Numerical Analysis on bullet Penetration Resistance of Heat Treated Lightweight C-grade Bulletproof Steel Plates

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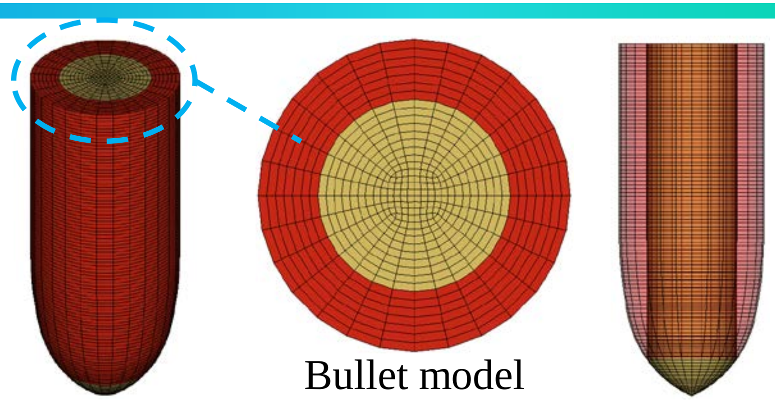
Contents

1. Finite element models

1.1 Meshing

Outer diameter *D* of bullet : 7.62mm.
Outer diameter *d* of bullet core : 4.7mm.
Maximum element size: 0.8mm.
Minimum element size: 0.2mm.
Weight of bullet: 5.5g.
Bullet core and the outer layer are connected with the same nodes.



Bullet model (*v*=720m/s)

Actual size of the bulletproof steel plate :305mm×305 mm

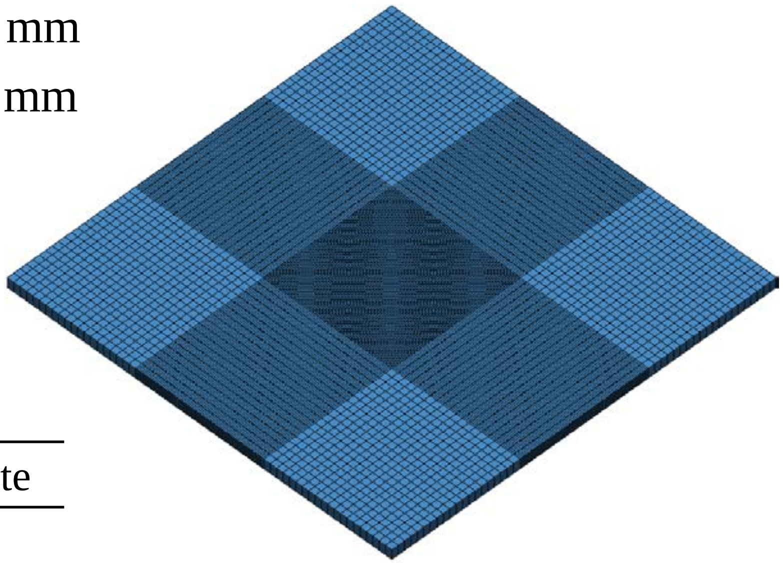
Model size of the bulletproof steel plate :120mm×120 mm

Maximum element size: 2.0mm.

Minimum element size : 0.5mm.

Layer number of thickness direction: 4-8(according to different thickness)

Information	Bullet	Bulletproof Steel Plate
Node amount	44667	73205-131769
Element amount	43252	57600-115200



Bulletproof Steel Plate model

1.2 Material models

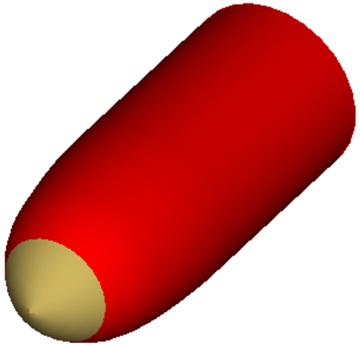
Bullet | Bulletproof Steel Plate

Mat-Plastic-Kinematic

MATL3 in Dyna module of HyperMesh platform

Constitutive equation: $\sigma_Y = \left[1 + \left(\frac{\dot{\varepsilon}}{c}\right)^{\frac{1}{P}}\right]\left(\sigma_0 + \beta E_P \varepsilon_P^{eff}\right)$

$$E_P = \frac{E_{\tan} E}{E - E_{\tan}}$$



σ_Y—actual yield stess
σ_0—initial yield stess
β—hardening parameter
C、P—strain rate parameter
ε_P^{eff} —effective plastic strain;
E—elastic modulus;
E_{tan}—shear modulus;
E_p—plastic hardening modulus.

Material parameters of bullet

Material parameter	Bullet outer layer	Bullet core
(kg/m^3)	7.8	7.8
γ	0.3	0.3
E（GPa）	210	210
σ_s (MPa)	235	345
Failure strain ε	1.2	1.2

1.2 Material models

Bullet | **Bulletproof Steel Plate**

Chemical composition of C-grade bulletproof steel plates

Steel	C	Si	Mn	P	S	Al	Nb+V+Ti	Cr +Ni	B
C-grade	0.38～0.44	0.31～0.37	1.15～1.25	≤0.015	≤0.015	0.046	≥0.114	≥1.0	0.0016

Hot stamping technology was listed in Ref.[7].

MAT-simplified-Johnson-Cook

MATL98 in Dyna module of HyperMesh platform

Effect of temperature is not considered.

Constitutive equation:

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)(1 - \mathrm{T}^{*m})$$

σ—equivalent stress;
ε—equivalent strain;
A、B、C、n—material parameters;
$\dot{\varepsilon}$ — effective plastic strain rate
$\dot{\varepsilon}_0$ —referring strain rate

Material parameters of bulletproof Steel Plate

Material parameter	Material No. C1	C2	R
(kg/m^3)	7.8	7.8	7.8
γ	0.3	0.3	0.3
E（GPa）	204	197	206
σ_s (MPa)	1515	1400	1470
Tensile stress（MPa）	2200	2035	1775
Fracture elongation	0.063	0.052	0.058

Johnson-Cook constitutive models of steel plates

Material	Johnson-Cook constitutive models
C1	$\sigma = (1670 + 3197\varepsilon^{0.0.525})\left(1 + 0.00414\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$
C2	$\sigma = (1500 + 3536\varepsilon^{0.5477})\left(1 + 0.0043\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$
R	$\sigma = (1600 + 1328\varepsilon^{0.5238})\left(1 + 0.005724\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$

1.3 Boundary condition

Bullet restriction: NO.

Incident direction: Z

Velocity: 720m/s

Steel plate restriction: Infinite Boundary Constraint Element

Contact： Face to face

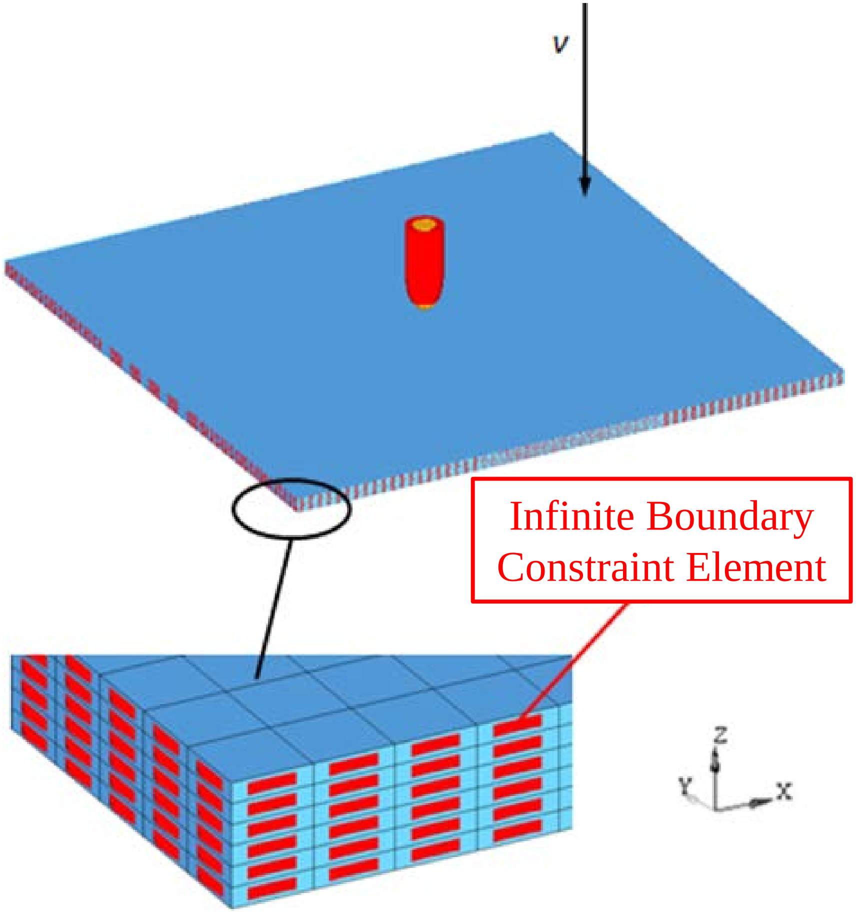
Total computing time： 100μs

Time step： 2μs

Output data： Velocity

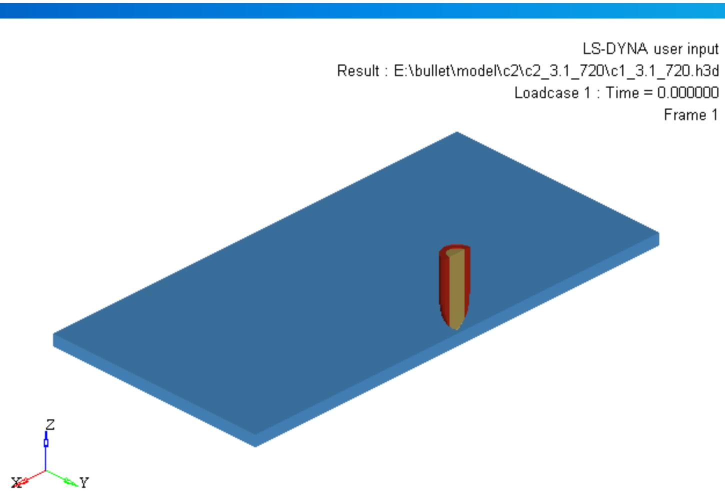
Force

Energy

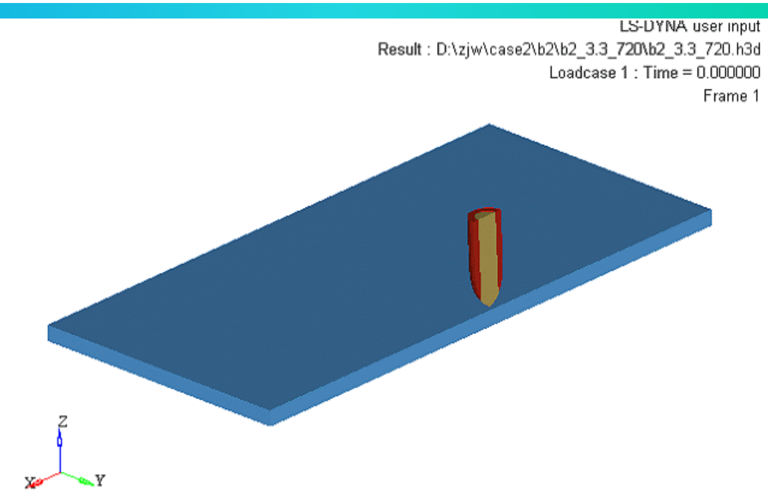


2. Results comparison

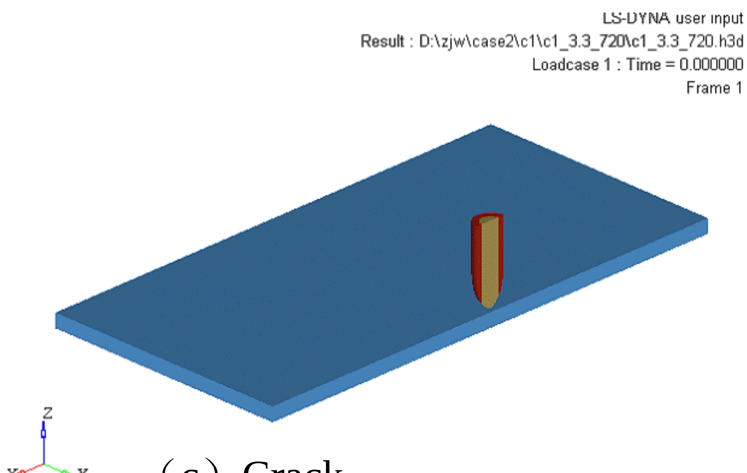
2.1 Approaches of deformation



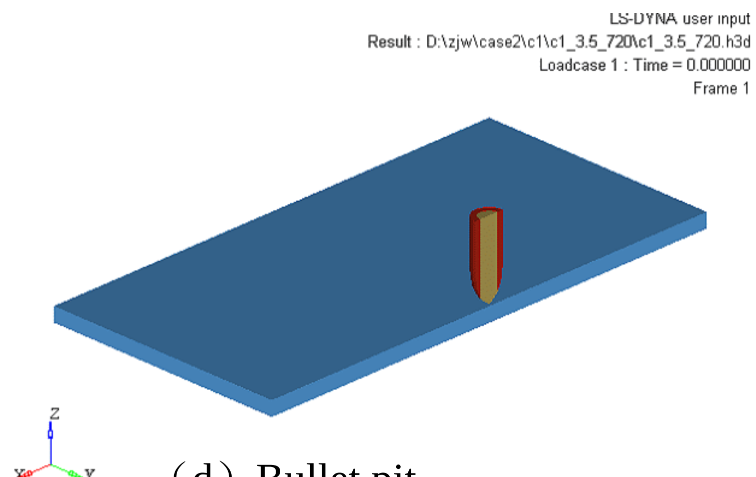
（a） Thoroughly penetration



（b） Rear collapse



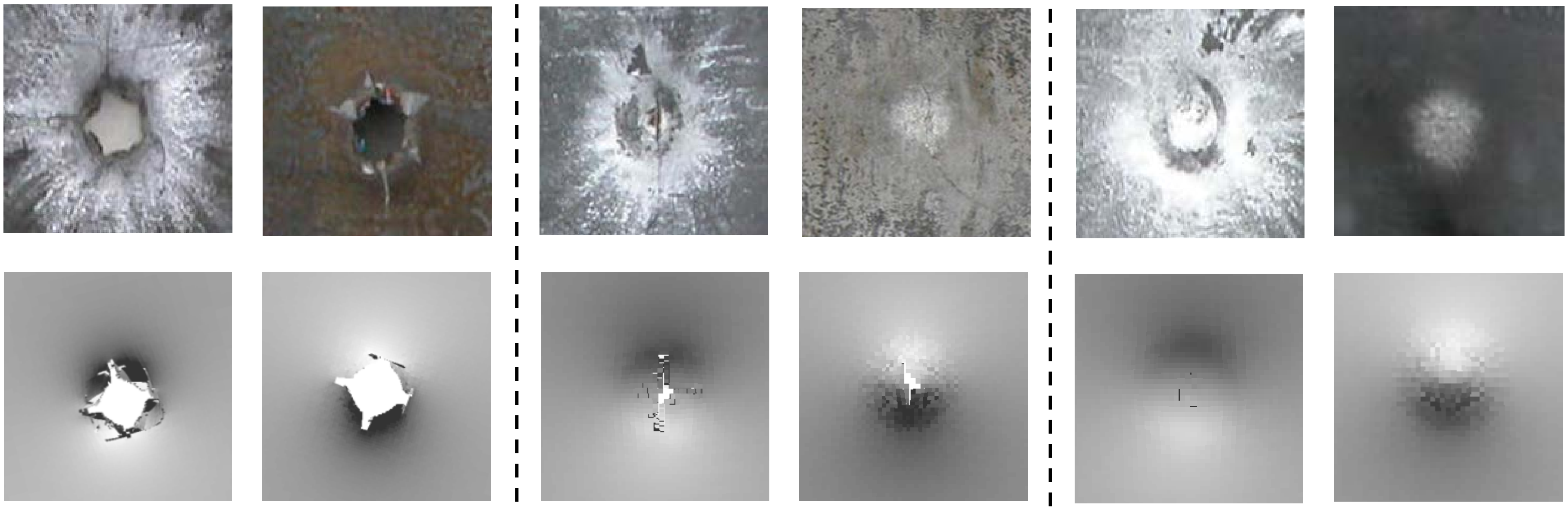
（c） Crack



（d） Bullet pit

2.2 Comparison of plate deformation

Front Back | Front Back | Front Back

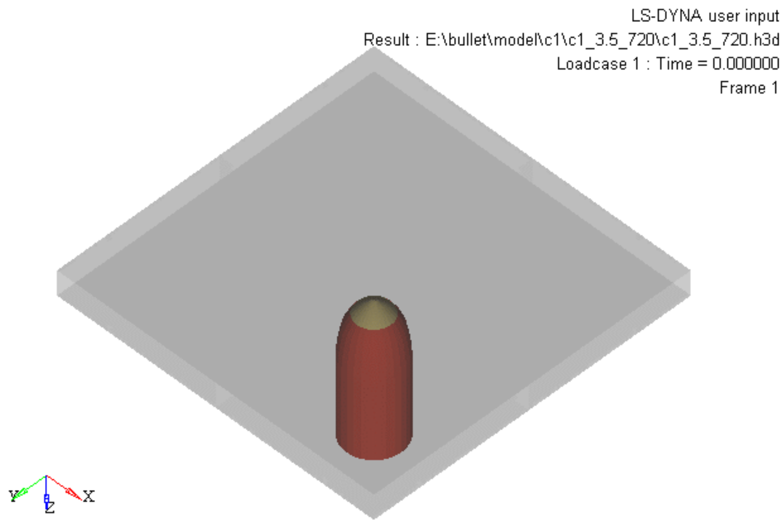


Thoroughly penetration | Crack | Bullet pit

- The shape of bullet holes are very similar when thoroughly penetration occurs.
- The orientation of cracks are basically the same when cracking occurs.
- Even yielding bullet pits, there’ s no obviously difference.

2.3 Comparison of bullet deformation

Comparison of bullet core between simulation and experiment at the speed of 720m/s

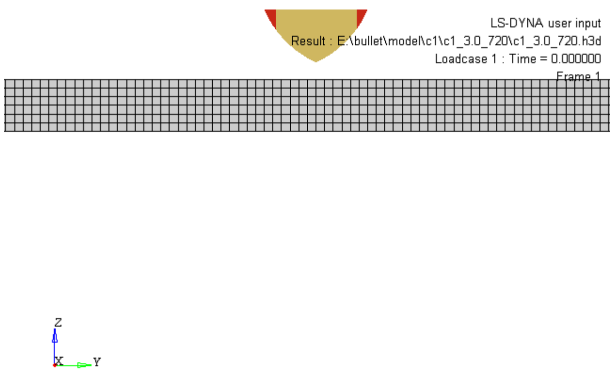


3. Analysis and discussion

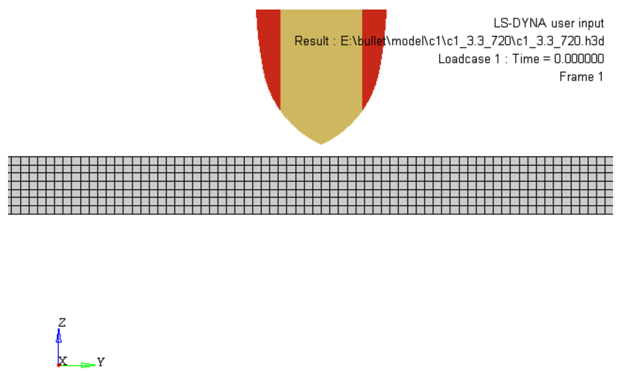
3.1 Steel plate C1

Simulation results of steel plate C1

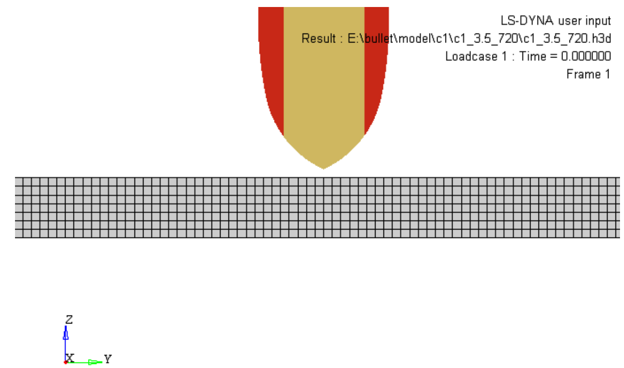
Bullet speed (m/s)	Plate thickness *t* （mm）	Deformation mode	Deformation height *h* （mm)	Energy absorption of plate （J）	Maximum contact force （KN）	Residual speed (m/s)	Energy absorption of bullet （J）
720	3.0	Thoroughly penetration	11.0	486	150	86	240
	3.1-3.4	crack	7.2-10.3	516-530	161-164	0	245-268
	3.5	Yielding bullet pit	6.8	545	166	0	276



Thickness: 3.0mm



Thickness: 3.3mm

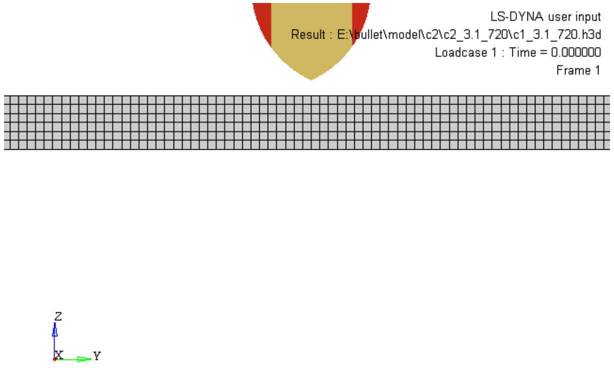


Thickness: 3.5mm

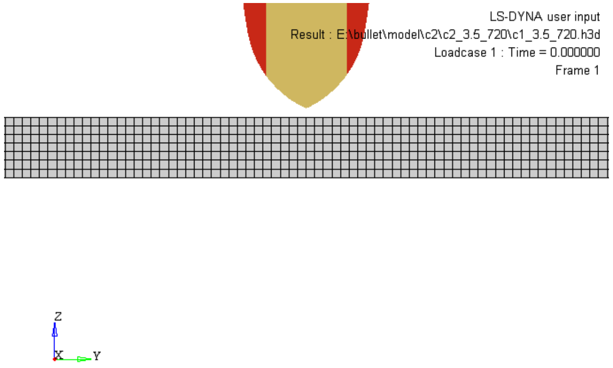
3.2 Steel plate C2

Simulation results of steel plate C2

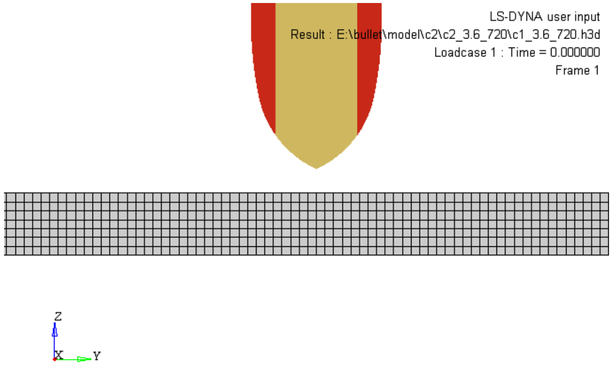
Bullet speed (m/s)	Plate thickness *t* （mm）	Deformation mode	Deformation height *h* （mm)	Energy absorption of plate （J）	Maximum contact force （KN）	Residual speed (m/s)	Energy absorption of bullet （J）
720	3.1	Thoroughly penetration	10.3	464	148	116	212
	3.2-3.6	crack	7.3-10.2	522-527	153-160	0	236-272
	3.7	Yielding bullet pit	6.8	545	162	0	284



Thickness: 3.1mm



Thickness: 3.5mm

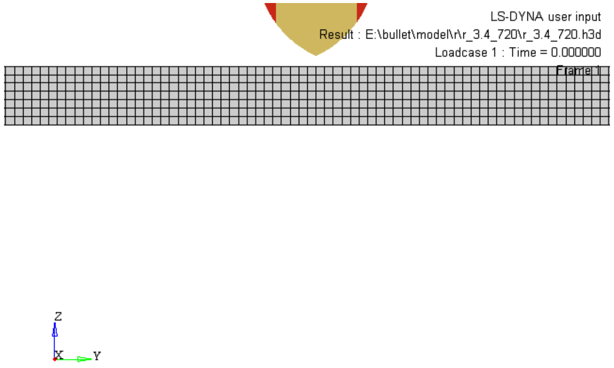


Thickness: 3.7mm

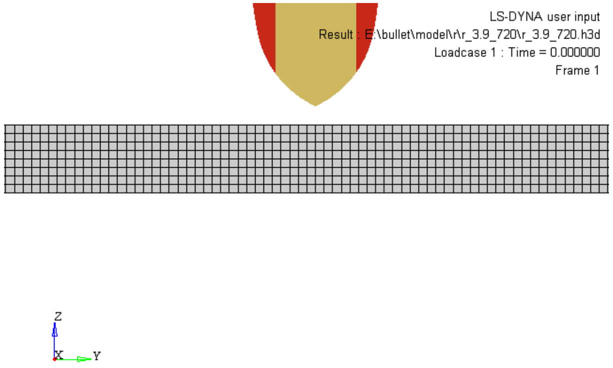
3.3 Steel plate R

Simulation results of steel plate R

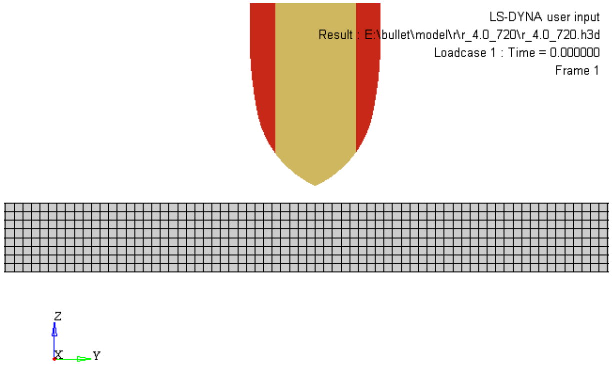
Bullet speed (m/s)	Plate thickness *t* （mm）	Deformation mode	Deformation height *h* （mm)	Energy absorption of plate （J）	Maximum contact force （KN）	Residual speed (m/s)
	3.4	Thoroughly penetration	9.7	410	153	47.2
720	3.5-3.9	crack	6.8-8.6	464-476	155-167	0
	4.0	Yielding bullet pit	6.0	508	168	0



Thickness: 3.4mm



Thickness: 3.9mm



Thickness: 4.0mm

4. Conclusions

01 Finite element models

02 Results comparison

03 Analysis and discussion

04 Conclusions

4. Conclusions

◆The constitutive equation considering the sensitivity of strain rate of material. Work hardening, strain rate hardening and dynamic yield stress equation with plastic hardening modulus are included in bullet material model and Johnson-Cook equation is applied to fit the stress-strain curves of bulletproof steel plates.

◆The comparisons of bullet deformation, plate deformation and cracking all indicate the reliability of simulation results.

◆When the plates C1, C2 and R with tensile strength of 2200MPa，2035MPa and 1775MPa respectively are shoot at 720m/s, the limit thickness, simultaneously acquired by both simulation and experiment, are respectively 3.5mm, 3.7mm and 4.0mm.

◆As a powerful method to analyze the limit thickness of bulletproof steel plate, numerical simulation effectively reduces work and cost.

Thanks!