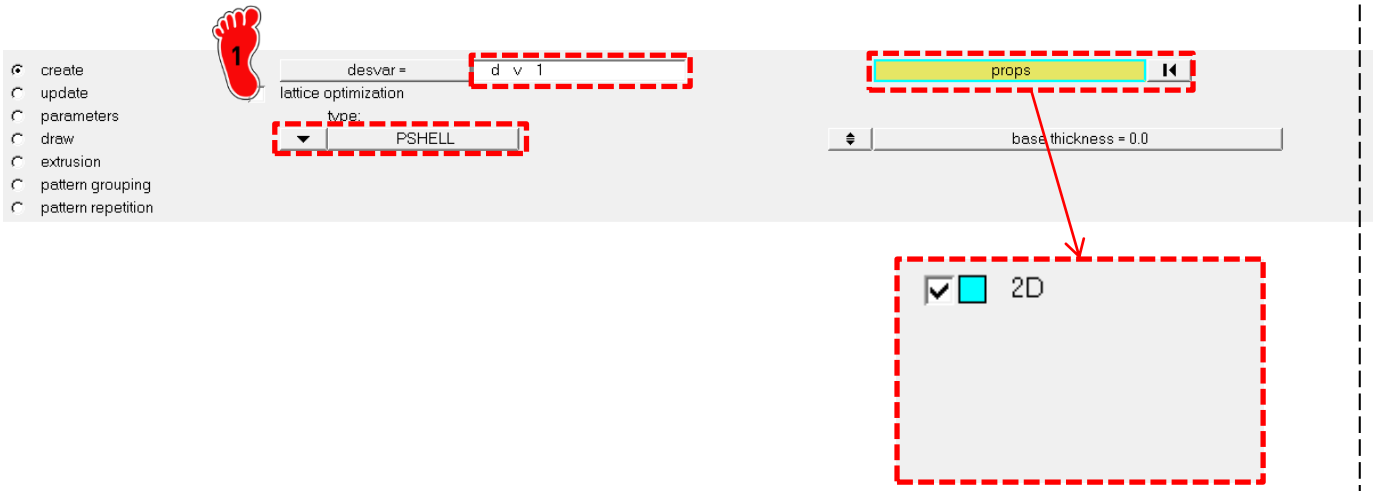
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



RESPONSE SETTING (1)

1 Analysis > optimization > Responses

Volumefrac > create

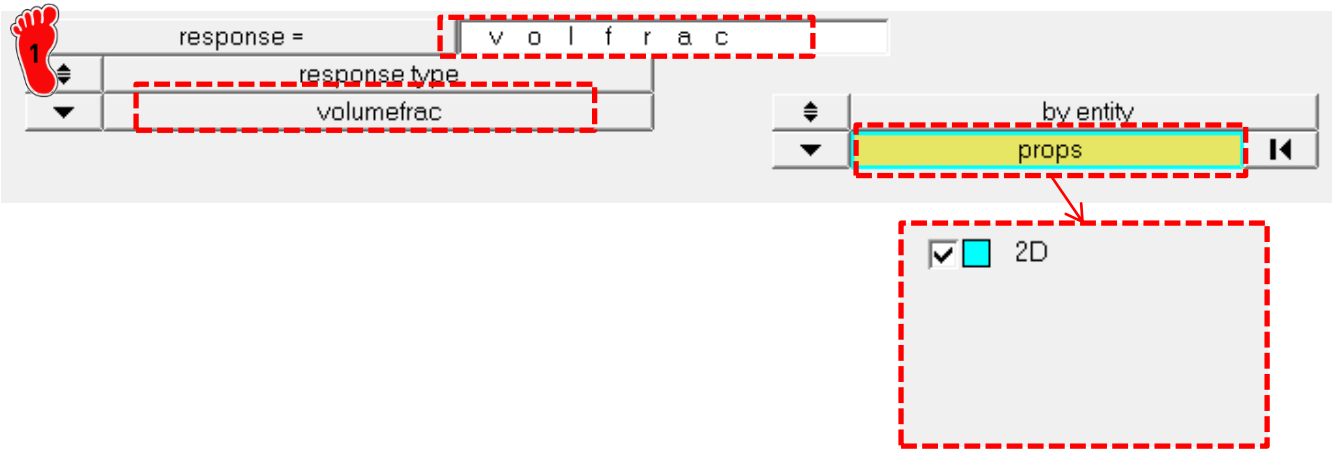
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



RESPONSE SETTING (2)

→ **Design variable**

→ **Responses**

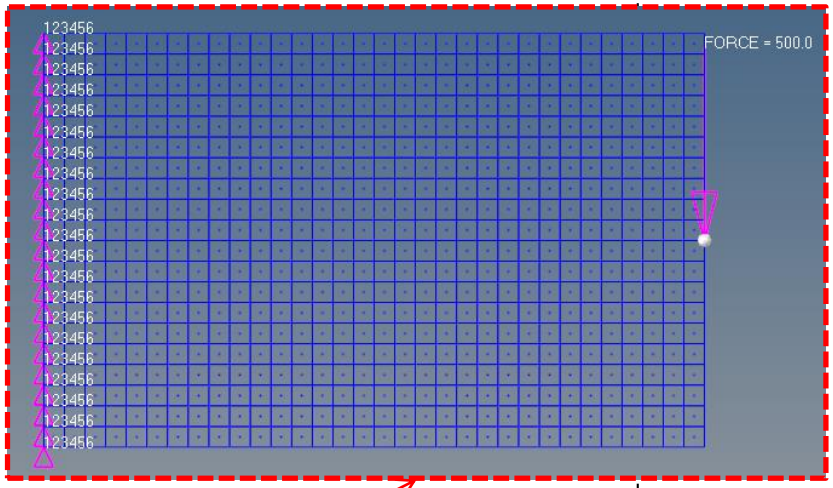
→ **Objective**

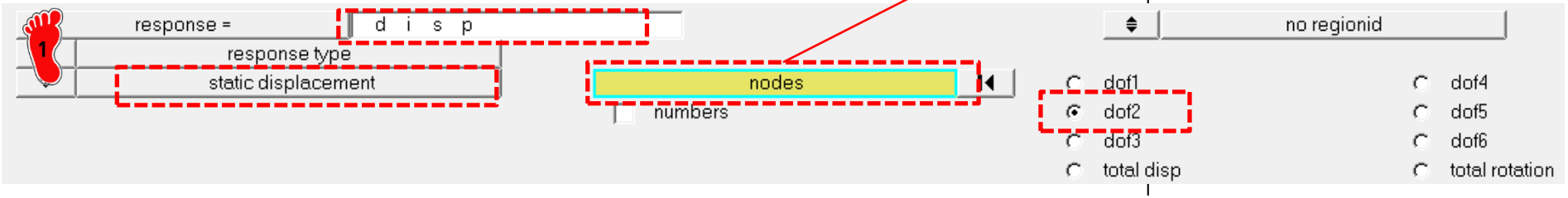
→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Responses

Y방향(dof2) 변위 > create





OBJECTIVE SETTING

→ **Design variable**

→ **Responses**

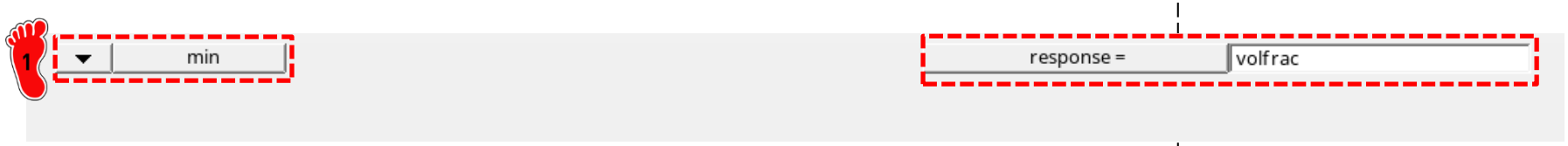
→ **Objective**

→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Objective

create



CONSTRAINTS SETTING

→ **Design variable**

→ **Responses**

→ **Objective**

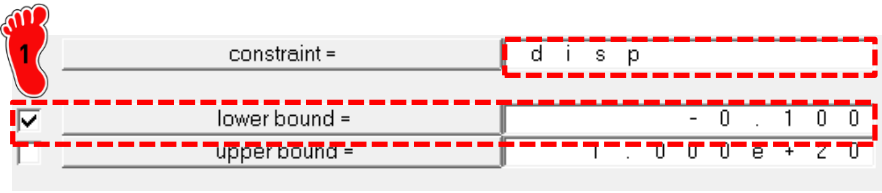
→ **Dconstraints**

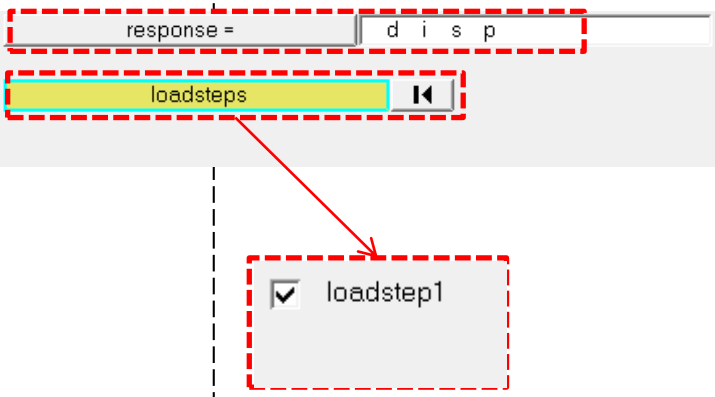
→ **Opti control**

1 Analysis > optimization > Dconstraints

Y-displacement ≥ -0.1mm

create





CONTROL SETTING

1 Analysis > optimization > Dconstraints

create

→ **Design variable**

→ **Responses**

→ **Objective**

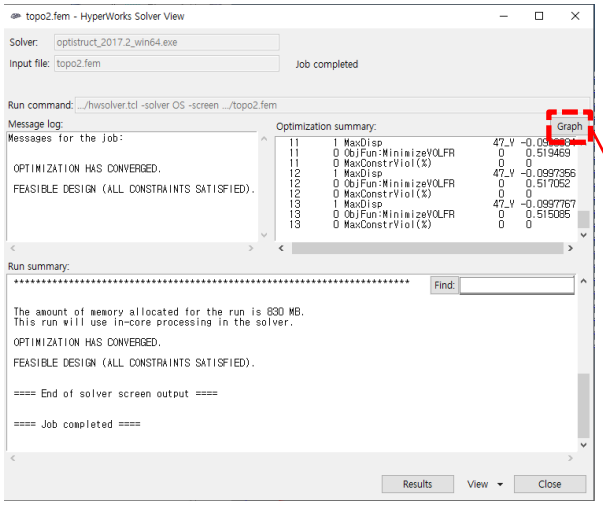
→ **Dconstraints**

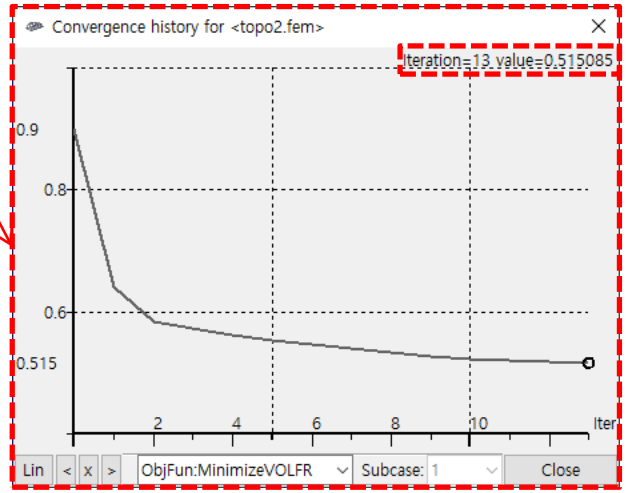
→ **Opti control**

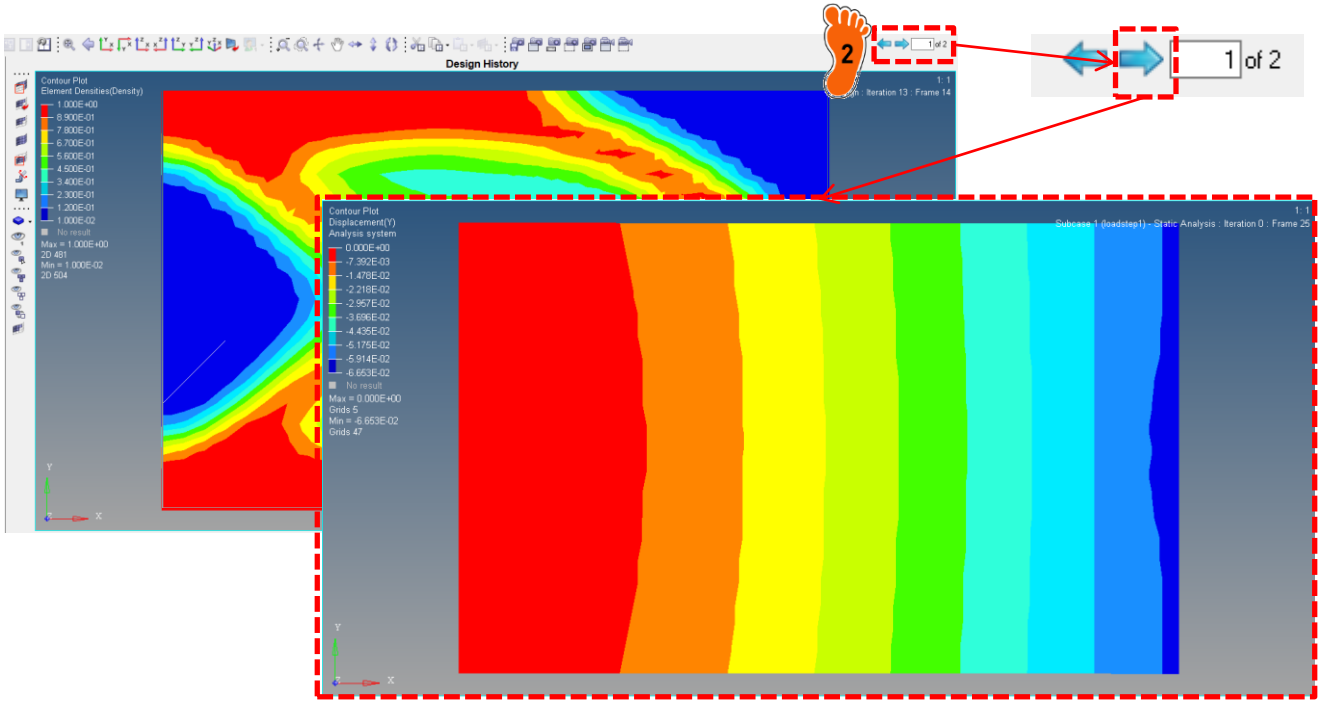
1

☑	DESMAX=	50	☑	OBJTOL=	0.005
☐	MINDIM=	0.000	☐	DELSIZ=	0.500
☐	MATINIT=	0.600	☐	DELSHP=	0.200
☐	MINDENS=	0.010	☐	DELTOP=	0.500
☑	DISCRETE=	3.000	☐	GBUCK=	0
☑	CHECKER=	1	☐	MAXBUCK=	10
☐	MMCHECK=	0	☐	DISCRT1D=	1.000

후처리 (1)



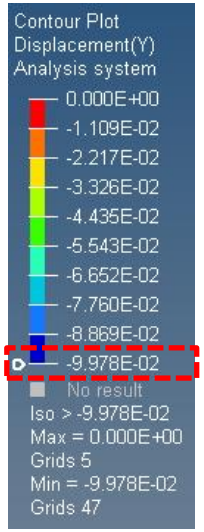




1 Graph click

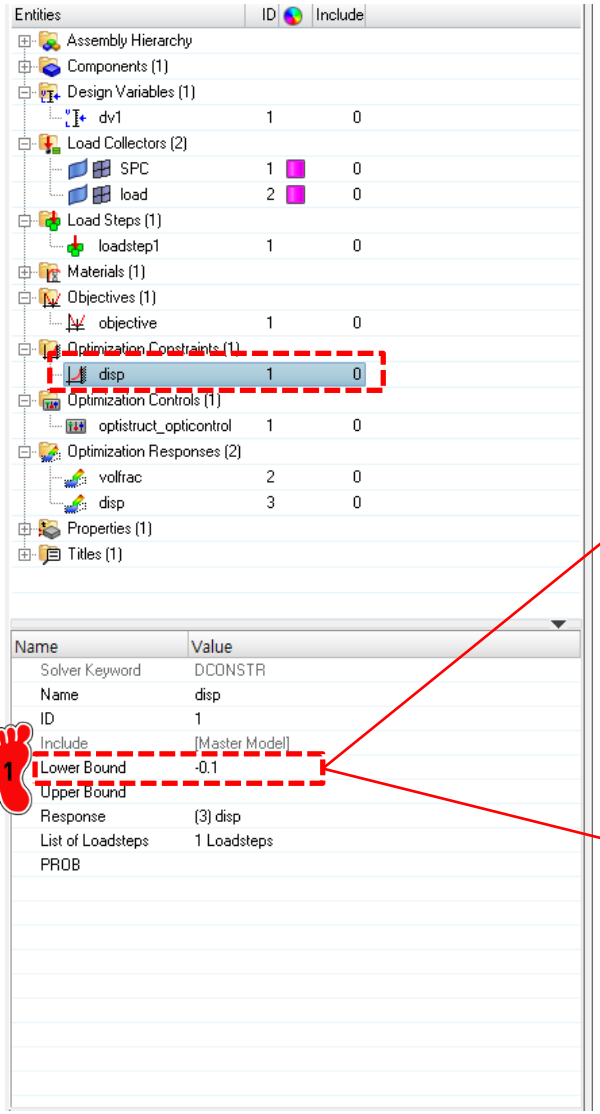
목적함수 확인 > 51.5 %

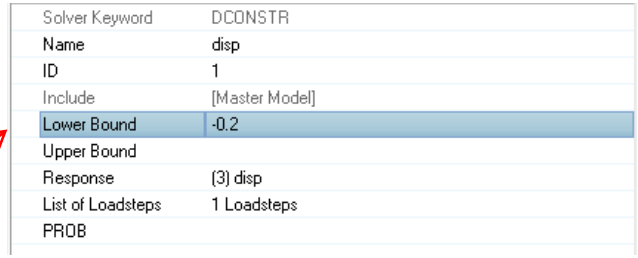
2 Displacement(y) 확인

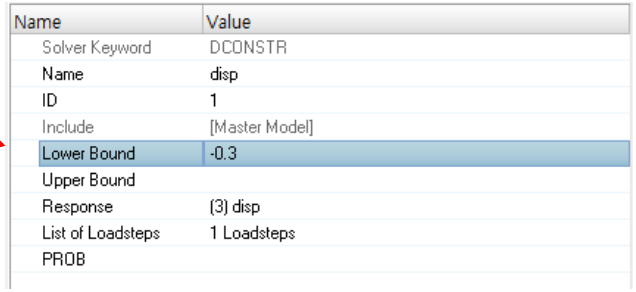


후처리 (2)

1 변위 조건 바꿔가면서 확인

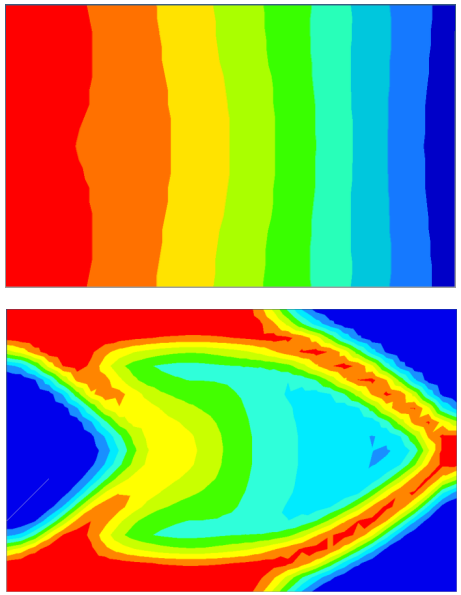


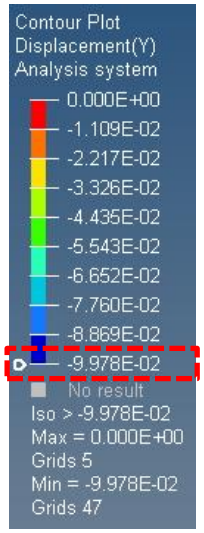




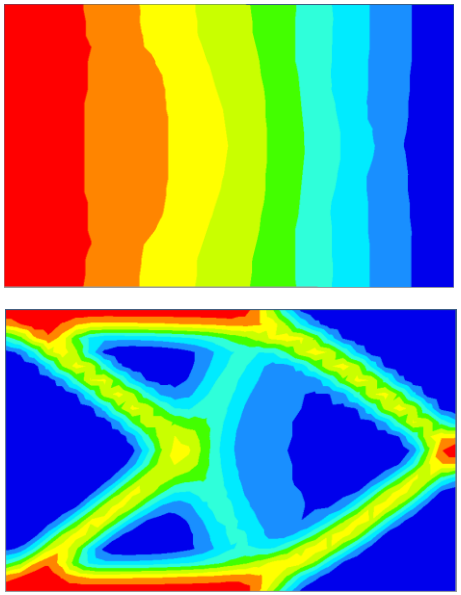
후처리 (4)

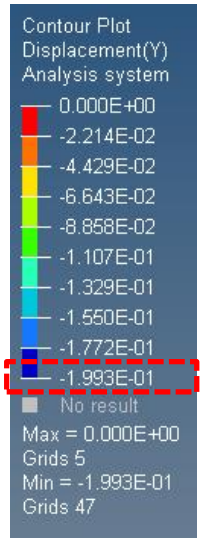
변위 제약조건 0.1
→ 부피율: 51.5%



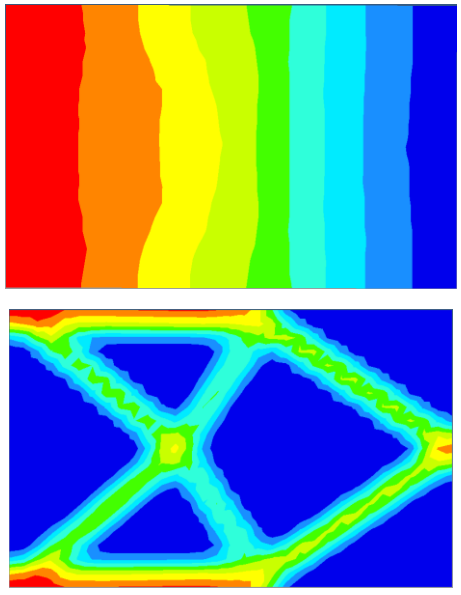


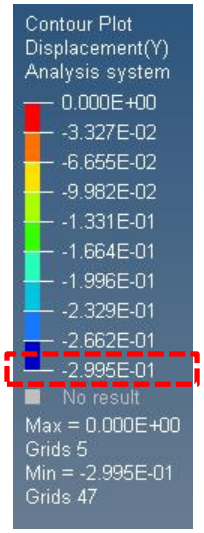
변위 제약조건 0.2
→ 부피율: 30.6%





변위 제약조건 0.3
→ 부피율: 22.5%

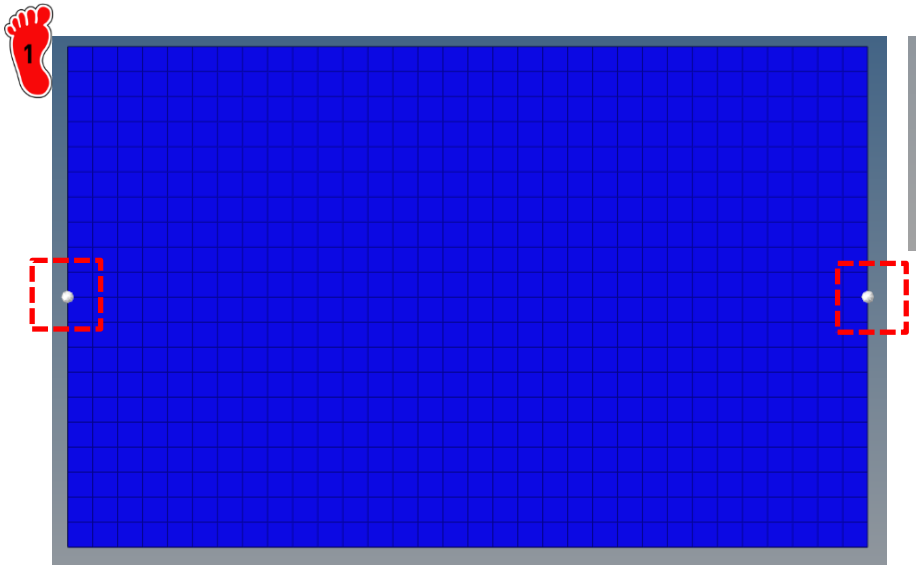


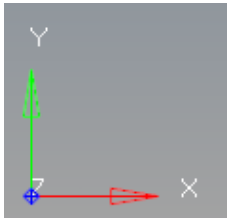


2D STRUCTURE

목적함수: 고유주파수 최대화
구속조건: 부피율

구속조건 변경

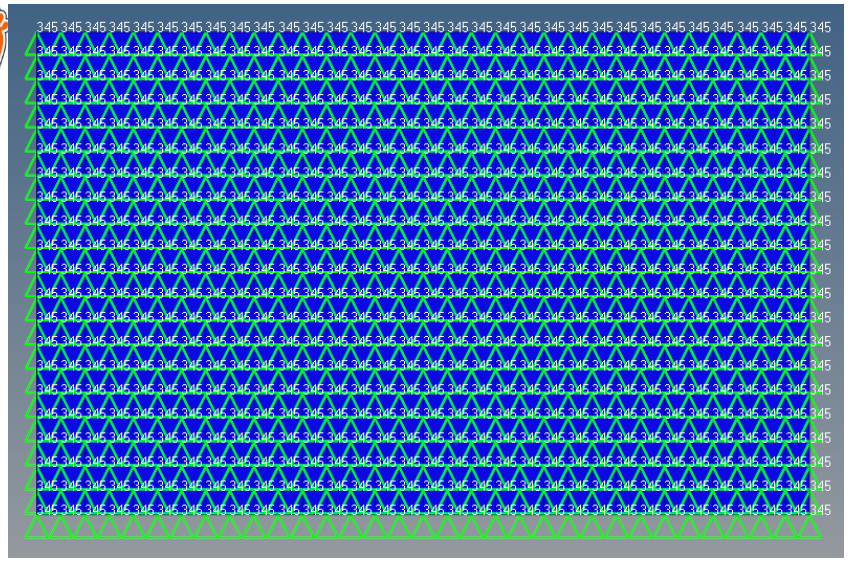




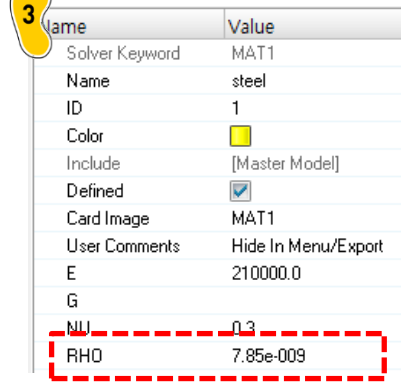
1 양 끝 가운데 절점을 핀지지로 구속조건 설정

dof1	=	0.000
dof2	=	0.000
dof3	=	0.000
dof4	=	0.000
dof5	=	0.000
dof6	=	0.000
load types =		S P C

2 전체 절점
Tz, Rx, Ry 구속



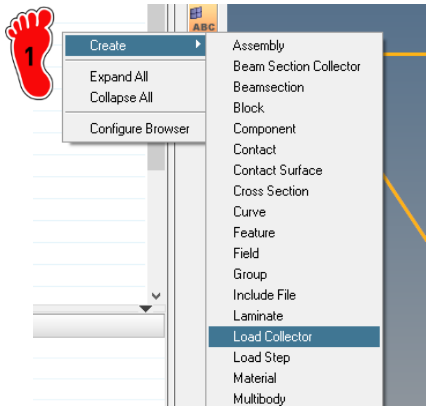
dof1	=	0.000
dof2	=	0.000
dof3	=	0.000
dof4	=	0.000
dof5	=	0.000
dof6	=	0.000
load types =		S P C

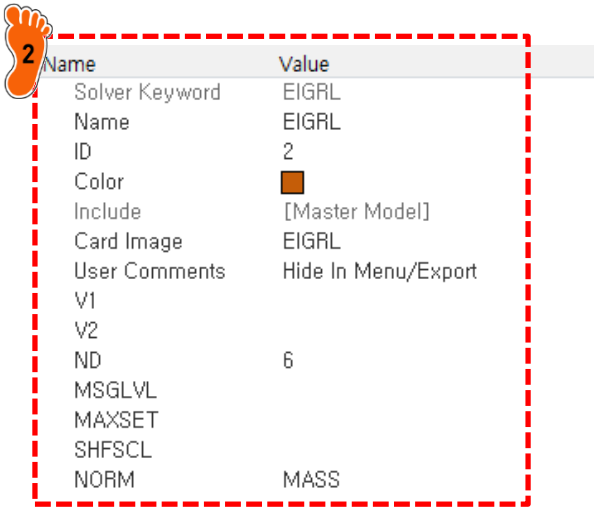


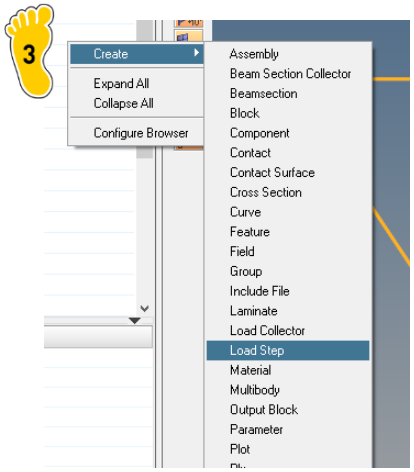
Name	Value
Solver Keyword	MAT1
Name	steel
ID	1
Color	
Include	[Master Model]
Defined	☑
Card Image	MAT1
User Comments	Hide In Menu/Export
E	210000.0
G	
NU	0.3
RHO	7.85e-009

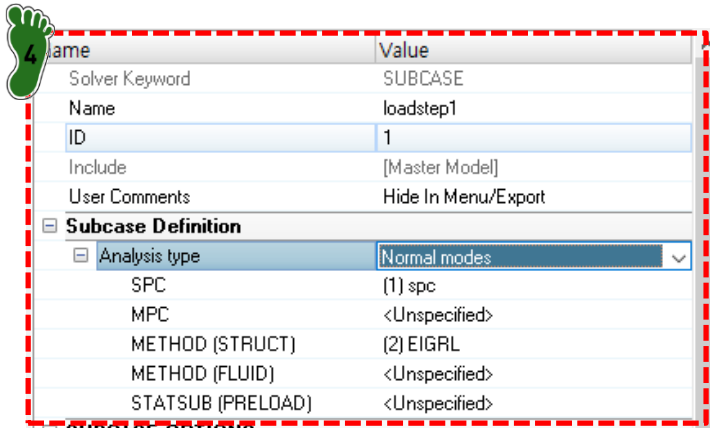
3 Material > Rho > 7.85e-9 추가

구속조건 및 하중조건 설정









1 Create > Load Collector

2 Name > EIGRL
Card Image > EIGRL
ND > 6

3 Create > Load Step

4 Analysis type
>Normal Modes
SPC > spc
METHOD(STRUCT)
> EIGRL

DESIGN VARIABLE SETTING

1 Analysis > optimization > topology

create

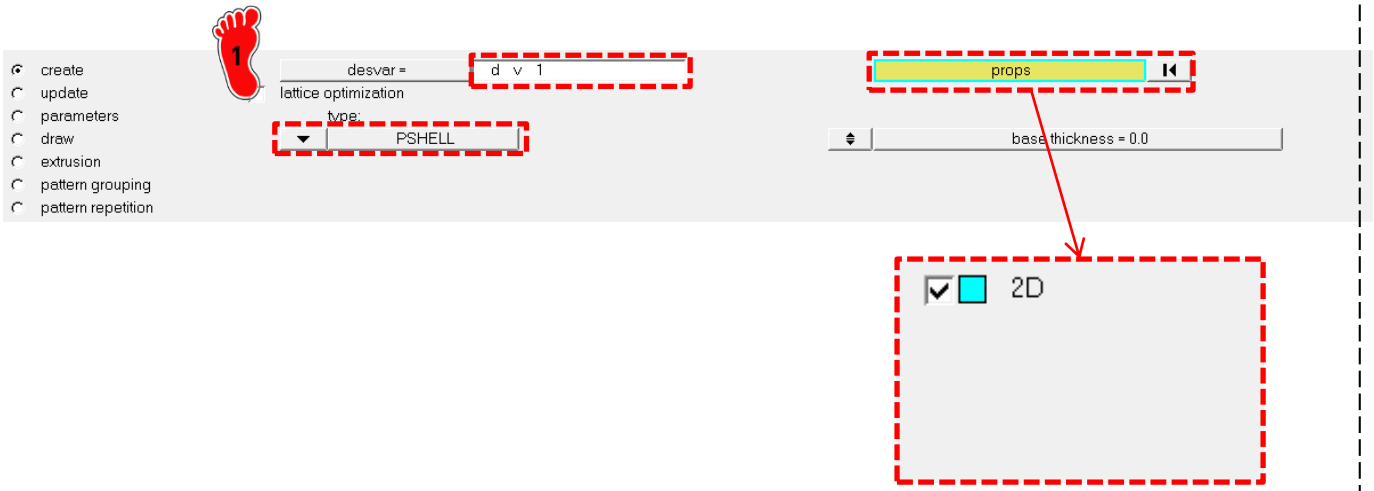
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



RESPONSE SETTING (1)

1 Analysis > optimization > Responses

Volumefrac > create

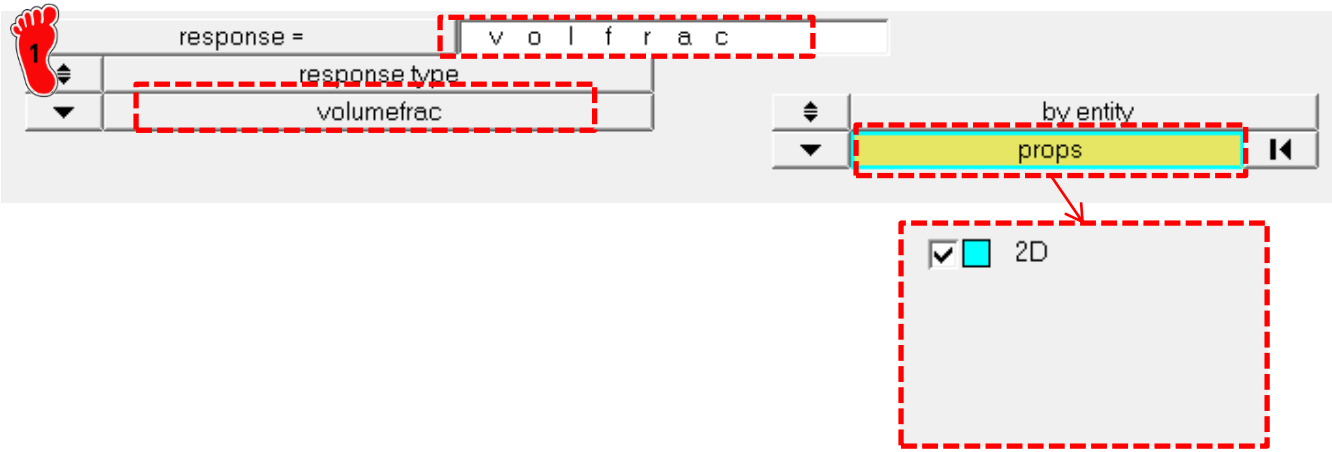
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



RESPONSE SETTING (2)

→ **Design variable**

→ **Responses**

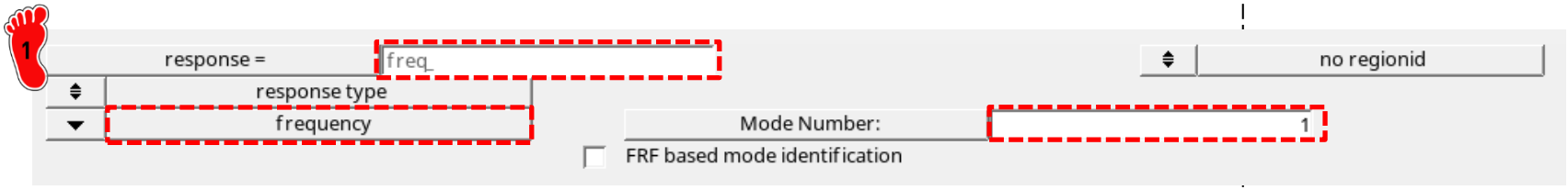
→ **Objective**

→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Responses

Frequency > create
Mode number > 1
Loadsteps check X



OBJECTIVE SETTING

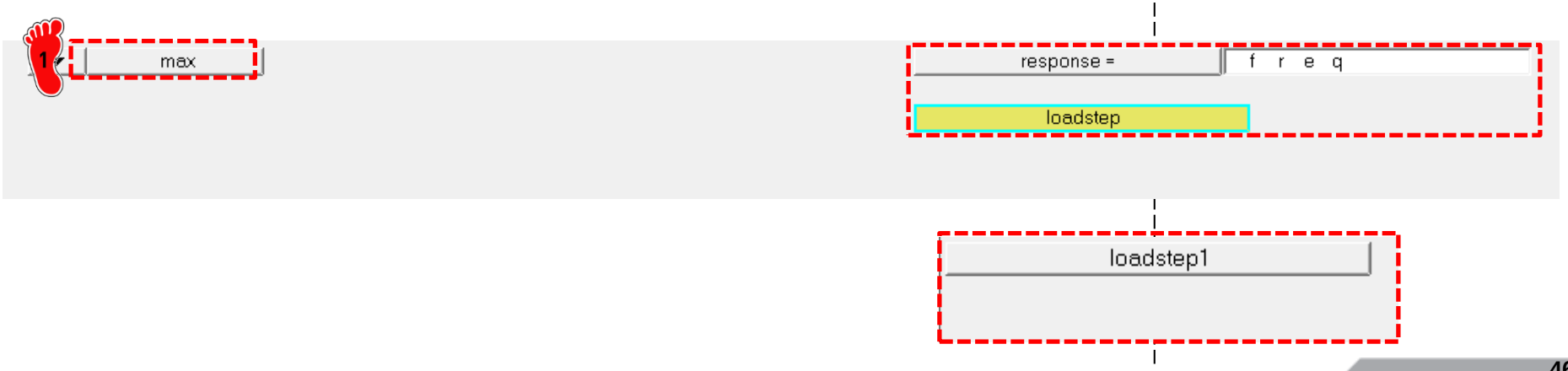
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



CONSTRAINTS SETTING

→ **Design variable**

→ **Responses**

→ **Objective**

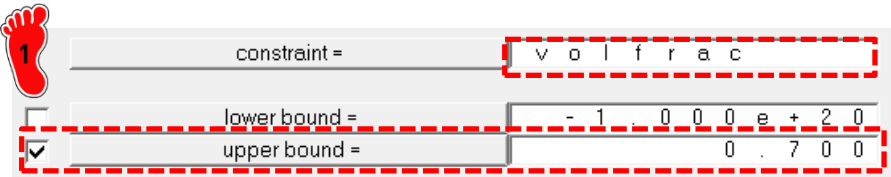
→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Dconstraints

Volfrac ≤ 70%

create



CONTROL SETTING

1 Analysis > optimization > Dconstraints

create

→ **Design variable**

→ **Responses**

→ **Objective**

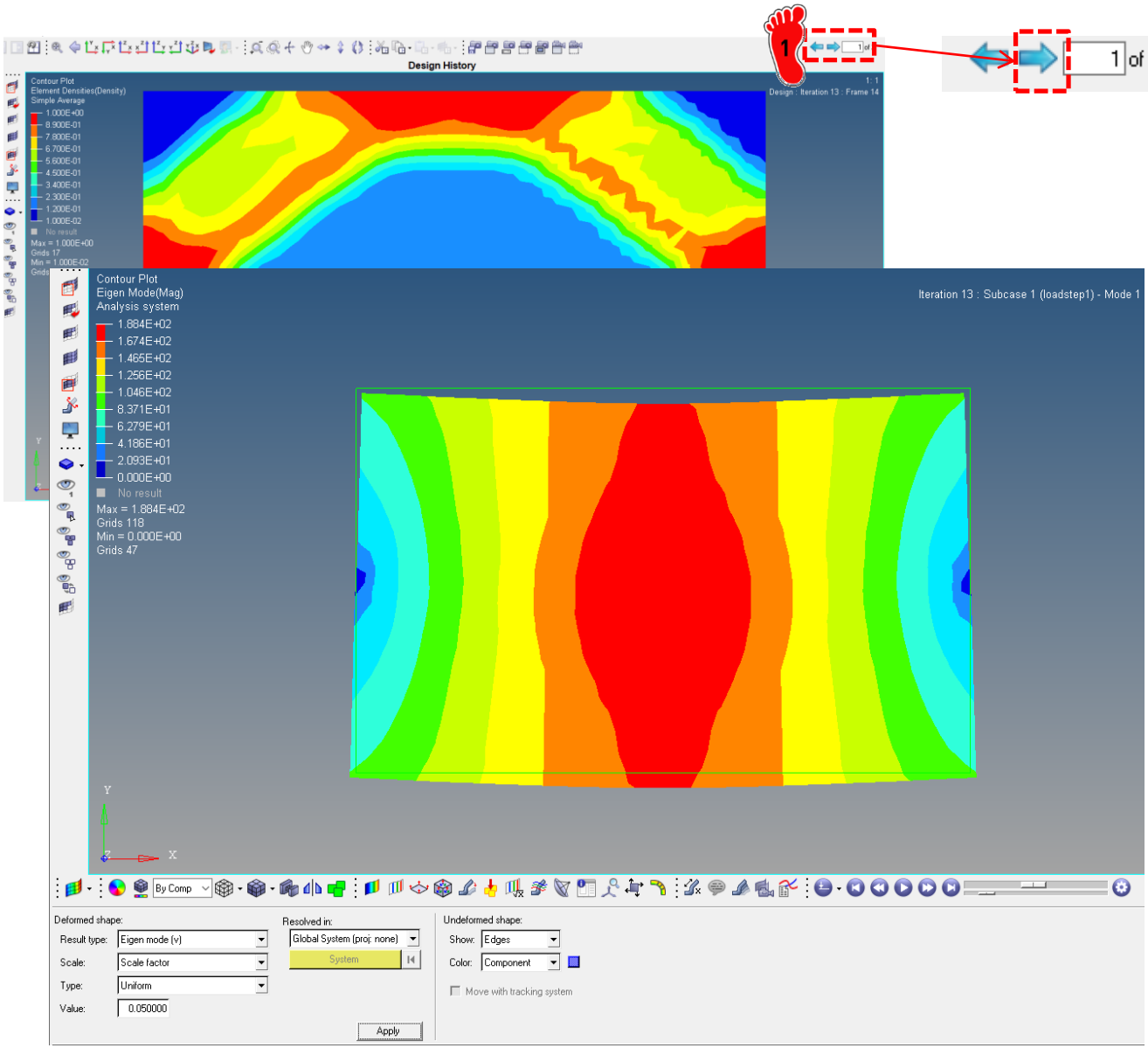
→ **Dconstraints**

→ **Opti control**

1

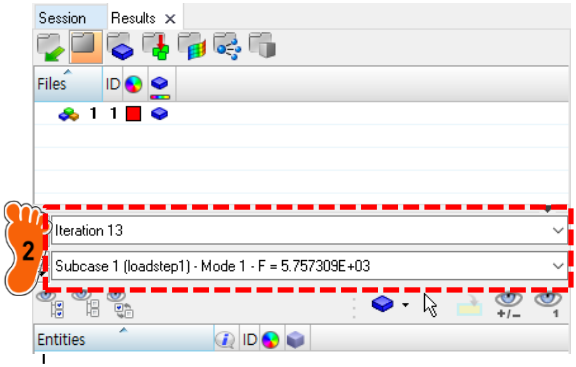
☑	DESMAX=	50	☑	OBJTOL=	0.005
☐	MINDIM=	0.000	☐	DELSIZ=	0.500
☐	MATINIT=	0.600	☐	DELSHP=	0.200
☐	MINDENS=	0.010	☐	DELTOP=	0.500
☑	DISCRETE=	3.000	☐	GBUCK=	0
☑	CHECKER=	1	☐	MAXBUCK=	10
☐	MMCHECK=	0	☐	DISCRT1D=	1.000

후처리



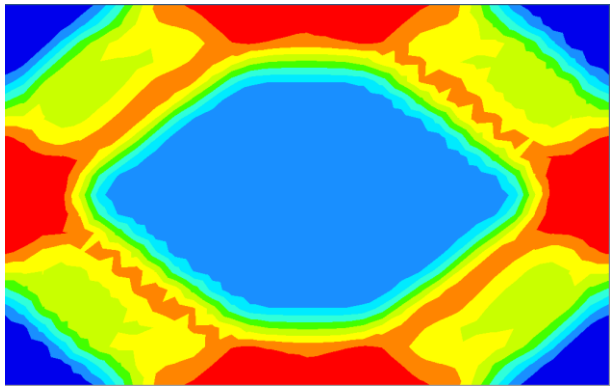
1 Eigen Mode 확인

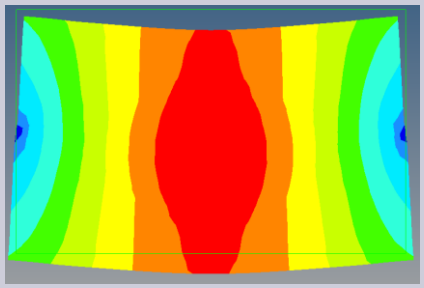
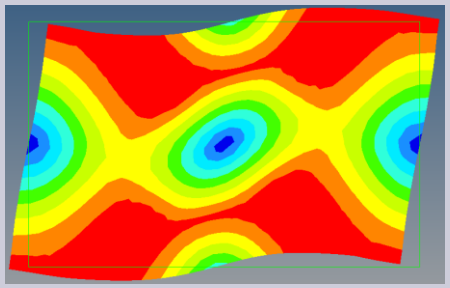
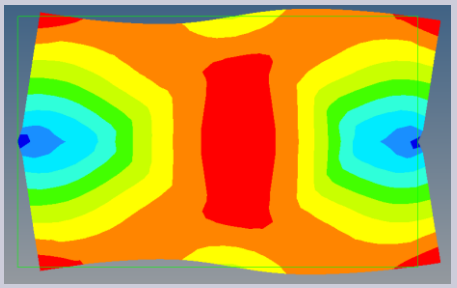
Create



후처리

최적화 결과

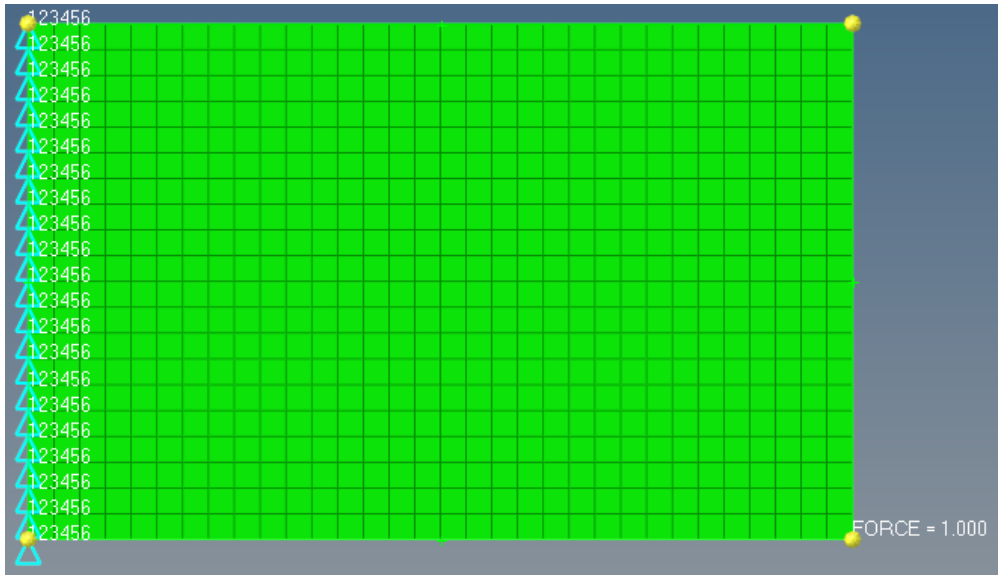


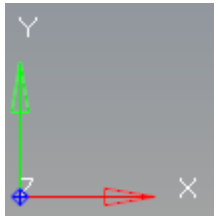
모드 차수	1차	2차	3차
변형 형상			
고유주파수	5757	5832	6304

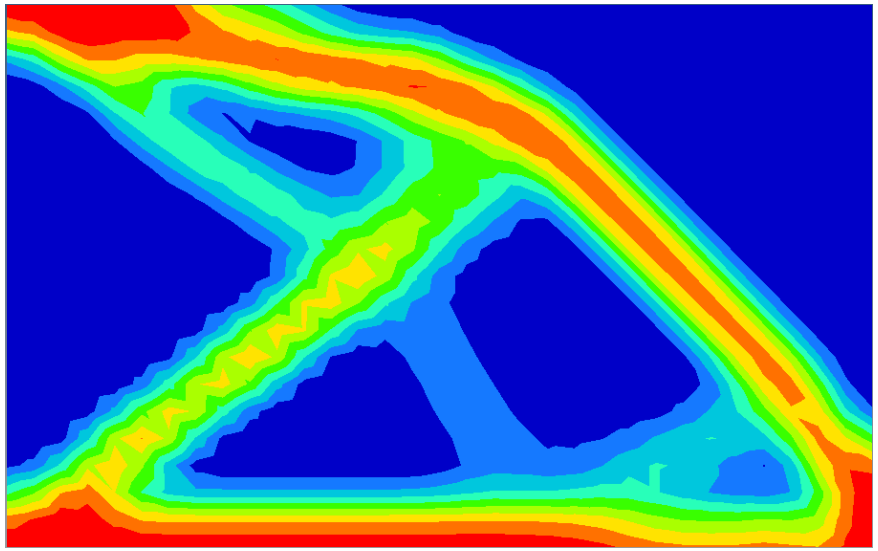
2D STRUCTURE

목적함수: 컴플라이언스 최소화
구속조건: 부피율 + 대칭조건

하중조건 변경







OBJ = 2.15e-4

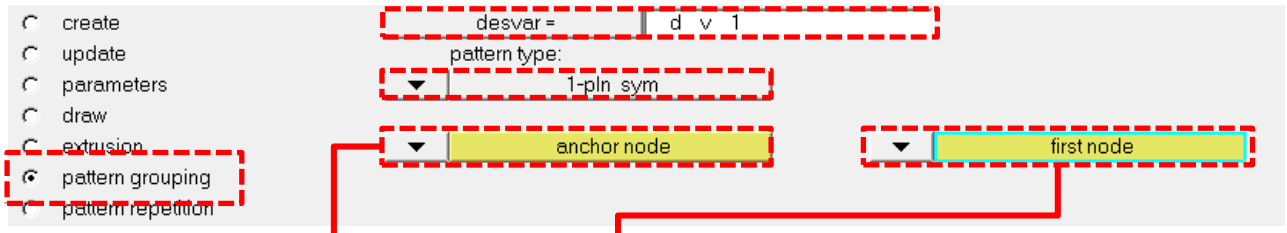
한쪽면 고정구속

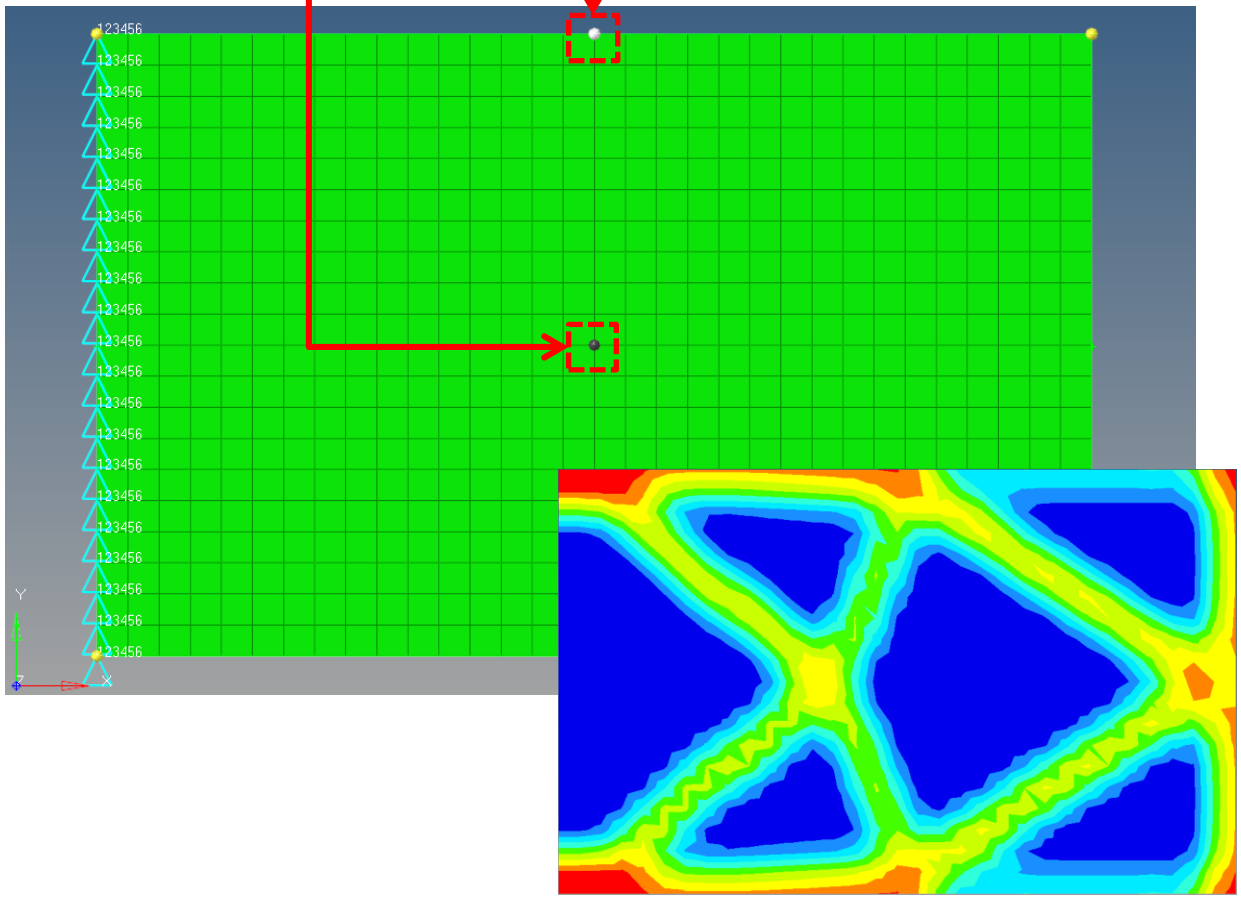
하단 끝점 Y방향 집중하중 (-1N) 부여

Minimize compliance
구속조건 : 부피율≤30%

최적설계 결과 확인

제조조건 입력



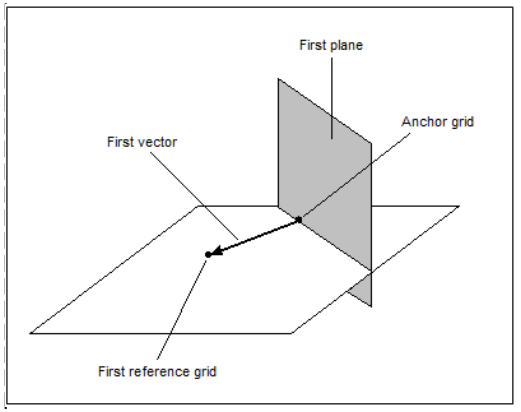


OBJ = 5.55e-4

1 Analysis > optimization > topology > pattern grouping

Pattern type > 1-pin sym

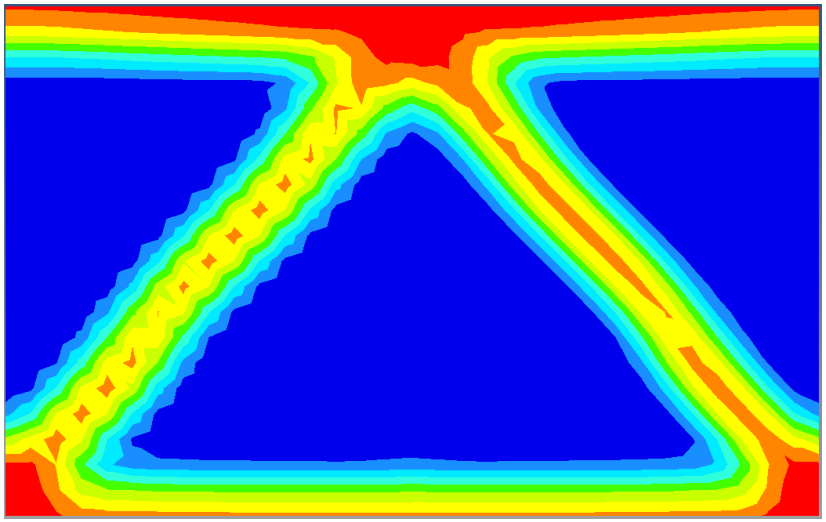
대칭면 : XZ가 대칭면이 되도록 node 선택



최적화 수행

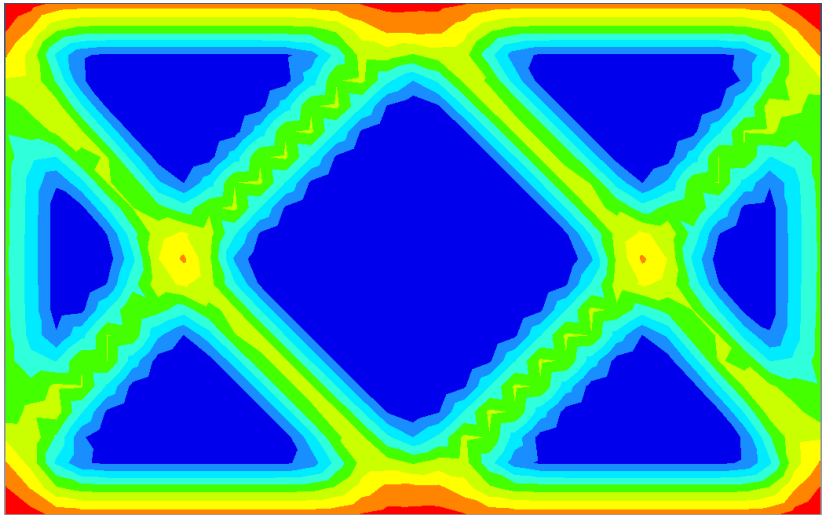
제조조건 입력

YZ 대칭



OBJ = 4.61e-4

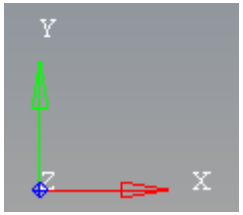
YZ+ZX 대칭



OBJ = 8.89e-4

1 YZ, YZ+ZX 대칭에 대해 수행

제조조건을 부여하는 경우
목적함수가 증가하는 것 확인
(대칭 없는 경우 2.15e-4)



3D STRUCTURE
AUTOMOTIVE CONTROL ARM

목적함수: 부피 최소화
구속조건: 변위 + 성형 방향 고려

서스펜션의 종류

Hotchkiss

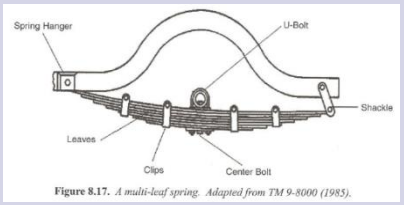
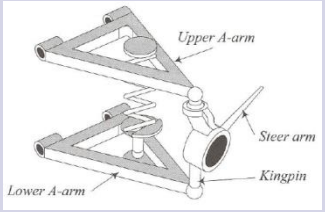
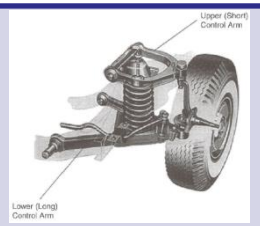


Figure 8.17. *A multi-leaf spring. Adapted from TM 9-8000 (1985).*

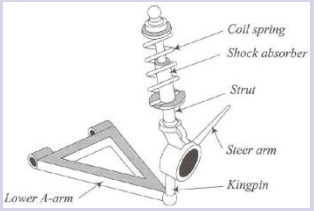
Double wishbone



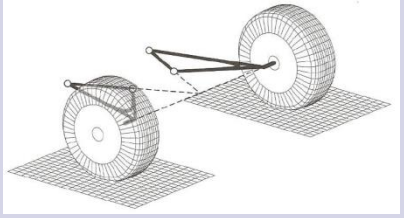


Trailing arm with twisted(torsion) beam

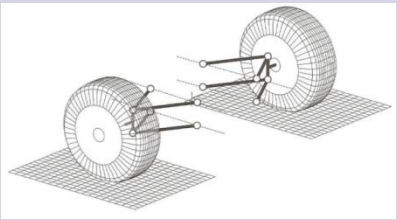
MacPherson



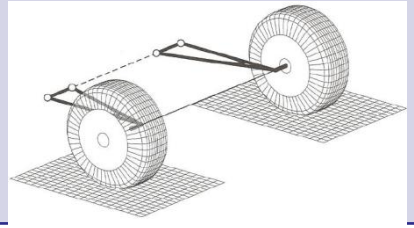
Semi-trailing arm

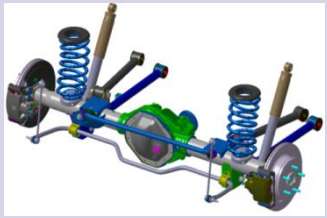


Multi-link

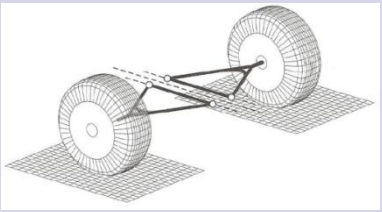


Trailing arm

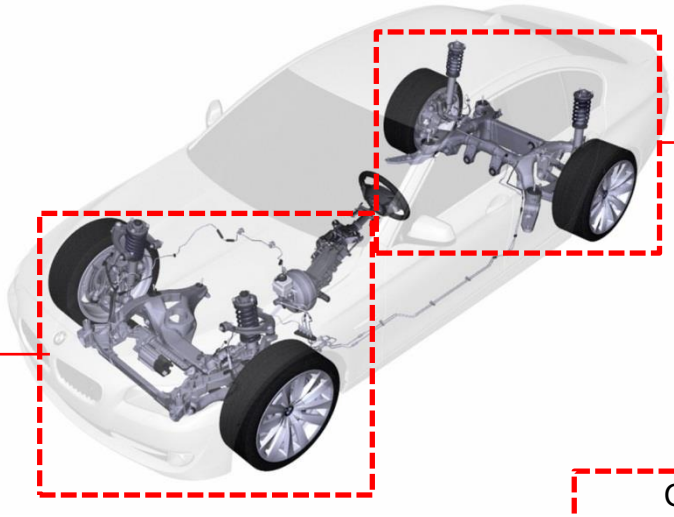




Swing(space) arm

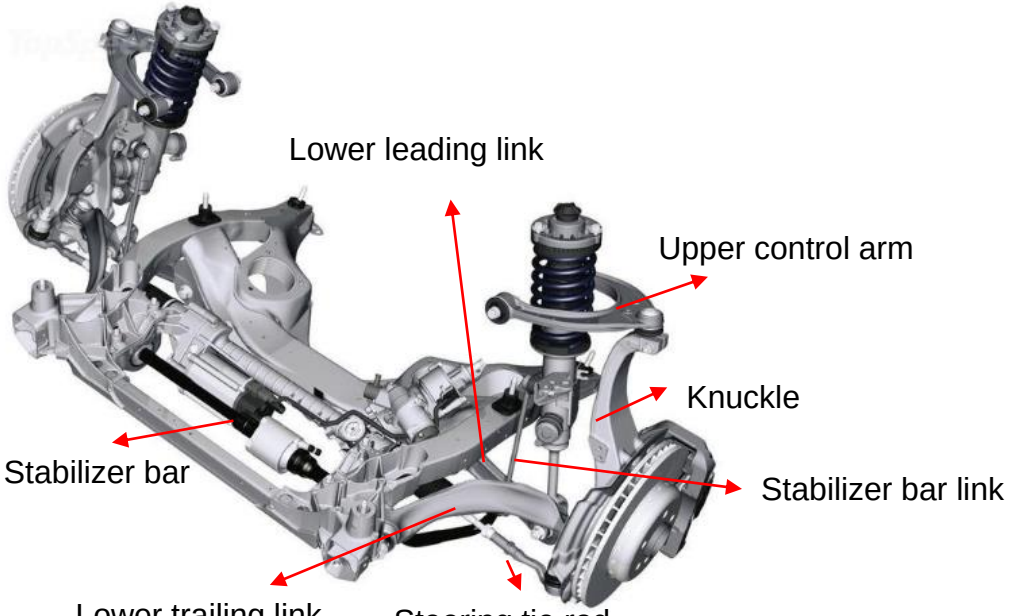


BMW NEW 5 SERIES

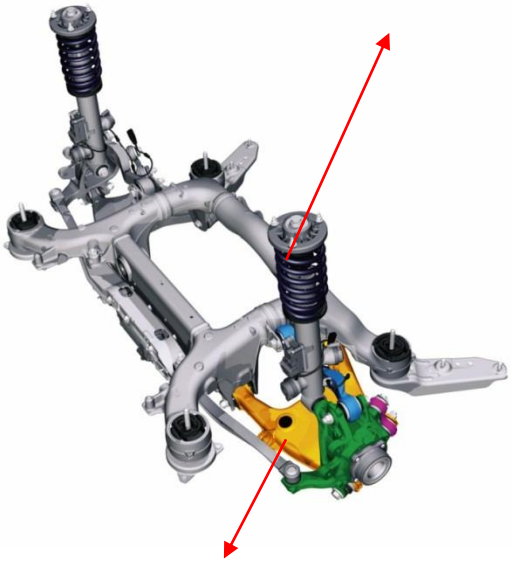


Rear: Macpherson type

Front: Double wishbone type



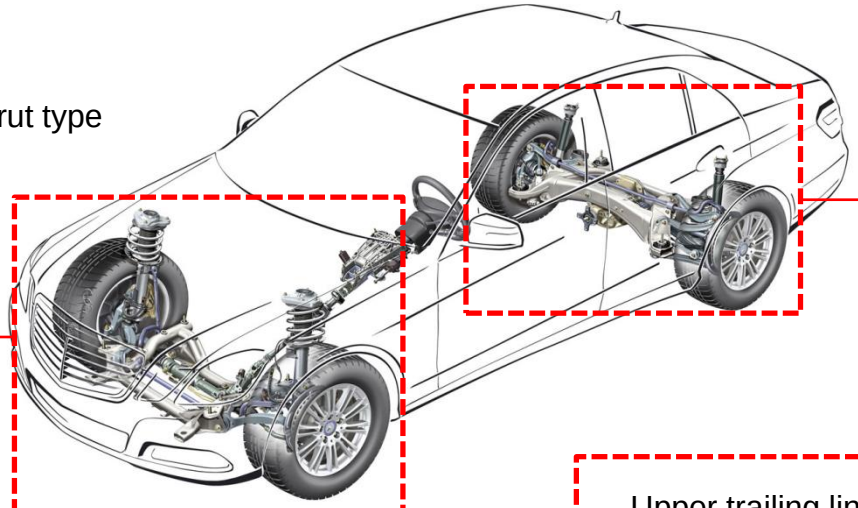
Coil spring, Shock absorber, Strut

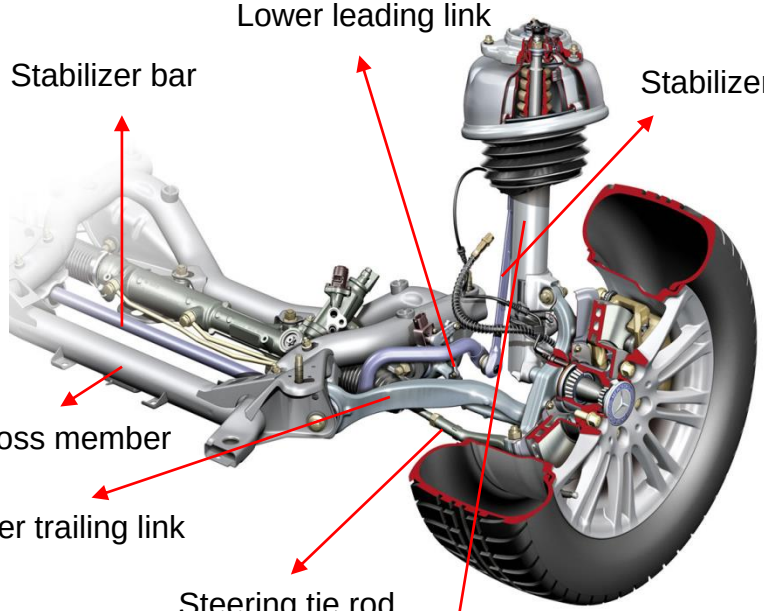


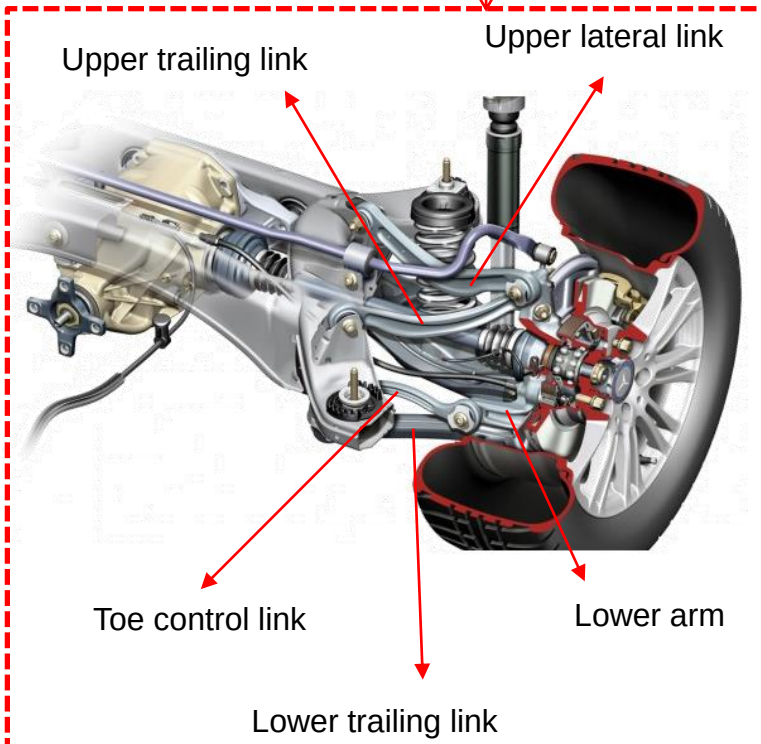
BENZ E CLASS

Front: Modified Macpherson strut type

Rear: Multi(5) link type







예제: AUTOMOTIVE CONTROL ARM

기하 형상, 하중 및 경계조건

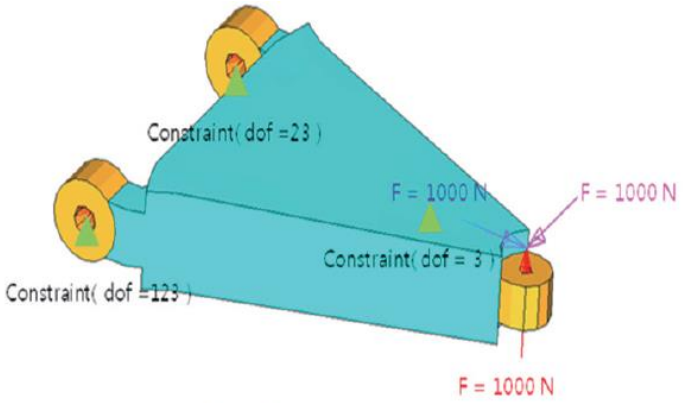
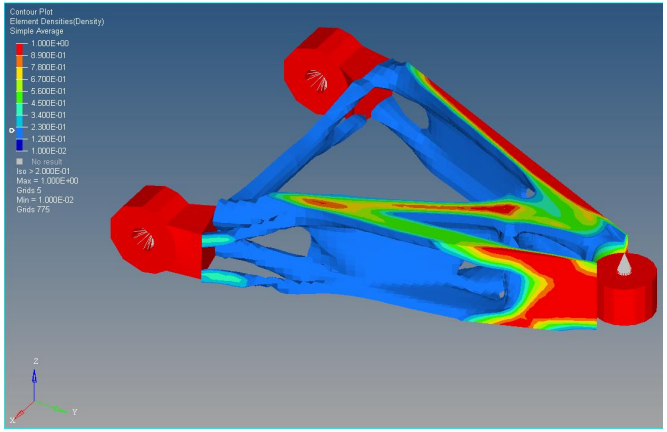


Fig 1 Finite element analysis

최적화 결과



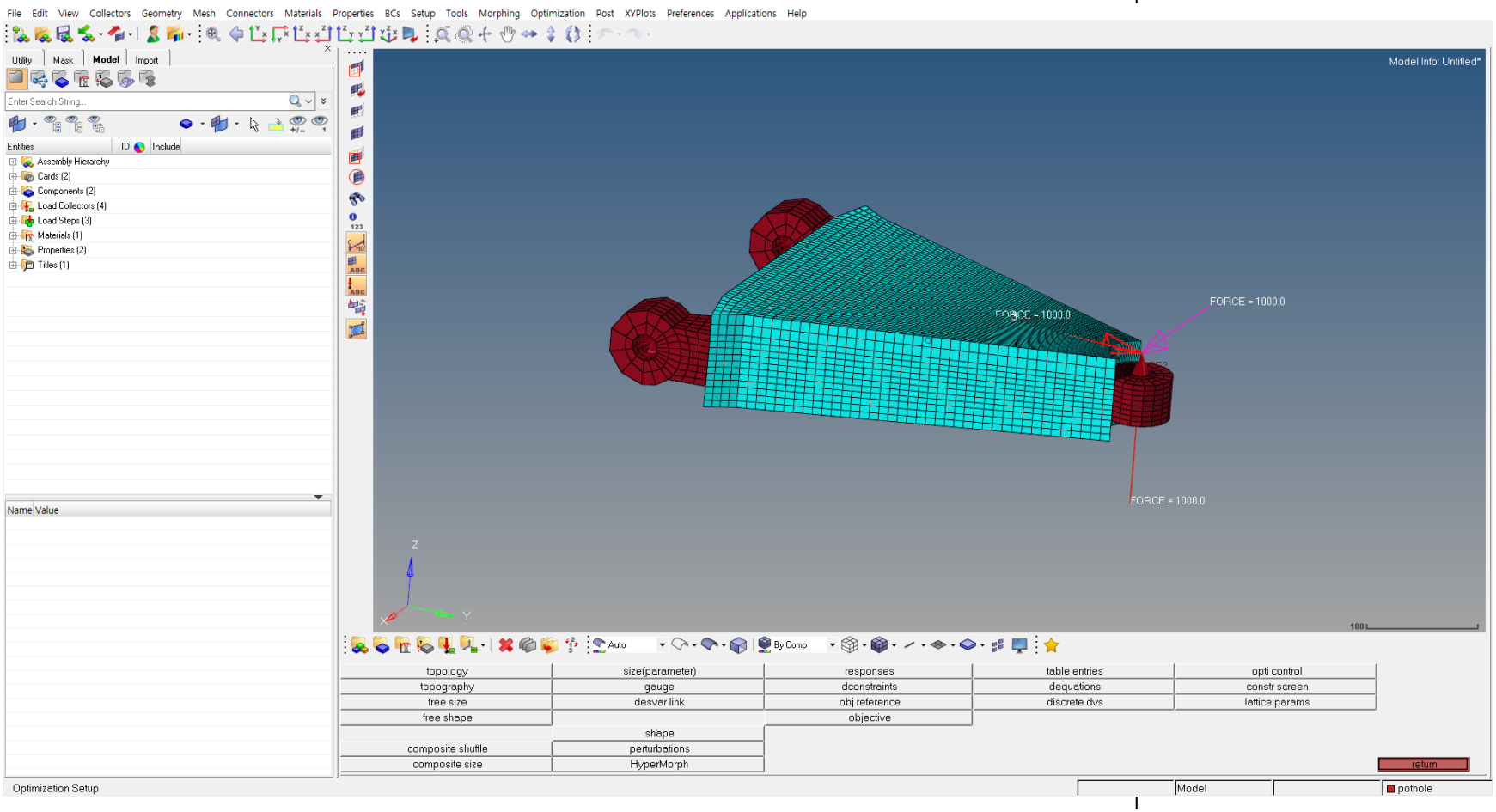
최적설계 문제 정식화

Objective:	Minimize volume.	
Constraints:	SUBCASE 1 -	The resultant displacement of the point where loading is applied must be less than 0.05mm.
	SUBCASE 2 -	The resultant displacement of the point where loading is applied must be less than 0.02mm.
	SUBCASE 3 -	The resultant displacement of the point where loading is applied must be less than 0.04mm.
Design variables:	Element density (and corresponding stiffness of the element) of each element in the design space.	

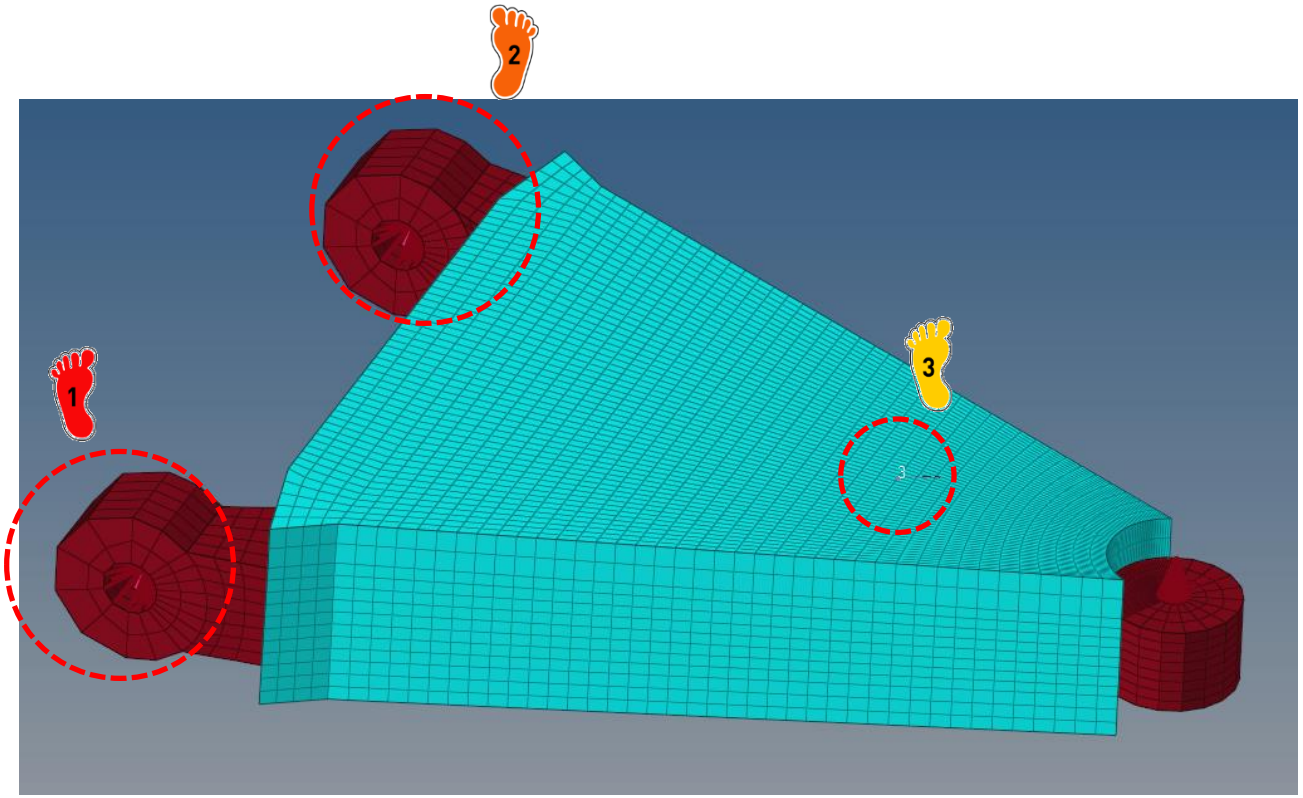
기하형상 불러오기

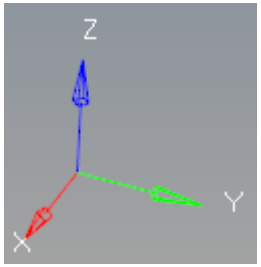
1 제공한 모델 파일을 열어서 기하형상 확인

메시, 재료 물성 및 특성이 입력되어있음



구속조건 및 하중조건 설정 [1]





1 Tx,Ty,Tz 구속

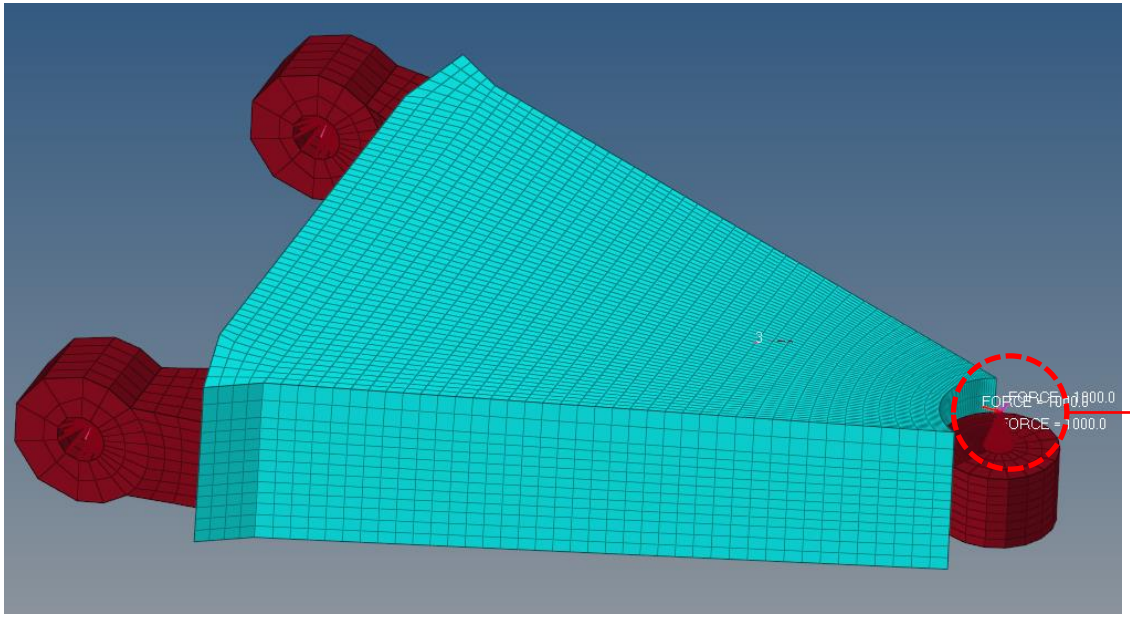
2 Ty, Tz 구속

3 Tz 구속

강체요소 가운데 절점을 구속조건으로 설정

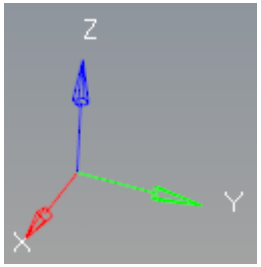
구속조건 및 하중조건 설정 [2]

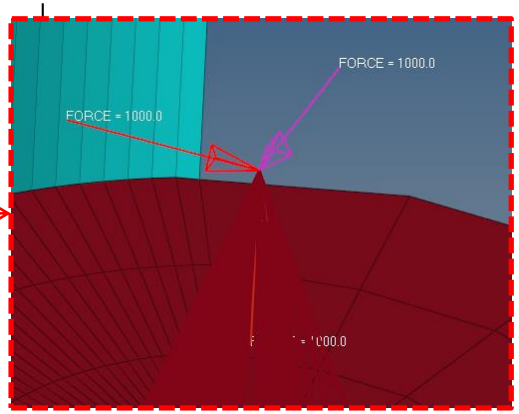
- Load Collectors (4)
  - spc 1 0
  - brake 2 0
  - corner 3 0
  - pothole 4 0
- Load Steps (3)
  - brake 1 0
  - corner 2 0
  - pothole 3 0



1 하중조건의 경우 하중세트를 구별하여 총 3가지의 하중을 생성

case1: x 방향 1000 N
case2: y 방향 1000 N
case3: z 방향 1000 N





DESIGN VARIABLE SETTING

→ **Design variable**

→ **Responses**

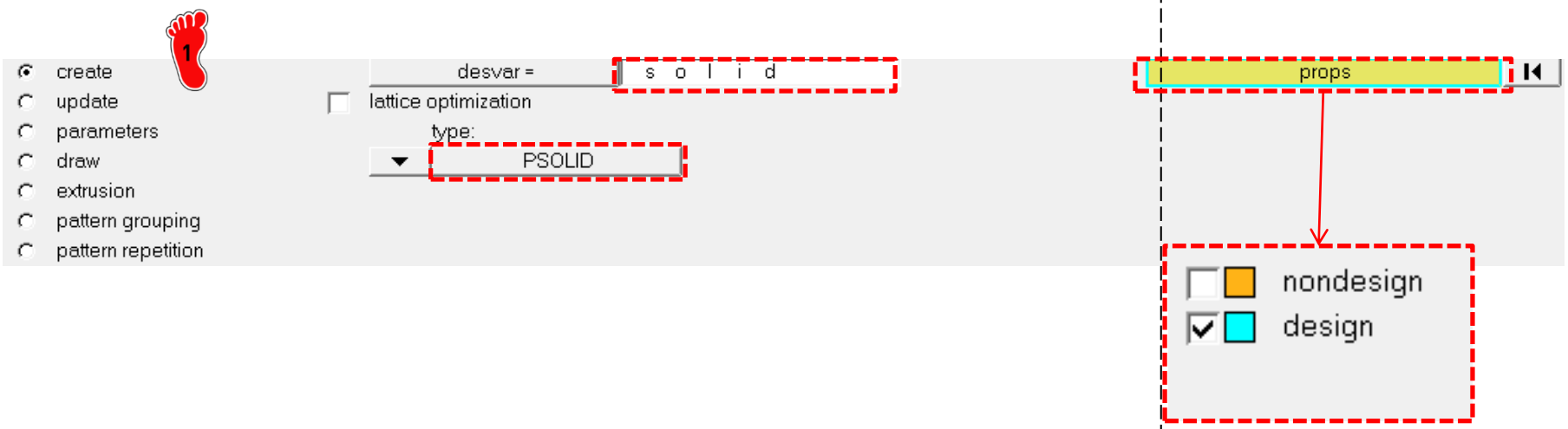
→ **Objective**

→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > topology

create



RESPONSE SETTING (1)

1 Analysis > optimization > Responses

Volumefrac > create

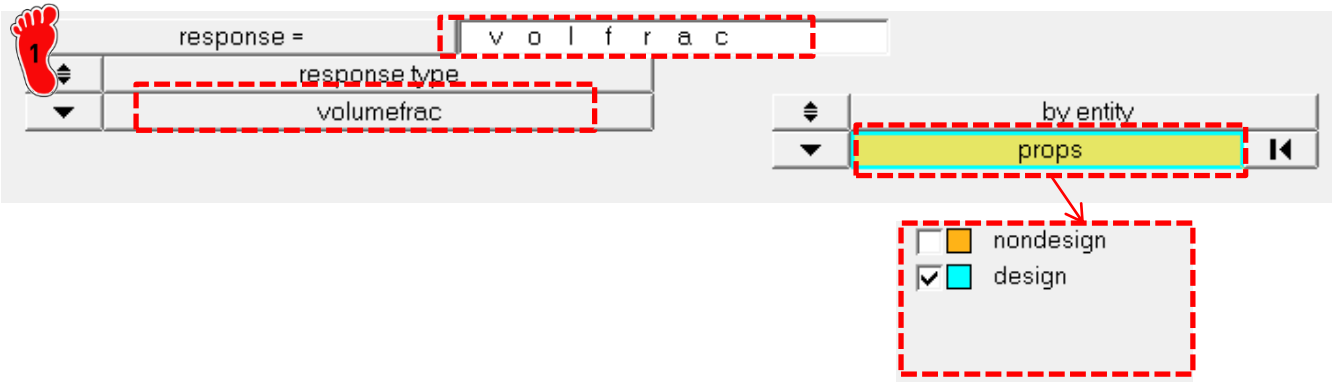
→ **Design variable**

→ **Responses**

→ **Objective**

→ **Dconstraints**

→ **Opti control**



RESPONSE SETTING (2)

→ **Design variable**

→ **Responses**

→ **Objective**

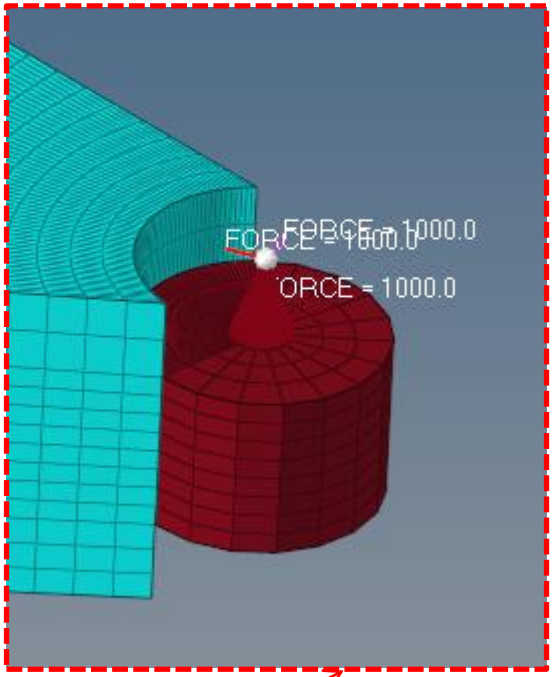
→ **Dconstraints**

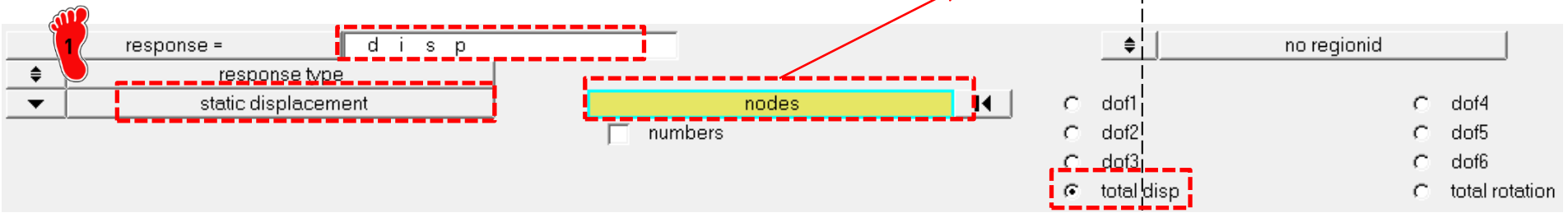
→ **Opti control**

1 Analysis > optimization > Responses

total disp

create





OBJECTIVE SETTING

→ **Design variable**

→ **Responses**

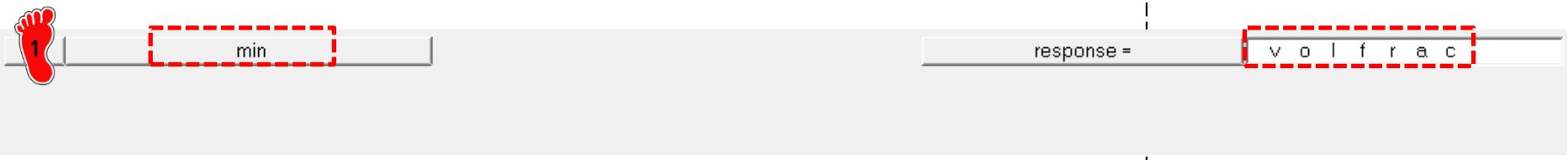
→ **Objective**

→ **Dconstraints**

→ **Opti control**

1 Analysis > optimization > Objective

create



CONSTRAINTS SETTING

→ **Design variable**

→ **Responses**

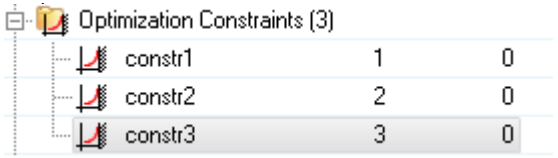
→ **Objective**

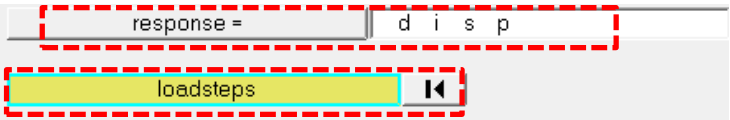
→ **Dconstraints**

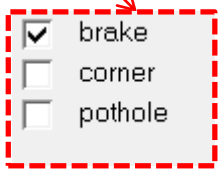
→ **Opti control**

1 Analysis > optimization > Dconstraints

3개의 constraints
Brake ≤ 0.05
Corner ≤ 0.02
Pothole ≤ 0.04
각각 생성







CONTROL SETTING

1 Analysis > optimization > Dconstraints

create

→ **Design variable**

→ **Responses**

→ **Objective**

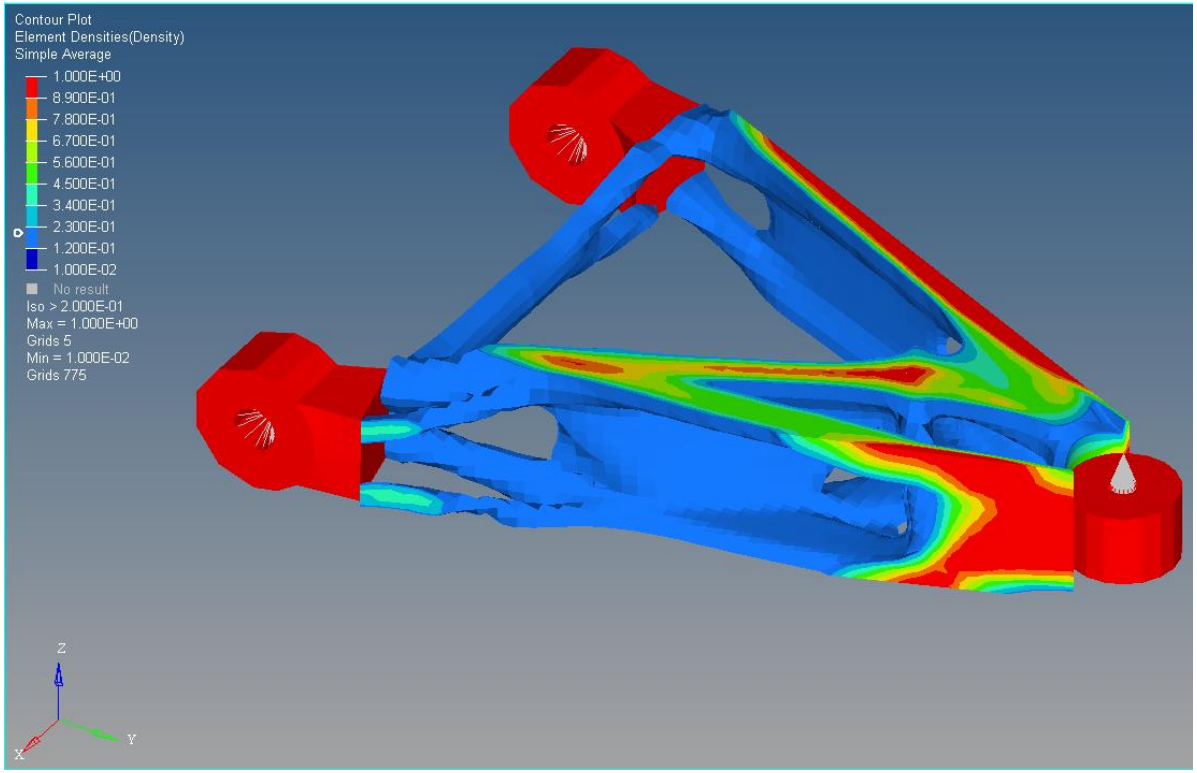
→ **Dconstraints**

→ **Opti control**

1

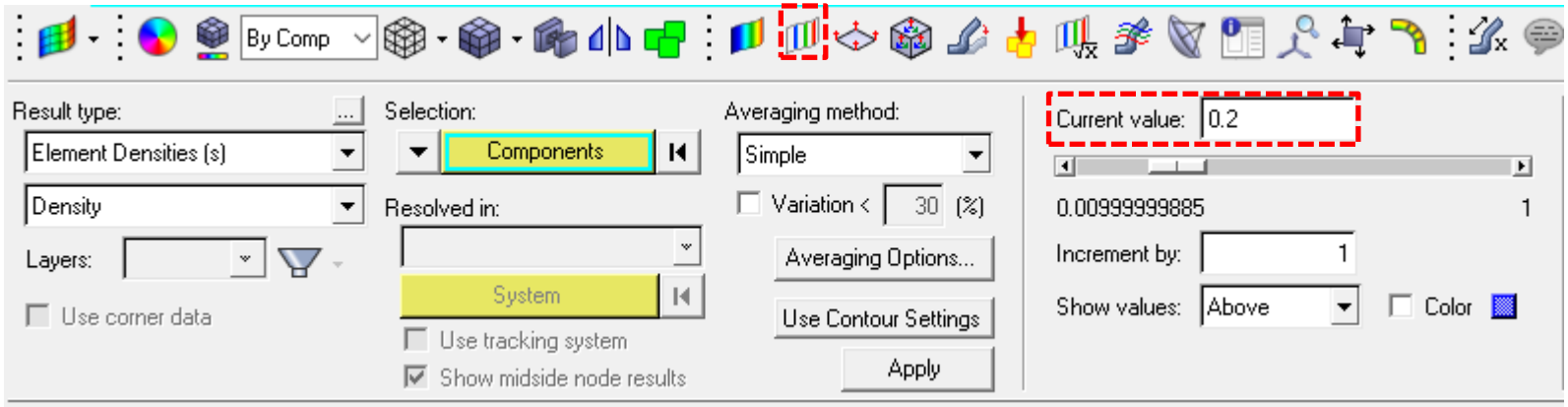
☑	DESMAX=	50	☑	OBJTOL=	0.005
☐	MINDIM=	0.000	☐	DELSIZ=	0.500
☐	MATINIT=	0.600	☐	DELSHP=	0.200
☐	MINDENS=	0.010	☐	DELTOP=	0.500
☑	DISCRETE=	3.000	☐	GBUCK=	0
☑	CHECKER=	1	☐	MAXBUCK=	10
☐	MMCHECK=	0	☐	DISCRT1D=	1.000

최적화 결과



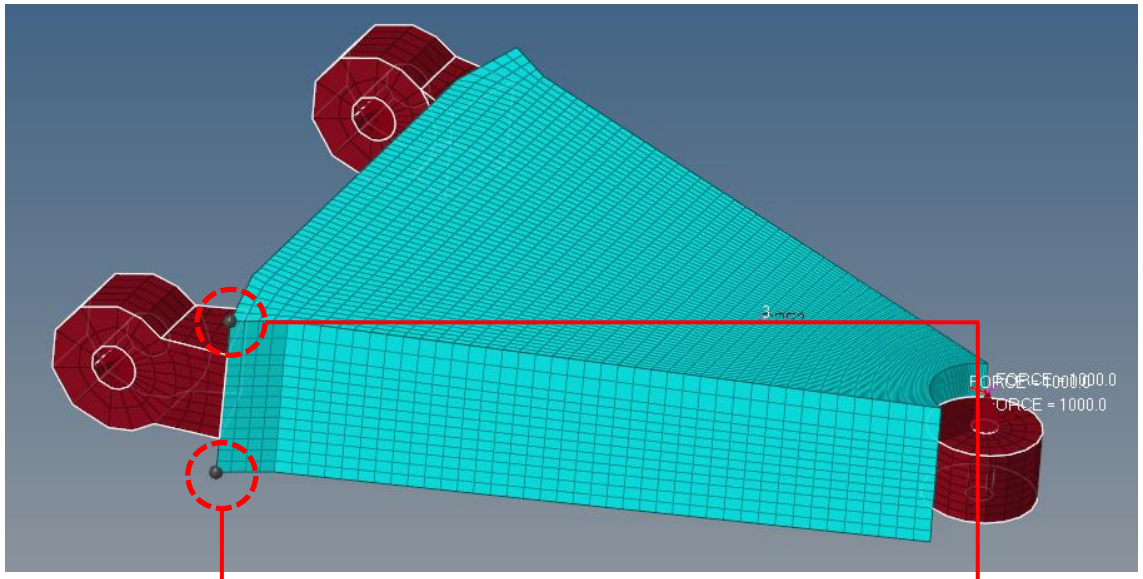
1 결과 형상 확인

2 Iso > apply



AUTOMOTIVE CONTROL ARM
(VOLUME MINIMIZATION PROBLEM)
제조 조건 추가

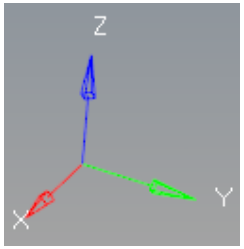
제조조건 입력

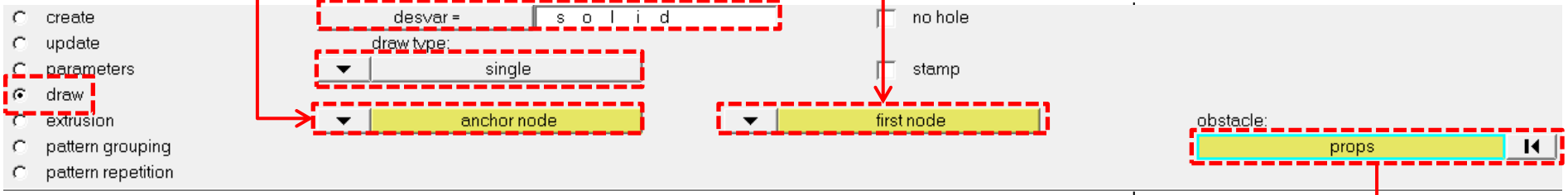


1 Analysis > optimization > topology > draw

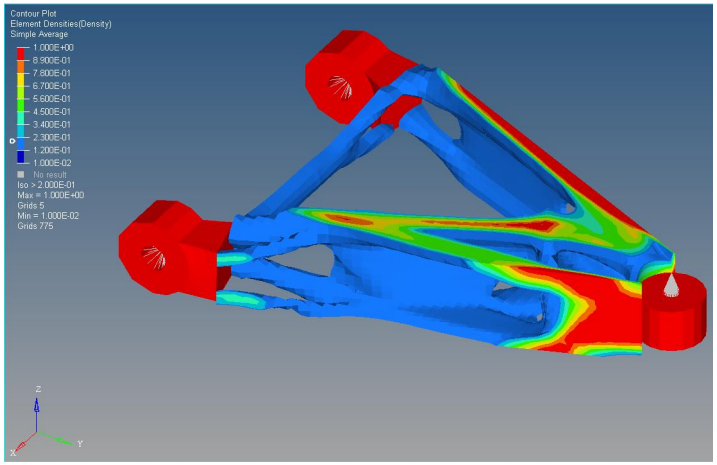
Draw direction
: First node > Anchor node

Z방향

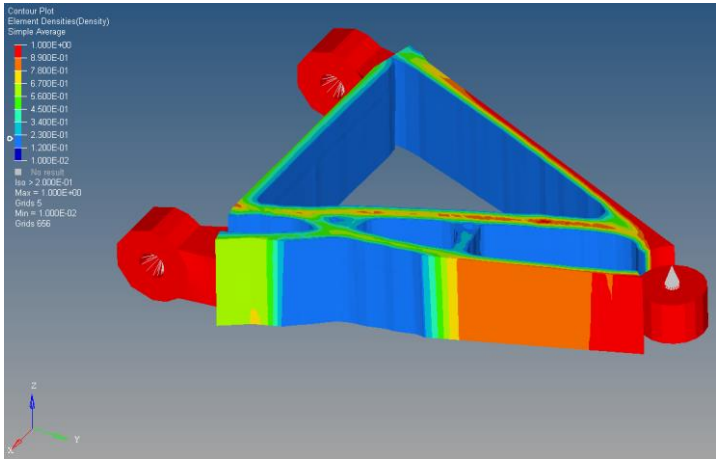




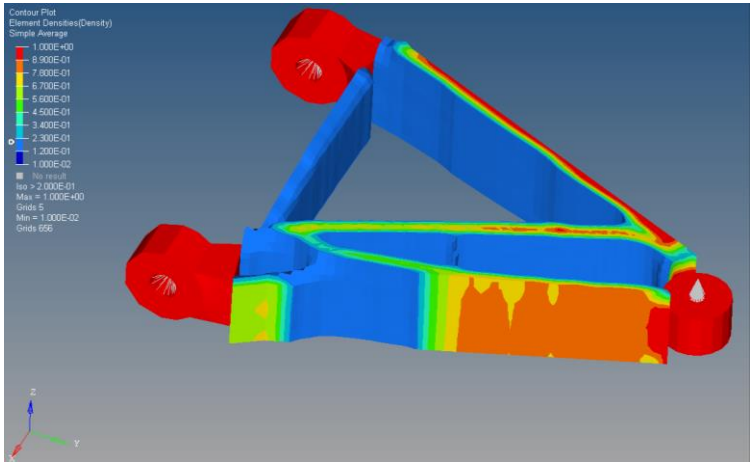
최적화 결과 비교



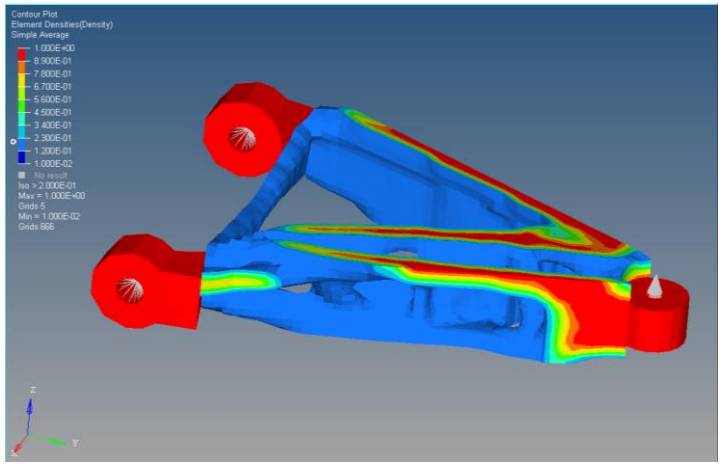
제조조건 없음
Obj = 0.0867



Extrusion(z), no twist
Obj = 0.1780



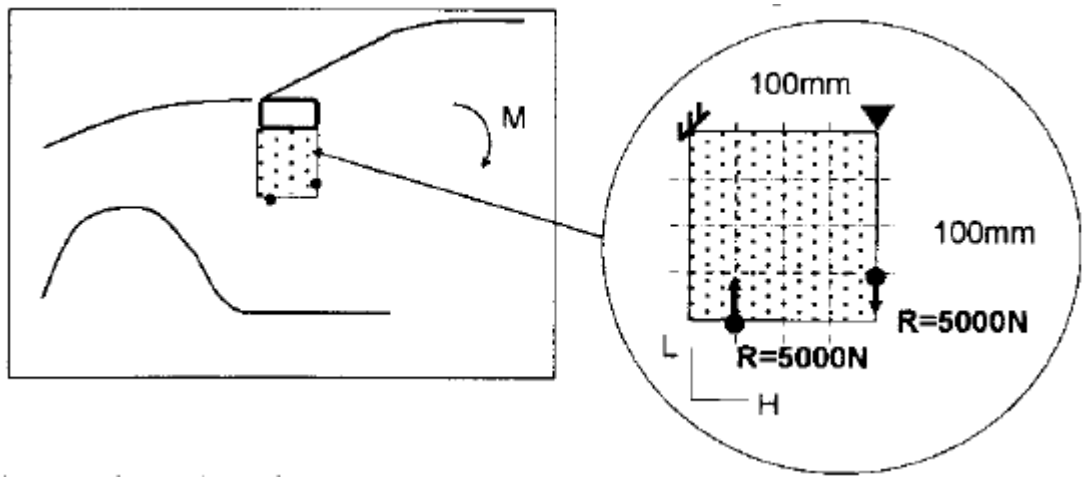
Draw single(z)
Obj = 0.1662



Draw split(z)
Obj = 0.1294

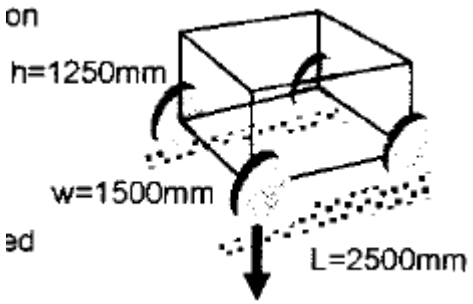
숙제: 2D 문제

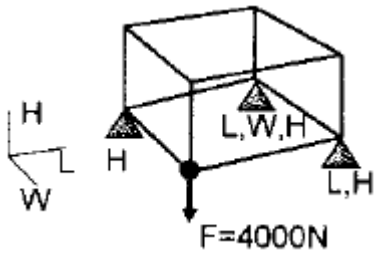
- The steering column bracket holds the steering column at two points (the solid black circle above). When the maximum moment is applied to the steering column, the bracket must react loads at the attachment R as shown.
- Determine the optimal shape of the steel bracket to maximize the stiffness under loads R. The bracket is flat (w=0) and at most 100mm x 100mm

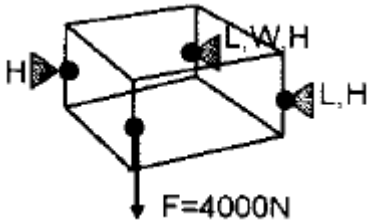


숙제: 3D 문제

- The van shown is supported on three wheels with the fourth wheel unsupported. This condition applies a force downward at the left front suspension (F=4000N). We wish to maximize the stiffness under this load condition for a fixed volume of structural material. The structure is made of a set of interconnected steel beams which are enclosed by the area shown.
- Determine the optimal shape for the four conditions shown below.







Suspension attachment: (1) at corners (2) mid-way up edge