Wind Turbine Blade 내부 Spar ‘I’ beam 최적설계

The Alchemist

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Contents

Problem Statement

▪ Problem Statement

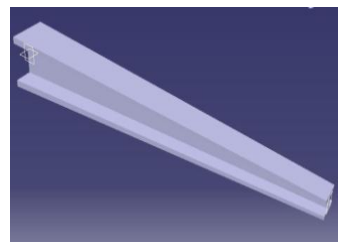
1. Necessary Condition

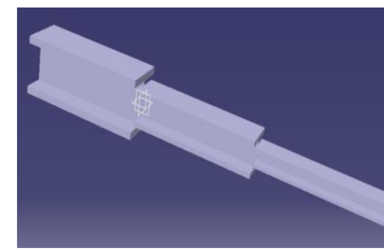
   - Do not exceed allowable stress

2. Optimization

   - Minimize total turbine blade area

3. turbine blade의 길이를 9m로 가정.



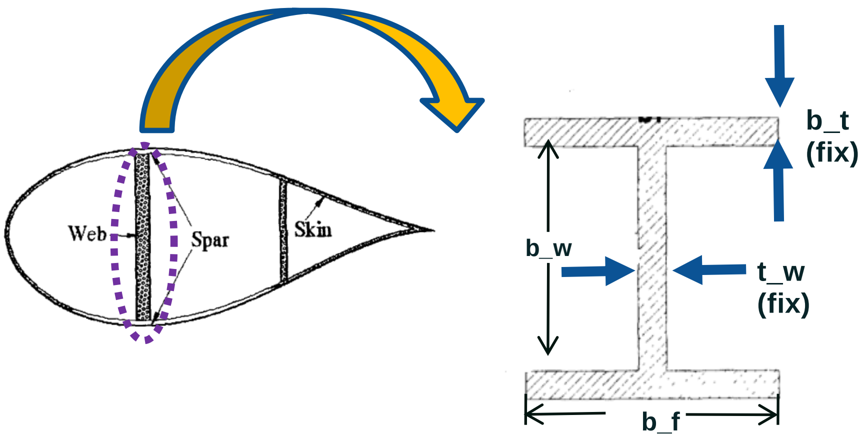


4. turbine blade를 3개의 part로 나누어 분석 진행.

	part1	part2	part3
b_t[mm]	64	95	140
w_t[mm]	28	55	80

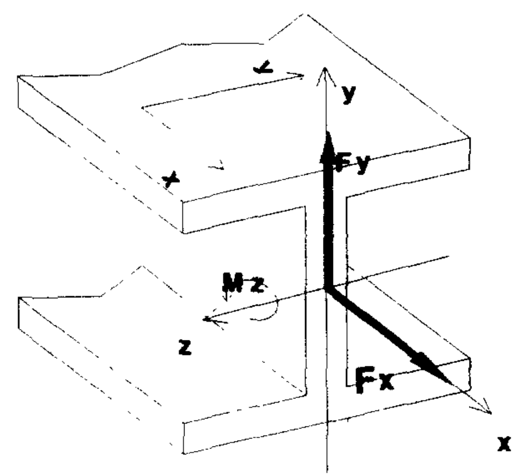
Data & Information collection

- ## Data & Information collection



Station R	0.286	0.51	0.755
$F_x[kn]$	325.7	239.9	131.4
$F_y[kn]$	90.4	71.3	44.2
$M_z[kn*m]$	1083.4	583.1	195.8

Station R	0.286	0.51	0.755
b_f [mm]	1031	783	512
b_w [mm]	803	465	214



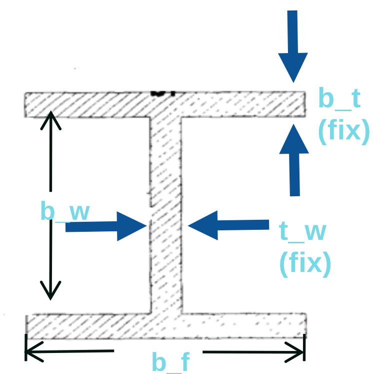
Problem formulation

▪ Objective Function

$$f = 2b_f b_t + b_w t_w$$

- Minimize total turbine blade area

▪ Design Variable



- b_f : I beam의 flange 길이
- b_w : I beam의 web 길이

▪ Constraints

$$\frac{F_x}{A} + \frac{M_z(y)}{I_z} \le \frac{X_t}{5}$$; Flange의 인장 응력

$$-\left(\frac{F_x}{A} + \frac{M_z(-y)}{I_z}\right) \le \frac{X_c}{5}$$; Flange의 압축 응력

$$\tau_{xy} = \frac{Fy}{A} \le \tau^*_{xy}(allow)$$; Web의 전단응력

$$F_x \le \frac{\pi E I_z}{Le^2}$$; Flange에 대한 좌굴해석

$$F_y \le \frac{\pi E I_z}{Le^2}$$; Web에 대한 좌굴해석

Optimization results

▣ Excel(Newton's method)

1st

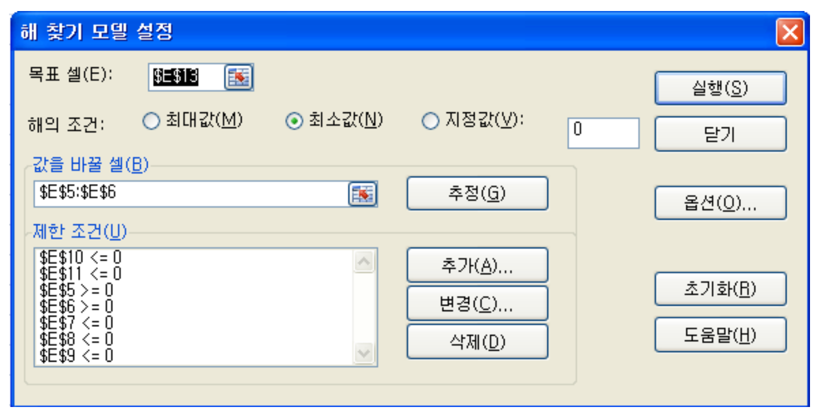
design variables	initial value	Newton method solution
x1=bf	5.120E+02	4.090E+01
x2=bw	2.140E+02	7.039E+02
constraint1	3.623E+02	-3.767E-09
constraint2	2.565E+02	-1.982E+02
constraint3	-1.756E+02	-1.808E+02
constraint4	-6.838E+06	-4.276E+05
constraint5	-2.191E+08	-1.581E+06
f	7.153E+04	2.494E+04

2nd

design variables	initial value	Newton method solution
x1=bf	7.830E+02	5.576E+01
x2=bw	4.650E+02	8.523E+02
constraint1	1.268E+02	9.131E-07
constraint2	2.251E+01	-1.884E+02
constraint3	-1.802E+02	-1.815E+02
constraint4	-5.575E+08	-3.960E+07
constraint5	-2.321E+08	-4.865E+06
f	1.743E+05	5.747E+04

3rd

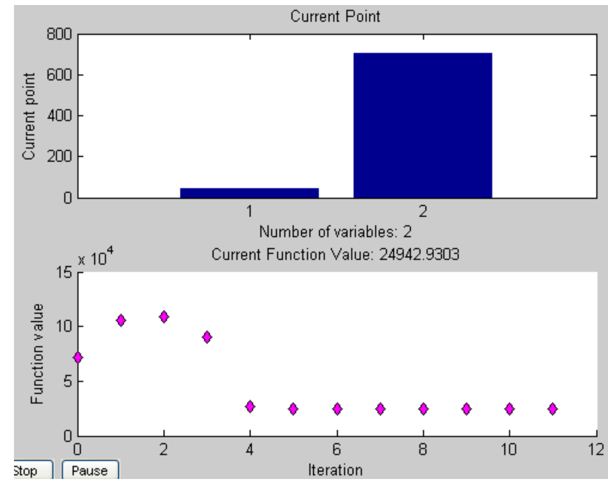
design variables	initial value	Newton method solution
x1=bf	1.030E+03	5.534E+01
x2=bw	7.900E+02	9.615E+02
constraint1	-1.049E+01	5.556E-07
constraint2	-1.128E+02	-1.819E+02
constraint3	-1.816E+02	-1.818E+02
constraint4	-2.348E+09	-1.261E+08
constraint5	-3.385E+08	-1.222E+07
f	3.516E+05	9.241E+04



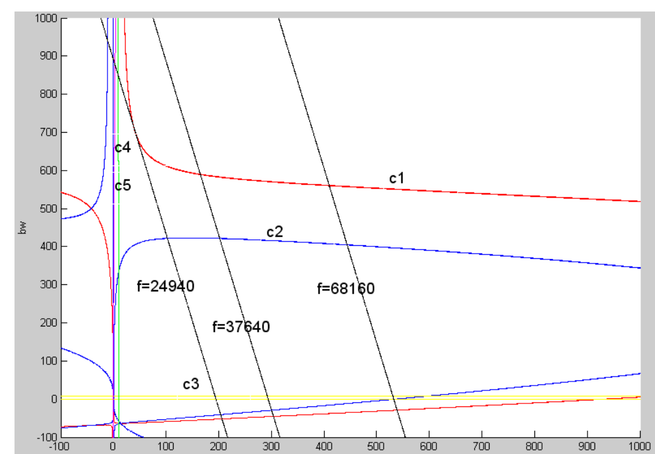
Optimization Tool ; MATLAB

- 1st part (fmincon; ‘interior-point’, ‘active set’ / pattern search)

```
x0=[512 214 ];
lb=[0,0];
ub=[inf,inf];
[x fval exitflag]=fmincon(@b1,x0,[],[],[],[],lb,ub,
@con_blade1,optimset('Algorithm','active-set'))

Active inequalities (to within options.TolCon = 1e-006):

  lower      upper     ineqlin   ineqnonlin
                                      1

x          =   40.8990  703.8520
fval       =  2.4943e+004
exitflag =      5
```



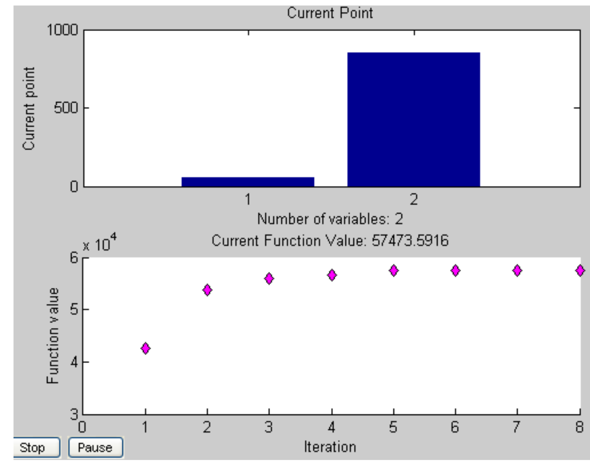
design	initial	Fmincon	Avtive-set	(480 590)	pattern	(480 590)
bf(mm)	5.12E+02	4.09E+01	4.09E+01	4.10E+02	4.02E+01	1.65E+02
bw(mm)	2.14E+02	7.03E+02	7.03E+02	5.60E+02	7.07E+02	5.90E+02
Con1	3.60E+02	2.21E-05	2.21E-05	4.18E-01	-1.23E-02	7.36E-02
Con2	2.50E+02	-1.98E+02	-1.98E+02	-1.07E+02	-2.00E+02	-1.22E+02
Con3	-1.70E+02	-1.80E+02	-1.80E+02	-1.80E+02	-1.80E+02	-1.80E+02
Con4	-6.80E+06	-4.27E+05	-4.27E+05	-5.45E+06	-4.18E+05	-2.11E+06
Con5	-2.10E+08	-1.58E+06	-1.58E+06	-2.55E+07	-1.53E+06	-9.25E+06
f(mm^2)	7.10E+04	2.49E+04	2.49E+04	6.81E+04	2.49E+04	3.76E+04



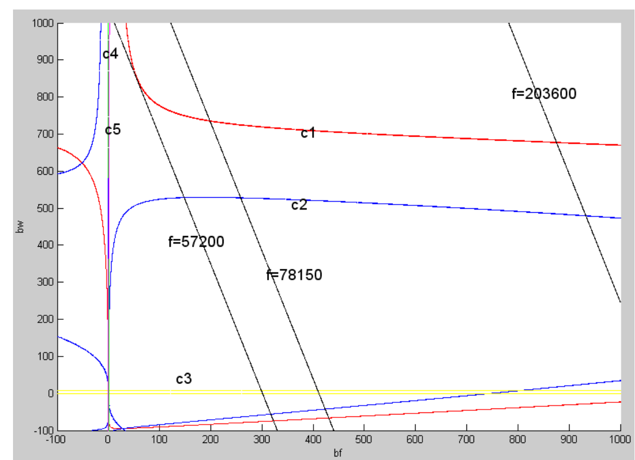
Optimization Tool ; MATLAB

- 2nd part (fmincon; ‘interior-point’, ‘active set’ / pattern search)

```
x0=[55 645];
lb=[0,0];
ub=[inf,inf];
[x fvalexitflag]=fmincon(@b2,x0,[],[],[],[],lb,ub,
@con_blade2,optimset('Algorithm','active-set'))

Active inequalities (to within options.TolCon = 1e-006):

  lower      upper      ineqlin    ineqnonlin
                                        1
x          =   55.7582   852.3552
fval       =  5.7474e+004
exitflag =     1
```



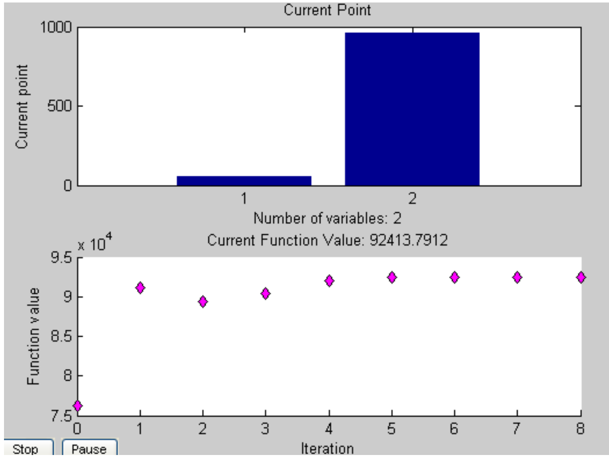
design	initial	fmincon	Active-set	(55 645)	pattern	(780 700)
bf(mm)	7.8E+02	5.50E+01	2.00E+02	5.50E+01	5.30E+01	5.27E+02
bw(mm)	4.6E+02	8.50E+02	7.30E+02	8.50E+02	8.60E+02	7.00E+02
Con1	1.2E+02	1.19E+00	2.10E+00	1.19E+00	5.87E-01	8.31E-03
Con2	2.2E+01	-1.88E+02	-1.20E+02	-1.88E+02	-1.92E+02	-1.07E+02
Con3	-1.8E+02	-1.81E+02	-1.81E+02	-1.81E+02	-1.81E+02	-1.81E+02
Con4	-5.5E+08	-3.90E+07	-1.42E+08	-3.90E+07	-3.76E+07	-3.75E+08
Con5	-2.3E+08	-4.82E+06	-2.40E+07	-4.82E+06	-4.53E+06	-6.88E+07
f(mm^2)	1.7E+05	5.72E+04	7.81E+04	5.72E+04	5.72E+04	2.03E+05



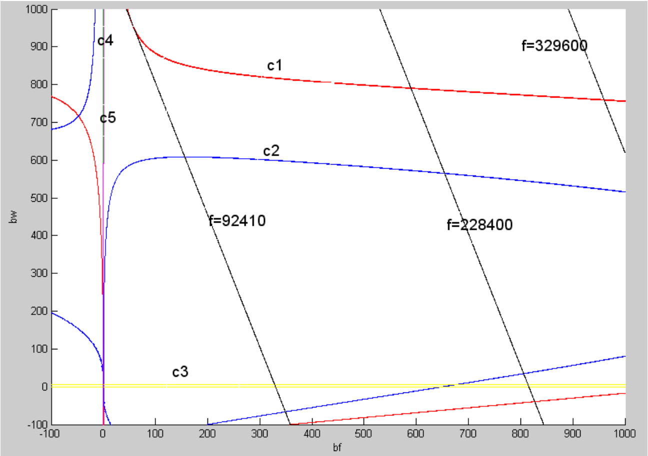
Optimization Tool ; MATLAB

▣ 3rd part (fmincon; 'interior-point', 'active set' / pattern search)

```
x0=[55 760];
lb=[0,0];
ub=[inf,inf];
x fval exitflag]=fmincon(@b3,x0,[],[],[],[],lb,ub,
@con_blade3,optimset('Algorithm','active-set'))

Active inequalities (to within options.TolCon = 1e-006):

  lower      upper     ineqlin   ineqnonlin
                                    1
x         =   55.3443  961.4674
fval      =  9.2414e+004
exitflag =    4
```



design	initial	fmincon	Active-set	(55,760)	pattern	(55,760)
bf(mm)	1.00E+03	5.50E+01	5.90E+02	5.50E+01	9.60E+02	5.10E+01
bw(mm)	7.90E+02	9.60E+02	7.90E+02	9.60E+02	7.60E+02	9.70E+02
Con1	-1.00E+01	5.90E-01	4.18E-01	5.90E-01	6.84E-02	1.77E+00
Con2	-1.10E+02	-1.81E+02	-1.05E+02	-1.81E+02	-1.02E+02	-1.87E+02
Con3	-1.80E+02	-1.81E+02	-1.81E+02	-1.81E+02	-1.81E+02	-1.81E+02
Con4	-2.30E+09	-1.25E+08	-1.34E+09	-1.25E+08	-2.18E+09	-1.16E+08
Con5	-3.30E+08	-1.21E+07	-1.93E+08	-1.21E+07	-3.40E+08	-1.10E+07
f(mm^2)	3.50E+05	9.22E+04	2.28E+05	9.22E+04	3.29E+05	9.18E+04



Optimization result

design	initial	excel	fmincon	pattern
bf(mm)	5.10E+02	4.09E+01	4.09E+01	4.02E+01
bw(mm)	2.10E+02	7.03E+02	7.03E+02	7.07E+02
Con1	3.60E+02	-3.76E-09	2.21E-05	-1.23E-02
Con2	2.50E+02	-1.98E+02	-1.98E+02	-2.00E+02
Con3	-1.70E+02	-1.80E+02	-1.80E+02	-1.80E+02
Con4	-6.80E+06	-4.27E+05	-4.27E+05	-4.18E+05
Con5	-2.10E+08	-1.58E+06	-1.58E+06	-1.53E+06
f(mm^2)	7.10E+04	2.49E+04	2.49E+04	2.49E+04

1st

design	initial	excel	fmincon	pattern
bf(mm)	7.8E+02	5.57E+01	5.50E+01	5.30E+01
bw(mm)	4.6E+02	8.52E+02	8.50E+02	8.60E+02
Con1	1.2E+02	9.13E-07	1.19E+00	5.87E-01
Con2	2.2E+01	-1.88E+02	-1.88E+02	-1.92E+02
Con3	-1.8E+02	-1.81E+02	-1.81E+02	-1.81E+02
Con4	-5.5E+08	-3.96E+07	-3.90E+07	-3.76E+07
Con5	-2.3E+08	-4.86E+06	-4.82E+06	-4.53E+06
f(mm^2)	1.7E+05	5.74E+04	5.72E+04	5.72E+04

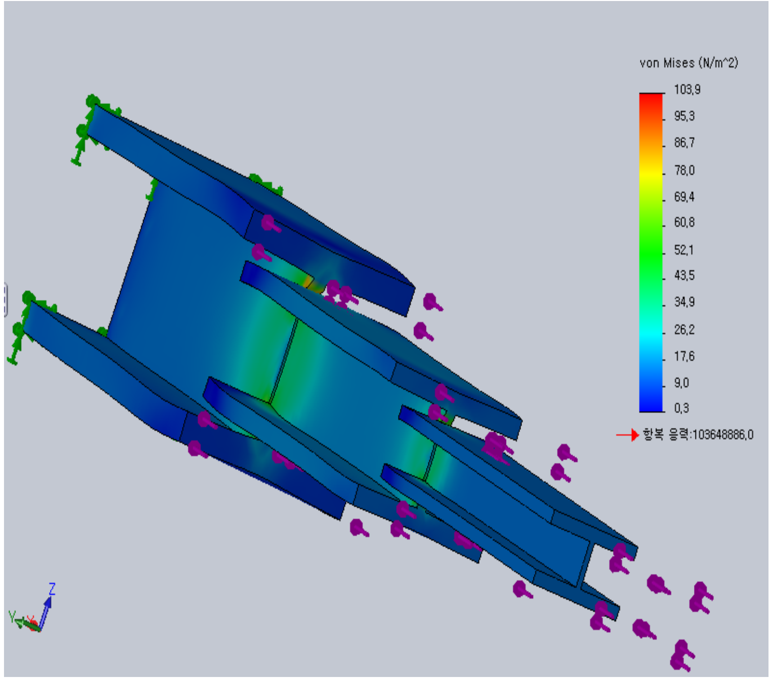
2nd

design	initial	excel	fmincon	pattern
bf(mm)	1.00E+03	5.53E+01	5.50E+01	5.10E+01
bw(mm)	7.90E+02	9.61E+02	9.60E+02	9.70E+02
Con1	-1.00E+01	5.55E-07	3.00E-04	1.77E+00
Con2	-1.10E+02	-1.81E+02	-1.80E+02	-1.87E+02
Con3	-1.80E+02	-1.81E+02	-1.80E+02	-1.81E+02
Con4	-2.30E+09	-1.26E+08	-1.20E+08	-1.16E+08
Con5	-3.30E+08	-1.22E+07	-1.20E+07	-1.10E+07
f(mm^2)	3.50E+05	9.24E+04	9.20E+04	9.18E+04

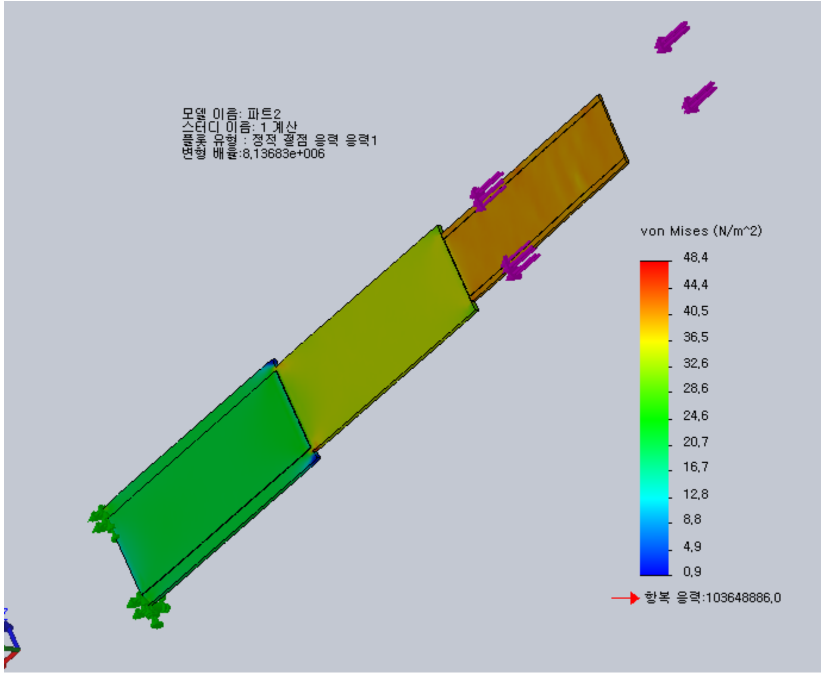
3rd

Optimization result model rod analysis

▣ Model rod analysis [using SOLIDWORKS]



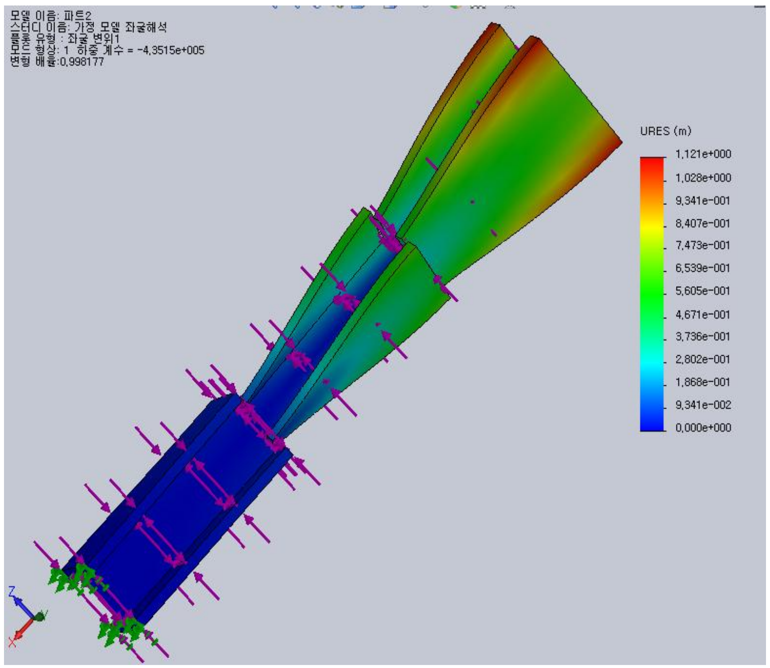
[가정한 모델의 정적하중 해석]



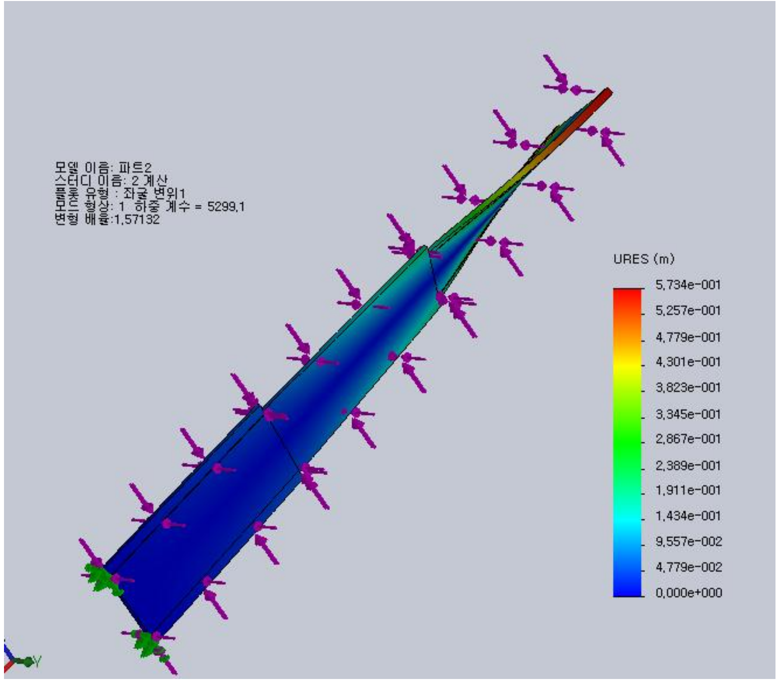
[최적화된 모델의 정적하중 해석]

Optimization result model buckling analysis

▣ Model buckling analysis [using SOLIDWORKS]



[가정한 모델의 좌굴 해석]



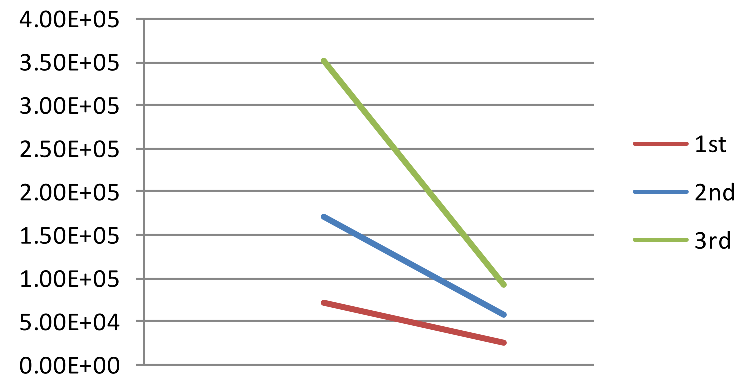
[최적화된 모델의 좌굴 해석]

Discussion

▪ Discussion

1. 최적화의 목적인 blade의 면적이 감소

design	1st	opt	2nd	opt	3rd	opt
bf(mm)	5.10E+02	4.00E+01	7.8E+02	5.50E+01	1.00E+03	5.50E+01
bw(mm)	2.10E+02	7.00E+02	4.6E+02	8.50E+02	7.90E+02	9.60E+02
f(mm^2)	7.10E+04	2.40E+04	1.7E+05	5.70E+04	3.50E+05	9.20E+04



2. 1st part, 2nd part, 3rd part 모두 Local minimum;
   초기값 설정에 따라 결과값이 변화

3. 알고리즘의 차이로 인해 최적 해의 값에 차이가 존재

Reference

1) 공창덕,방조혁,정종철,강명홍,정석훈,장병섭,안주연, 2006, “IEC1400-1 국제표준을 적용한 대형 수평축 풍력 발전용 회전날개 설계개선”

2) Mayer Rayner M., “Design of composite structures against fatigue : applications to wind turbine blades” , Mechanical Engineering Publications

3) Arora, Jasbir S, “Introduction to optimum design”, Elsevier.Academic Press

4) Ferdinand P. Beer , Jr., E. Russell Johnston, John T. DeWolf, “Mechanics of Materials” , Mc graw hill

Q & A