# **Explicit Dynamic Analysis (1)**

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### OUTLINE

#### Lecture Goals

- ✓ Tube(shell 요소)모델의 외연적 동적 해석(explicit dynamic analysis)
  - 을 수행하고 충돌 결과를 분석한다.

#### Contents

- ✓ Tube impact analysis (RADIOSS example)
- ✓ Axial crush load of square section

### • 해석 프로세스

- ▶ 기하형상 생성
- ▶ 재료 물성 및 특성 입력
- ▶ 요소망생성
- ▶ 구속조건 설정
- ▶ 하중조건 설정
- ▶ 해석케이스 정의 및 해석 실행
- ▶ 후처리

#### 차체구조

### INTRODUCTION

Crash analysis of body structure



### INTRODUCTION

표 7.7.1 내연적(Implicit)과 외연적(Explicit) 적분 알고리즘 비교

<ul> <li>·선형 과도응답해석의 경우 큰 시간 스텝을 적용할 수 있음</li> <li>·비선형 과도응답해석의 경우 수렴성 확보를 위해 작은 시간 스텝을 사용해야 하는 단점이 있음</li> <li>·대규모 모델인 경우에는 메모리 사용량 및 하드디스크 용량의 제한이 있을 수 있음</li> </ul>	<ul> <li>수렴성에 대한 문제 없이 해가 구해짐</li> <li>소규모 모델인 경우에는 암시적 방법에 비해 해석 시간이 좀 더 많이 소요되나 대규모 모델에서는 상대적으로 유리함</li> <li>시간 간격은 항상 임계 시간 간격보다 작은 값으로 정의</li> </ul>

 $f(x_{n+1}, x_n, \dots) = 0$ 

 $x_{n+1} = f(x_n, \dots)$ 

# TUBE IMPACT ANALYSIS (RADIOSS EXAMPLE)

### 예제: TUBE IMPACT EXAMPLE

Simulate buckling of a tube using half tube mesh with symmetric boundary conditions.

The figure illustrates the structural model used for this tutorial: a half tube with a rectangular section (38.1 x 25.4 mm) and length of 203 mm.



- The tube thickness is 0.914 mm.
- $\rho = 7.85e^{-6} \text{ Kg/mm}^3$
- E = 210 GPa
- v = 0.33
- σ<sub>0</sub> = 0.206 GPa

- Initial density
- Young's modulus
- Poisson coefficient
- [a] Yield Stress

### HYPERCRASH 실행



## 유한요소해석 모델 불러오기





### 재료 물성 입력

Barlat2000 (87)

#### HyperCrash Elasto-plastic 재료의 종류 (/MAT/LAW#)

• This model expresses material stress as a function of strain, strain rate and temperature. Johnson-Cook (2) Zerilli-Armstrong (2) Particular type of Mises plasticity model with analytical forms of the hardening law and rate Hyd. Elasto-plastic (3) dependence. Hyd. Johnson-Cook (4) Ductile damage (22) JC is suitable for high-strain-rate deformation of many materials Ductile damage (23)  $\sigma = (\underline{a+b}\varepsilon_p^n)(\underline{1+c\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}})(\underline{1-T^{*m}})$ Plastic brittle for shell (27) Hill orthotropic (32) Influence of temperature change Piecewise linear (36) Influence of strain rate Hill ortho. tab. (43) Cowper-Symonds (44) Influence of plastic strain Zhao (48)  $\sigma$ = Stress n = Hardening Exponent Steinberg-Guinan (49) = Plastic strain c = Strain rate coefficient Gurson (52) a =Yield stress Tsai-Wu tabulated (53)  $\dot{\varepsilon} = \text{Strain rate}$ Barlat (57) b = Hardening modulus  $\dot{\varepsilon}_0$  = Reference strain rate Piecewise non-linear (60) Hansel trip steel (63) Strain Hardening Necking U&A trip steel (64) True Stress Strain Curve **Ultimate Strength** Elastomer (65) Engineering Stress Strain Curve Plasticity compression tension (66) New Eastic Curve After Pastic Deformation Anisotropic Hill (72) **Yield Strength** Stress Thermal Hill orthotropic (73) Elastic Fracture Limit Thermal Hill orthotropic for solids (74) Semi Analytic Plastic (76) Strain Yoshida Uemori (78) Johnson-Holmquist (79) Elastic Region Plastic Region Area Under Curve = Total Energy Dissipation Potential Hot stamping (80) % Elongation Swift-Voce (84) 년 0.2% Elongation Offset Strain

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### 재료 물성 입력

Heat

ALE

Support\*

	<u></u> .				•
Model LoadCase RADIOSS Tool:	s Dat	60 Review	→I		
Browser		Create New	Airbag material	Fille	i –
		Create Template	Composite and Fabric	F	
Part		🗙 Delete	Connection	F.	i .
👔 Material		Clone	Elastic and Hyperelastic	•	1
😅 Property		Cross Reference	Elasto-plastic	▶ Johnson-Cook (2)	i -
Add to Material	•	Mesh Support	Honeycomb	<ul> <li>Zerilli-Armstrong (2)</li> </ul>	1
Friction		Lock	Hydrodynamic	Hyd. Elasto-plastic (3)	1 - I
i -		UnLock	Rock and Concrete	Hyd. Johnson-Cook (4)	1 - C
		2			
itte		New MAT 2			
ocal Unit System		None			
RHO_[] Initial density*		7.85E-6			
RHO_0] Reference density		0			
E] Young's modulus*		210			
Nu] Poisson's ratio		.3			
Iflact Electronic to the second		0. Classis issue for Johnson Cook of	and the state of t		

[Iflag] Flag for input type ): Classic indut for Johnson-Cook darameter a.d.n is [a] Plasticity yield stress\* [b] Plasticity hardening parameter 0 [n] Plasticity hardening exponent 0 [EPS p max] Failure plastic strain 0 [SIG\_max0] Plasticity maximum stress 0 [c] Strain rate coefficient 0 Include picked parts [EPS\_DOT\_0] Reference strain rate 0 Add selected parts by box [Fsmooth] Strain rate Smoothing £ [F\_cut] Cutoff frequency for strain rate filtering 0 [Flag] Hardening coefficient(define between 0 and 1) Add selected parts of Tree 0: Isotropic model [Chard] Hardening coefficient(unloading) 0 [m] Temperature exponent Remove selected parts of Tree [T\_melt] Melting temperature 0 [rhoC\_p] Specific heat per unit of volume 0 Add selected parts of Browser 0 [T\_r] Room temperature [ICC] Strain rate computation 0: Default set to Clean selected part(s) п 1 PART





						_				
Mod	del LoadCase	RADIOSS Tools	Dat	645	Review	•	1			
Ŀ	Browser			6	Create New	•	Airbag	Þ	1	
$\bigcirc$	Part				Create Template	Þ	Line	Þ		
8	Material			X	Delete		Surface	Þ	Pcompp	
øţ,	Property				Clone		Volume	Þ	Shell (1)	

<b>D</b>	
HELL	
6	3
Title	New PROP 3
Local Unit System	None
[Ismstr] Flag for shell small strain formulation	0: Use value in /DEF_SHELL
[Ishell] Flag for 4 node shell element formulation	0: Use value in /DEF_SHELL
[Ish3n] Flag for 3 node shell element formulation	0: use value in /DEF_SHELL
[Idrill] Flag for drilling degree of freedom stiffness	0: No
[P_thick_fail] Percentage of through thickness integration	0
[hm] Shell membrane hourglass coefficient	0
[hf] Shell out of plane hourglass	0
[hr] Shell rotation hourglass coefficient	0
[dm] Shell membrane damping	0
[dn] Shell numerical damping	0
[N] Number of integration points through the thickness	0
[Istrain] Flag to compute strains for post-processing	0: Use value in /DEF_SHELL
[Thick] Shell thickness*	.914
[Ashear] Shear factor	0
[Ithick] Flag for shell resultant stresses calculation	0: Default set to value defined with /DEF_SHELL
[Iplas] Flag for shell plane stress plasticity	0: Default set to value defined with /DEF_SHELL
Support*	11 items



Mesh Editing > Rigid Body

2 Slave nodes 항목에서 마우 스 우클릭 후 Select in graphics 선택 > Add nodes by box selection

'그림과 같이 tube 끝 절점

선택 후 save 클릭

클릭, 마우스 우클릭 후

Create New 클릭

선택

## 강체 요소 생성



RBODY	4
Title	New RBODY 1
Local Unit System	None
Master node in time History	
Lagrange multipliers	
Automatic master node	
Flag for activate/deactivate in run	0: Not ON/OFF in current Engine file (or docked)
[MASS] Mass	0
[Jxx] JXX inertia	0
[Jyy] JYY inertia	0
[Jzz] JZZ inertia	0
[Jxy] JXY inertia	0
[Jyz] JYZ inertia	0
[Jxz] JXZ inertia	0
[ISPHER] Inertia	0: Default, set to 2
[ISENS] Sensor	None
[NSKEW] Skew	None
[IKREM] Keep slave nodes in rigid wall	
[ICOG] Center of gravity computation	0: Default, set to 1
[loptoff] Manage domain decomposition of rigid body for	0: CPU cost of elements associated with rigid body is
[lexpams] Manage connection through the rigid body bet	0: if the rigid body overlaps the AMS and non AMS do
[Gnod_id] Slave nodes*	None

Add/Remove nodes by picking selection

Add/Remove nodes by ellipse selection



## 구속조건 설정 (1)



ע 🤤	D	1
71 - 5	Title	New BCS 1
6 1	ALE formul.	
di l	Lagrange mult. formul.	
11 il	▼ Translation	
-  i	[TX] X translation	
!	[TY] Y translation	
- 1	[TZ] Z translation	
- 1	▼ Rotation	
- i	[RX] X rotation	
- 1	[RY] Y rotation	
- 1	[RZ] Z rotation	
- 1	[Skew_id] Skew	None
- i	[Gnod_id] Support*	1 items
- 1	[Gnod_id] Support (Advanced selector)	
	III	

LoadCase > Boundary Condition 클릭, 마우스 우클릭 후 Create new 클릭 TX 제외하고 모두 체크 Standary Master node 선택 후 save

클릭



## 구속조건 설정 (2)



# 구속조건 설정 (3)

3 New BCS 3 □ □ □ □ □ □ □ □ □ □ □ □ □	오두 체크 고림과 같이 벽면 절점 선 후 save 클릭
New BCS 3           Image: Constraint of the second	▼ 모두 제그 2 그림과 같이 벽면 절점 선 후 save 클릭
□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	고림과 같이 벽면 절점 선 후 save 클릭
□           ≥56 items	2 그림과 같이 벽면 절점 선 후 save 클릭
✓         ✓ <t< th=""><th>고림과 같이 벽면 절점 선 후 save 클릭</th></t<>	고림과 같이 벽면 절점 선 후 save 클릭
☑         ☑ <t< th=""><th>2 그림과 같이 벽면 설섬 선 후 save 클릭</th></t<>	2 그림과 같이 벽면 설섬 선 후 save 클릭
☑       ☑    <	후 save 클릭
☑           ☑	
✓     ✓	
☑           ☑           ☑           ☑           None           256 items	
☑       ☑       None       256 items	
None 256 items	
None 256 items	
256 items	

### TUBE 속도 설정



## 접촉조건 설정

#### HyperCrash 접촉조건의 종류 (/INTER/TYPE#)

ALE/Lagrange with sliding (Type 1) Kinematic condition (Type 2) Surface/Surface(Type 3) Nodes/Surface (Type 5)

Rigid body/Rigid body (Type 6)

Multi usage (Type 7)

Drawbeads (Type 8)

ALE/Lagrange with Void (Type 9)

Tied with void(Type 10)

Edge to edge (Type 11)

Fluid/Fluid (Type 12)

Ellips. surface/Node (Type 14)

Ellips. surface/Surface (Type 15)

Node/Solid (Type 16)

Solid/Solid (Type 17)

Fluid/Structure (Type 18)

Surface/Surface with edge treatment (Type 19)

Multi usage constant stiffness (Type 20)

Surface/Rigid surface (Type 21)

Airbag surface (Type 23)

Surface/Surface (Type 24)

Sub-interface

- Interface Type 7 is a general purpose interface and can simulate all types of impact between a set of nodes and a master surface.
- This interface can simulate self-impact, especially buckling during a high speed crash.
- Interface Type 7 solves all problems.
- The main advantage of interface Type 7 is that the stiffness is not constant and increases with penetration preventing the node from going through the shell mid-surface.

### 접촉조건 설정



## 해석 케이스 설정



3

} (	<u>}</u>		Wadal > Cantral Card크리
Model LoadCase RADIOSS Tools Dat	Z RUN_NAME_NUMBER_LETTER : Ide	ntifies the run number	
E Browser	RUN NAME NUMBER LETTER		
Dart	Run Number	1	
	[DT_STOP] Final time for run	10.01	
A Duranti	Restart letter	: Default	2 파라미터 실성
Add to Material	ANIM_DT : Write anim	ation files	
	ANM_DT	0	A CONTRACTOR OF
Function		1	3 모델 export (RADIOSS 선택)
Function 2D	[TFREQ] Time frequency	<u> </u>	
Function Scale and Shift	PRINT : Sets printo	ut frequency for output file	
🗇 Control Card	PRINT		
	Print	-100	
	P		
		(	i
	ANIM_ELTYPE_RESTYPE : Genera	tes animation files containing	
	ANIM_ELTYPE_RESTYPE_SUPPORT element	t data for the specified result	
	Name of the variable to be sevedt	VONH: yoo Misso atropa	
	Name of the variable to be saved	VOIVIN. VOIT MISES SUESS	
	· Constatos an	motion files containing	i
		for the specified variable	
			i
	Variable name to be saved in animation file*	CONT: Contact forces	
File Quality Concentions Mark Edition			
File Quality Connections Mesh Editin	n		
🖀 New 🛛 🖡 🛃 🖆	-		
	-		i
New Model			
Na Import ►			
	1		
KADIOSS	1		
Print Nastran			
.UNV File			
C3-0111A			

#### 해석 실행 (RADIOSS) Radioss2017 실행 2 앞서 제작한 모델 불러온 뒤 RADIOSS 2017 Run 클릭 2 Der Works Solver Run Manager (@DESKTOP-L2LNH62) Х File Edit View Logs Solver HyperWorks Help õ BOX\_TUBE\_test1\_0000.rad Input file(s): Options: Use SMP: -nt 2 Use MPI options Use solver control Schedule delay Close Run \*\*\_0000.rad : Start File-해석 모델 \*\*\_0001.rad : 해석 조건 및 결과에서 추출 할 내용 정의





# AXIAL CRUSH LOAD OF SQUARE SECTION

### 예제: BEAM CRUSH ANALYSIS (1)



Figure 3.6.4-1 Average static crush force vs. section shape (All samples were the same mass and length)

### 예제: BEAM CRUSH ANALYSIS (2)

Geometry information

Length: 305 mm b: 70 mm square Thickness: 1.4 mm Yield stress: 247 MPa



## 유한요소해석 모델 불러오기



## 재료 물성 입력 (1)

64	Review			
6	Create New	Airbag material	•	
	Create Template	Composite and Fabric	•	
$\times$	Delete	Connection	•	
	Clone	Elastic and Hyperelastic	•	
i	Cross Reference	Elasto-plastic	Johnson-Cook (2)	
	Lock	Honeycomb	Zerilli-Armstrong (2)	
	UnLock	Hydrodynamic	Hyd. Elasto-plastic (3)	
	Move entity(s) to	Rock and Concrete	Hyd. Johnson-Cook (4)	
	See in Browser	Visco-elastic	Ductile damage (22)	
	Group Selected Rows	Fluid	Ductile damage (23)	
_		Non turbulent flow	Plastic brittle for shell (27)	
		Turbulent flow	Hill orthotropic (32)	
		Other	Piecewise linear (36)	ar
		User Material	Hill ortho. tab. (43)	119
			Cowper-Symonds (44)	us
			Zhao (48)	

an isotropic elasto-plastic material using user-defined functions

PLAS TAB	
28	
D	2
Title	New MAT 2
Local Unit System	None
[RHO_I] Initial density*	7.85E-6 2
[RHO_0] Reference density	0
[E] Young's modulus*	240
[Nu] Poisson's ratio*	3
[Eps_p_max] Failure plastic strain	0
[Eps_t] Tensile failure strain	0
[Eps_m] Tensile failure strain	0
[C_hard] Hardening coefficient	0
[F_smooth] Strain rate smoothing	
[F_cut] Cutoff frequency for strain rate filtering	0
[Eps_f] Maximum tensile failure strain	0
[VP] Strain rate choice flag	0: Strain rate are total strain rate
[fct_IDp] Pressure vs. yield factor function	None
[Fscale] Y-Scale factor for yield factor function	1
[Fct_IDE] Function identifier for the scale factor of Young mod	None
[Elnf] Saturated Young's modulus for infinitive plastic strain	0
[CE] Parameter for Young's modulus evolution	0
Heat	

Model > Material 클릭, 마우스 우클릭 후 Create New > Elasto-plastic > Piecewise linear(36) 재료 생성 재료 물성치 입력 [RHO\_I]: 7.85e-6 kg/mm<sup>3</sup> [E]: 240 GPa [Nu]: 0.3

## 재료 물성 입력 (2)



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## 특성 입력

PROP ×		
SHELL		
Local Unit System	None	
[Ismstr] Flag for shell small strain formulation	0: Use value in /DEF_SHELL	
[Ishell] Flag for 4 node shell element formulation	0: Use value in /DEF_SHELL	
[Ish3n] Flag for 3 node shell element formulation	0: use value in /DEF_SHELL	
[Idrill] Flag for drilling degree of freedom stiffness	0: No	
[P_thick_fail] Percentage of through thickness integration point	r 0	
[hm] Shell membrane hourglass coefficient	0	
[hf] Shell out of plane hourglass	0	
[hr] Shell rotation hourglass coefficient	0	
[dm] Shell membrane damping	0	
[dn] Shell numerical damping	0	
[N] Number of integration points through the thickness	0	
[Istrain] Flag to compute strains for post-processing	0: Use val /DEF_SHELL	
[Thick] Shell thickness*	1.4 1	
[Ashear] Shear factor	0	
[Ithick] Flag for shell resultant stresses calculation	0: Default set to value defined with /DEF_SHELL	
[lplas] Flag for shell plane stress plasticity	0: Default my value defined with /DEF_SHELL	
Support*	h PART 2	
Save	Cancel	



### 강체 요소 생성

RBODY	
Local Unit System	None
Master node in time History	
Lagrange multipliers	
Automatic master node	
Flag for activate/deactivate in run	0: Not ON/OFF in current Engine file (or docked)
[MASS] Mass	0
[Jxx] JXX inertia	0
[Jyy] JYY inertia	0
[Jzz] JZZ inertia	0
[Jxy] JXY inertia	0
[Jyz] JYZ inertia	0
[Jxz] JXZ inertia	0
[ISPHER] Inertia	0: Default, set to 2
[ISENS] Sensor	None
[NSKEW] Skew	None
[IKREM] Keep slave nodes in rigid wall	
[ICOG] Center of gravity computation	0: Default, set to 1
[loptoff] Manage domain decomposition of rigid body for RADI	0: CPU cost of elements associated with rigid body is not tak
[lexpams] Manage connection through the rigid body between	0: if the rigid body overlaps the AMS and non AMS domains,
[Gnod_id] Slave nodes*	21 items
[Gnod_id] Slave nodes (Advanced selector)	



Mesh Editing > Rigid Body 클릭, 마우스 우클릭 후 Create New 클릭 Slave nodes 항목에서 마우 스 우클릭 후 Select in graphics 선택 > Add nodes by box selection 선택

## 구속조건 설정 (1)

BCS

Title

D



## 구속조건 설정 (1)

BCS			
D		3	
Title		New BCS 3	
ALE formul.			
Lagrange mult. formul.			
₽	Translation		
	[TX] X translation		
	[TY] Y translation		
	[TZ] Z translation		
▽	Rotation		
	[RX] X rotation		
	[RY] Y rotation		
	[RZ] Z rotation		
[Skew_id] Skew		None	
[Gnod_id] Support*		1 items	

Boundary Condition에서 마우스 우클릭 후 Create new 클릭 > 강체의 중앙 부분의 절점은

부딪치는 방향의 자유도를 제외한 모든 자유도 구속

### TUBE 변위 설정



### 접촉조건 설정

TYPE7				
D	1			
Title	New INTER 1			
Self Impact				
ocal Unit System	None			
Formulation	0: Classical			
(Istf) Stiffness definition	0: Default, set to value defined in /DEFAULT/INTER/TYPE7			
[Ithe] Heat contact				
[Igap] Gap/element option	0: Default, set to value defined in /DEFAULT/INTER/TYPE7			
[Fpenmax] Maximum fraction of initial penetration	0			
[lbag] Vent hole closure when contact	0: Default, set to value defined in /DEFAULT/INTER/TYPE7			
[Idel] Node and segment deletion	0: Default, set to value defined in /DEFAULT/INTER/TYPE7			
[lcurv] Slave gap with curvature	0: No curvature			
[ladm] Local curvature flag	0: Not activated			
[Stfac] Scale factor for stiffness	1			
[dtmin] Limiting nodal time step	0			
[Irem_gap] Flag for deactivating slave nodes if element size < ga	0: Default, set to value defined in /DEFAULT/INTER/TYPE7			
[Irem_i2] Flag for deactivating the slave node, if the same contact	0: default, set to the value defined in /DEFAULT/INTER/TYPE7			
[Gapmin] Min. gap for impact activ.	.9			
I_BC] Bound. cond. deactivation				
[Inacti] Stiffness deactiv. (init. penetration)	0: Default, set to value defined in /DEFAULT/INTER/TYPE7			
[VisS] Critical damping coeff. on interface stiffness	0			
[VisF] Critical damping coeff. on interface friction	0			
[Tstart] Start time	0			
[Tstop] Stop time	0			
[Bumult] Sorting factor	0			
[Ifric] Friction formulation	0: Static Coulomb			
[Fric] Coulomb friction	.2			
[Iform] Friction penalty formulation	0: Default, set to value defined in /DEFAULT/INTER/TYPE7			
[Ifiltr] Friction filtering	0: No filtering			
[sens_ID] Sensor to Activate/Deactivate the interface	None			
[fct_IDf] Friction coefficient with temperature function identifier	None			
[AscaleF] Abscissa scale factor on FCT_IDK	0			
[fric_ID] Friction identifier for friction definition for selected pairs	None M			
[Mast_id] Master surface*	1 items 2			

LoadCase > Contact Interface클릭 > 마우스 우클릭 후 > "Multi usage (Type 7) 클릭 (contact interface 생성) 2 파라미터 설정 Self Impact: 체크 [Stfac]: 1 [Gapmin]: 0.9 [Fric]: 0.2 접촉 파트 설정 (모델 선택)

선택)

### 해석 케이스 설정

L

		(	<mark>1</mark> Model > Control card 설정
RUN_NAME_NUMBER_LETTER :	dentifies the run number		
RUN_NAME_NUMBER_LETTER			 
Run Number	1		파라미터 설정
[DT_STOP] Final time for run	4.01		
Restart letter	: Default		1
			│ 모델 export (RADIOSS 선택
ANM_DT : Write animatic	n files		
ANIM_DT			
[TSTART] Start time	0		
[TFREQ] Time frequency	0.01		
ANN MEAT - Concrator anima	tion files containing vectorial data fo	r the specified veriable	
C No Veriable come to be cound in estimation fil	tion mes containing vectorial data lo	i the specified variable	
S.No Variable hame to be saved in animation his	5		
1 FOPT			
ANIM_VECT_RESTYPE_SUPPORT			
Variable name to be saved in animation file*	FOPT: Forces and moments for rigi	d bodies, rigid walls and sect	

## 후처리 (1)





Results X

Files

Loadcase 1

9 9 9 V

1) Notes (1)

Besults Sets (0)

Name Value

E 🙀 Plot Styles (3)

Heasures (2)

Entities

Time = 4.0003e+000









Analytic solution

 $P_M = 386t^{1.86}b^{0.14}\sigma_Y^{0.57} = 30237 \text{ N}$  $P_{MAX} = 2.87P_M = 86780 \text{ N}$  $P_1 = 1.42P_M = 42936 \text{ N}$  $P_2 = 0.57P_M = 17235 \text{ N}$ 

Ideal graph



Crush Distance (in)





FEM solution  $P_{MAX} = 52145 \text{ N}$ 





예제에서 수행한 정 사각형의 정적 충돌 하중을 100%로 놓고, 나머지 형상 중 하나를 결정하여 평균 정적 충돌 하중을 구하시오.

AVERAGE STATIC CRUSH FORCE



Figure 3.6.4-1 Average static crush force vs. section shape (All samples were the same mass and length)