BIOMIMETICS DESIGN OF BULLET PROOF SHIELD

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CONTENT

Background . Problem Statement . Objectives . Scope . Contribution

1.0 PROJECT INTRODUCTION

BACKGROUND

Ballistic Impact

High velocity impact by an object with small mass

Ballistic Limit Velocity (V_{BL})

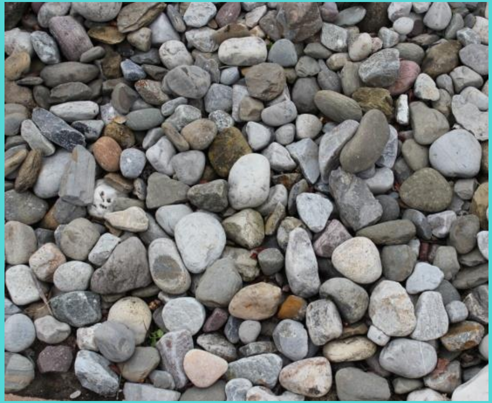
Highest velocity of a certain projectile where the structure can resist without perforation

Reference: Hideaki Kasano. Impact perforation of orthotropic and quasi-isotropic CFRP laminates by a steel ball projectile. *Advanced Composite Material*, 2001. 10(4): 309-318.

BACKGROUND







BACKGROUND

BACKGROUND

- Protests and terrorist attack ongoing all around the world.
- Deadly violence exploded in Kiev, Ukraine.
- Anti-government protest began in Thailand .

PROBLEM STATEMENT

Low ballistic proof capability of current riot shield is exposing the user to life threatening condition during riot control operation

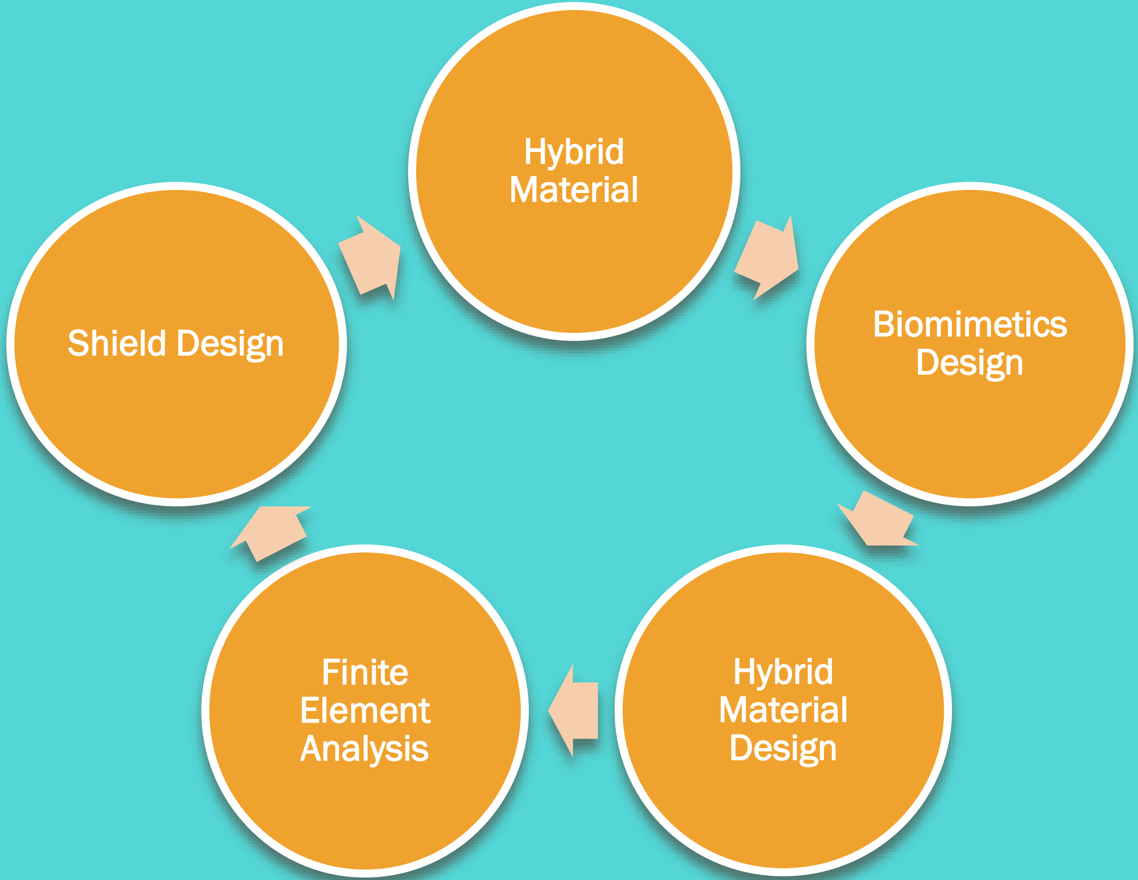
RESEARCH OBJECTIVES

- To study the design process based on biomimetics approach
- To produce a design concept of bullet proof hybrid material using biomimetics approach

RESEARCH OBJECTIVES

- To conduct an impact analysis on hybrid material using a numerical method.
- To conduct engineering design of bullet proof shield based on the generic product design and development approach

SCOPE



Hybrid Material
Biomimetics Design
Hybrid Material Design
Finite Element Analysis
Shield Design

KNOWLEDGE CONTRIBUTION

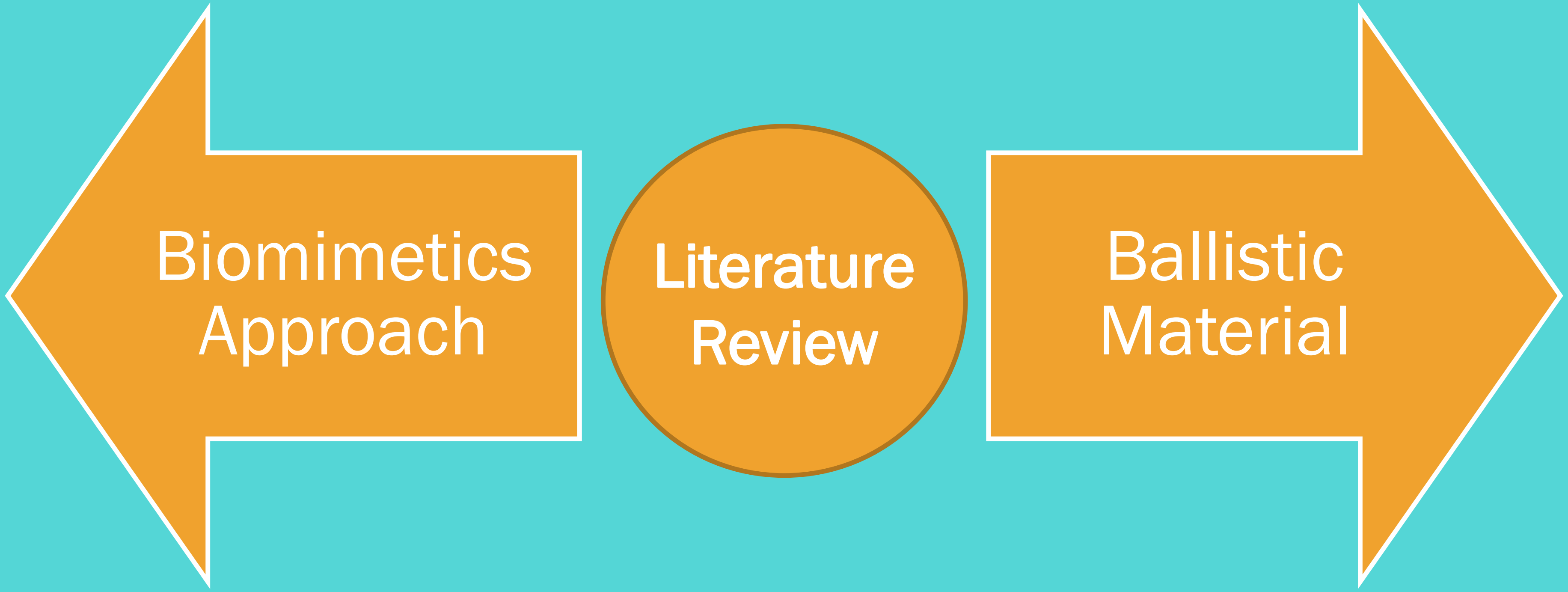
- 24th Malaysia Science and Technology Congress 2015
  - Potential of biomimetics Design in Development of Impact Resistance Composites
- 1st International Conference on Innovation in Science and Technology
  - The Potential of Biomimetics Design in the Development of Impact Resistant Material

Ballistic Material . Biomimetics Approach

LITERATURE REVIEW

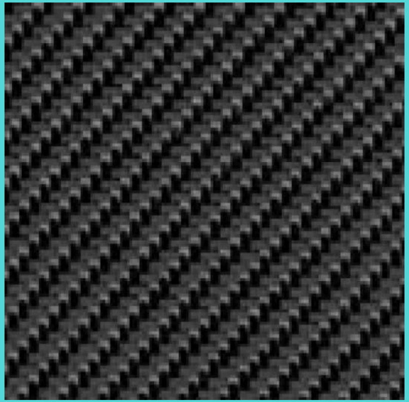
2.0

DIRECTIONS


Biomimetics Approach
Literature Review
Ballistic Material

COMPOSITES MATERIAL

UHMWPE



Carbon

Aramid

Glass

CURRENT RESEARCH

First Author	Field of Study	Fiber Material	Year
Diantang Zhang	Low velocity Impact	UHMWPE	2013
M.R. Ahmad	Fabric System	UHMWPE	2013
H. Harel	Delamination Controlled	UHMWPE	2002
M.V. Hosur	Fabric System	Carbon	2004
M.R. Ahmad	Ballistic Impact Behavior	Aramid	2007
N.K. Naik	Ballistic Impact Behavior	E-Glass	2008
E.P. Gellert	Thickness and Ballistic Impact	E-Glass	2000
Shaktivesh	Ballistic Impact Performance	E-Glass	2013
L.J. Deka	Damage evolution, Energy Absorption	E-Glass	2008

HYBRID MATERIAL

Designed to optimally perform in specific engineering applications

Allows the limited performance of monolithic materials to expand it properties for better performance

Reference: Kromm FX, Quenisset JM, Harry R, Lorriot T. An example of multimaterial design. *Advanced Engineering Materials*, 2002. 4:371-4

BIOMIMETICS DESIGN

Transfer of ideas from biology to technological applications

Source:Schmitt O. H. Some interesting and useful biomimetics transforms. *Proc. 3rd Int. Biophysics Congress.* 29 August to 3 September, 1969. Boston, MA, p297.

BIOMIMETICS DESIGN

Unlimited sources of ideas or inspirations

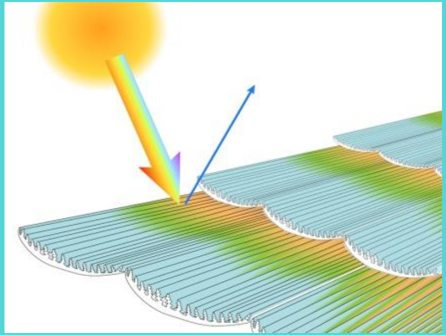
Transfer of biology inspiration to technology applications

Extracting of inspirations or ideas from nature to solve problem

Reference : Schmitt O. H. Some interesting and useful biomimetics transforms. *Proc. 3rd Int. Biophysics Congress.* 29 August to 3 September, 1969. Boston, MA, p297.

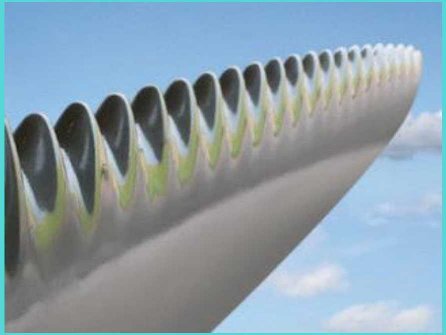
BIOMIMETICS DESIGN

Photonic Structure



Drag Reduction

Drag Reduction



Hydrophobic

CURRENT RESEARCH

First Authors	Biological Model	Functions	Year
L. Feng	Lotus Leaf	Hydroponic surface, self cleaning	2002
Niranjan A. Malvadkar	Butterfly wing	Wetting Properties	2010
Noshir S. Pesika	Gecko foot	Reversible Adhesive, Self cleaning	2009
Philip Ball	Shark Skin	Drag Reduction	1999
Xuefeng Gao	Water Strider Leg	Super-hydrophobic	2004
George Mayer	Nacre	Fracture resistance	2005
Juha Song	Fish Scale	Protection	2011

Biomimetics Approach

Problem Based Approach

Reference: M. Helms, Swaroop S. Vattam and Ashok K. Goel. Biologically inspired design: process and products. *Design studies*, 2009. 30:606-622.

PROBLEM DEFINITION

Problem defined sufficiently is a need for an effective search of biological analogies in nature.

PROBLEM DEFINITION

- Absorb or dissipate a great amount of kinetic energy from projectile
- Stop the projectile from perforation

REFRAME THE PROBLEM

- What solutions do nature has that can protect them from damage?
- What solution do nature has that offer strong and durable structure?

REFRAME THE PROBLEM

- Technical or engineering terms are difficult to match with biology from nature
- Rephrase into biological term

BIOLOGICAL SOLUTION SEARCH

- Uncountable organism living in this planet
- Journal, Magazine, Books, Encyclopedia

Reference : U. Lindemann, J. Gramann. Engineering Design Using Biological Principles. *International Design Conference*. 18 May -21 May. Dubronik. 2004.1-6.

BIOLOGICAL MODEL 1

Polypterus Senegalus

Fish Scale

BIOLOGICAL MODEL 2

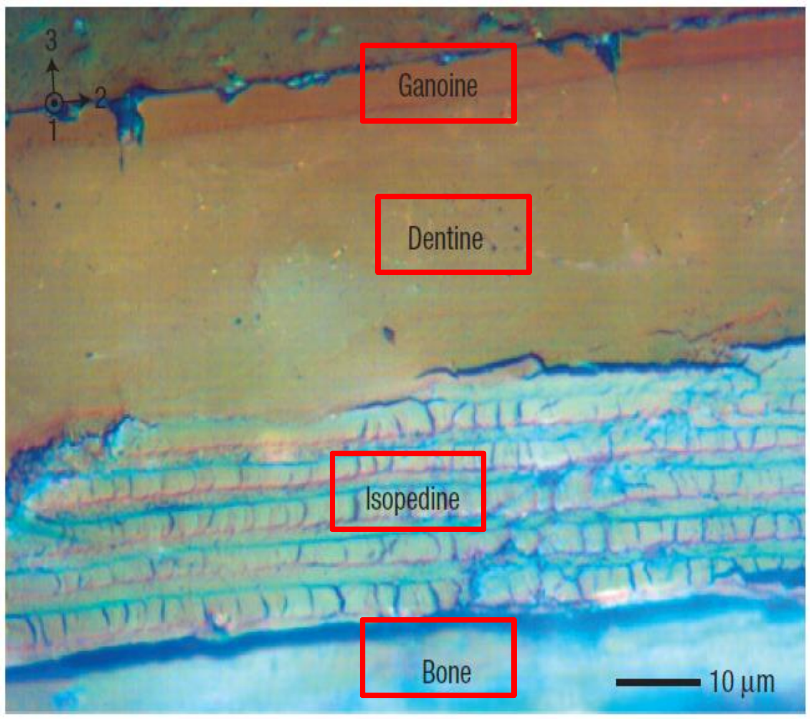
Mantis Shrimp

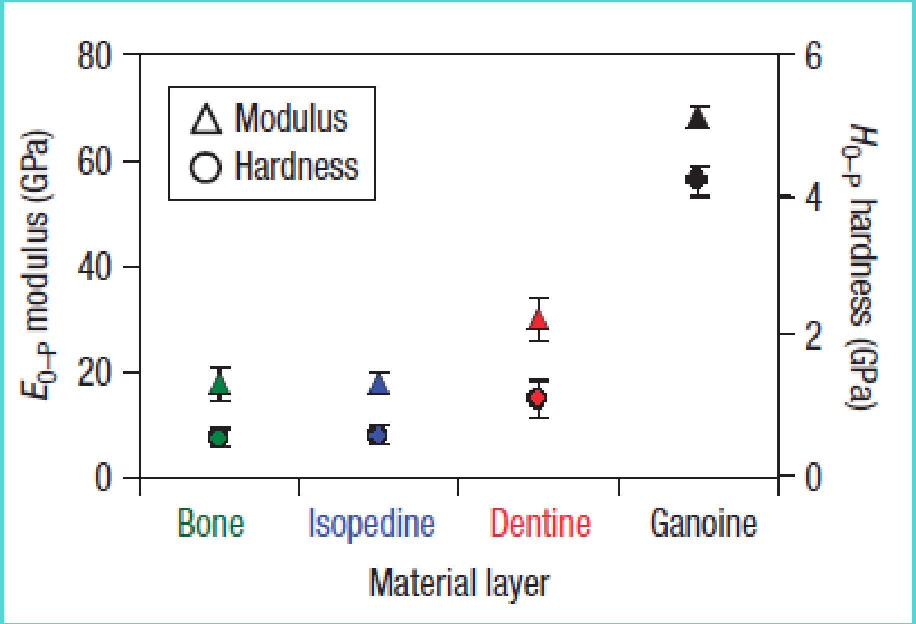
Shrimp Hammer

DEFINE BIOLOGICAL SEARCH

Study of the principle from the biological system

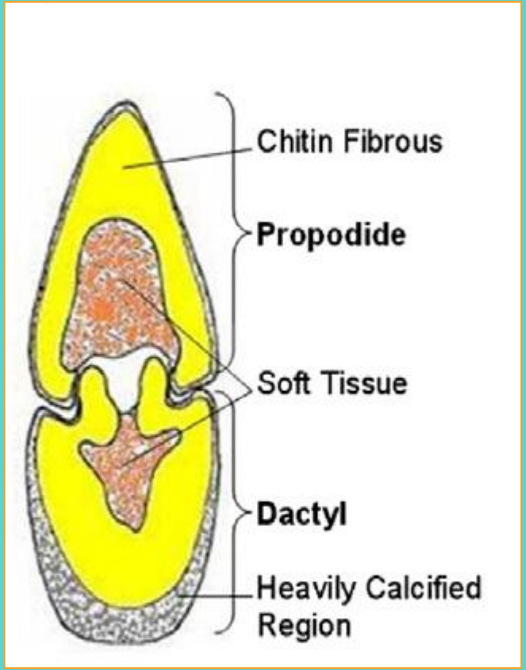
DEFINE BIOLOGICAL SOLUTION





Reference: Benjamin J.F. Bruet, Juha Song et al. Materials design principles of ancient fish armour. Nature Materials, 2008. 7:748-756.

DEFINE BIOLOGICAL SOLUTION



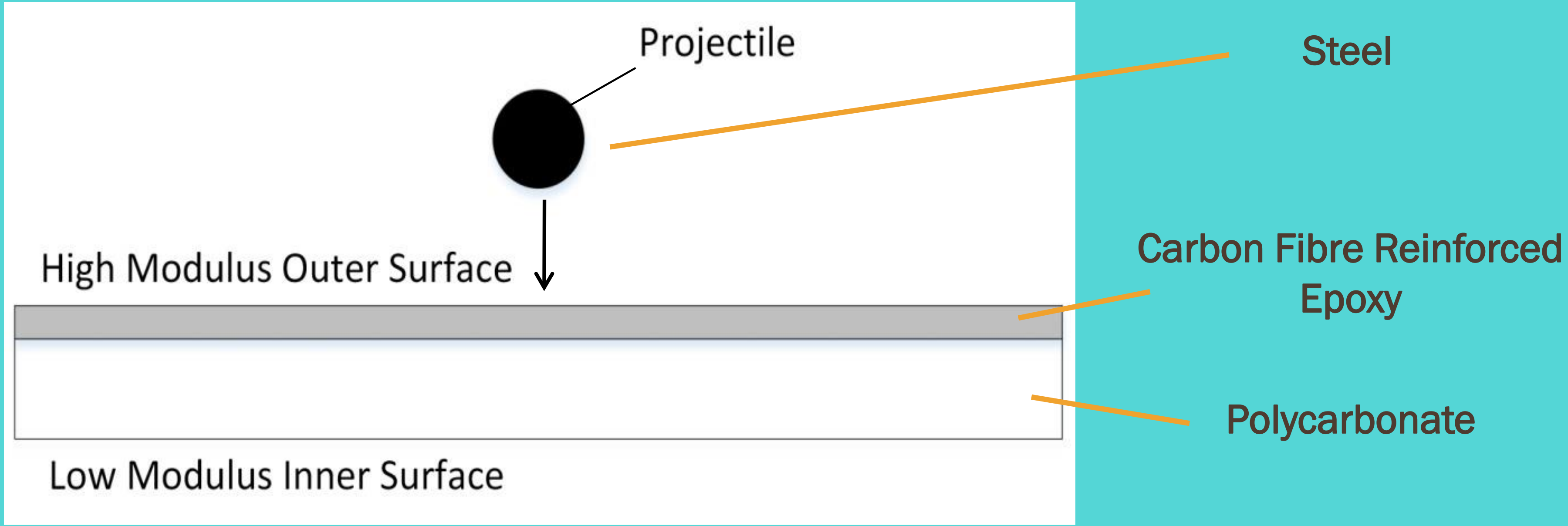
Reference: Marc Andre Meyers, Po-Yu Chen et al. Biological materials: Structure and mechanical properties. *Progress in Materials Science*, 2008. 53: 1-206.

PRINCIPLE EXTRACTION

The thickness of each layer of material are increasing from outer layer to inner layer

The modulus of material is decreasing from outer layer to inner layer

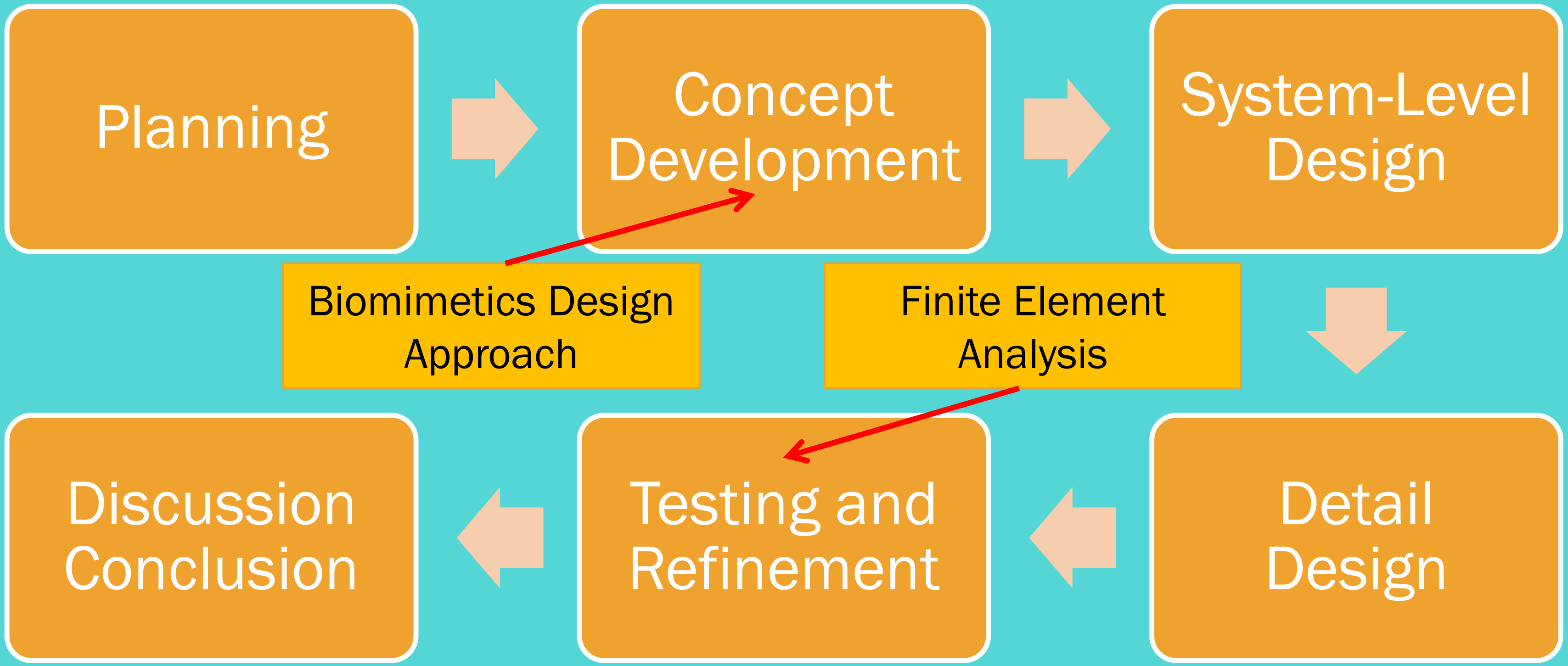
PRINCIPLE APPLICATION



Flow Chart . Tool . Method

3.0 RESEARCH METHODOLOGY

FLOW CHART


Planning
Concept Development
System-Level Design
Biomimetics Design Approach
Finite Element Analysis
Discussion Conclusion
Testing and Refinement
Detail Design

TOOL

ANSYS 14.0

Explicit Dynamic

Drop tests, Impact and Penetration

Problem time magnitude from 1s to 0.0001s

Quasi-static . Drop . **Ballistics** . Detonation & Blast . Hypervelocity Impact

DESCRIPTION OF TARGETS

Categories	Description	Total Thickness (mm)
1	1.5mm CFRP with 2mm PC sheet	3.5
	1.5mm CFRP with 3mm PC sheet	4.5
	1.5mm CFRP with 4mm PC sheet	5.5
2	2mm PC sheet with 1.5mm CFRP	3.5
	3mm PC sheet with 1.5mm CFRP	4.5
	4mm PC sheet with 1.5mm CFRP	5.5
3	3.5mm PC sheet	3.5
	4.5mm PC sheet	4.5
	5.5mm PC sheet	5.5

NUMERICAL SETTING

Projectile considered rigid and remains un-deformed

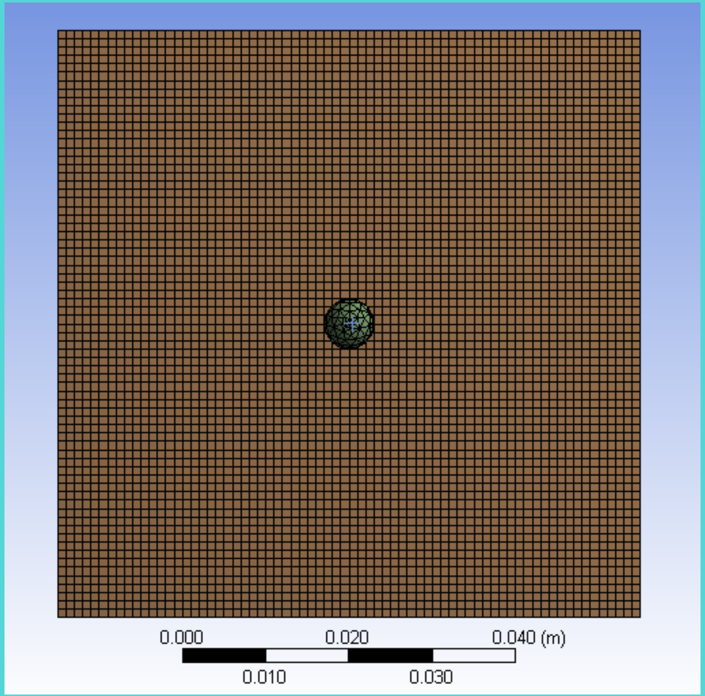
CFRP = Uniform quad method, 1mm element size

PC = Body sizing, 1mm element size

Maximum allowable energy error = 0.2

Geometric strain limit = 1.5

Inertia of eroded material was retained



Finite element model of the steel ball and CFRPPC target

Validation . Simulation Result . Ballistic Limit Velocity

4.0 HYBRID MATERIAL ANALYSIS

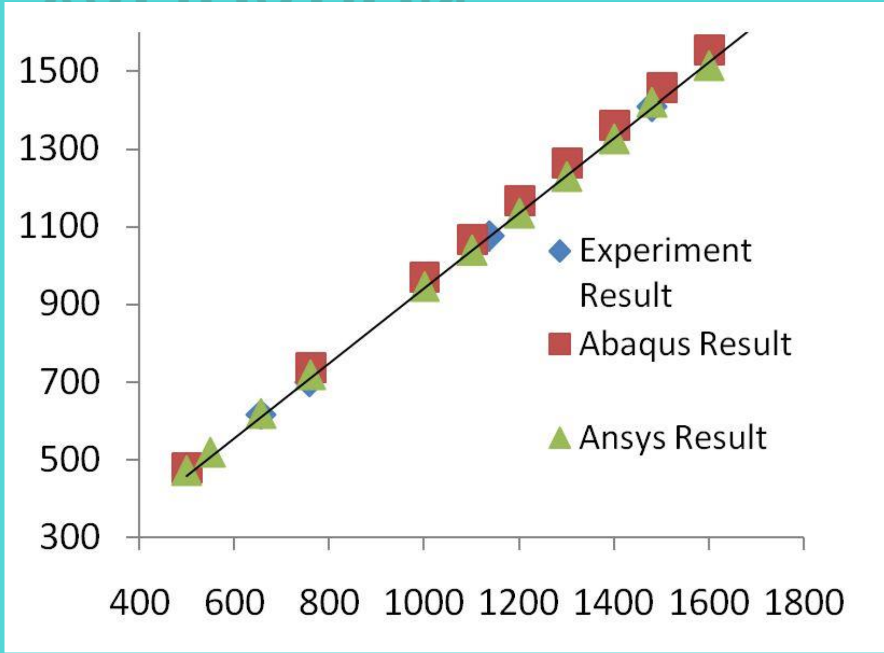
ASSUMPTION

Projectile perforates the targets accompanied by target fragment

Mass of fragment assumed equal to the target thickness multiply by target density

Energy loss remains constant for the same target

VALIDATION



Residual velocity versus impact velocity of 1.5mm thickness CFRP

Similar numerical setting were done and compared with the existing results from other.

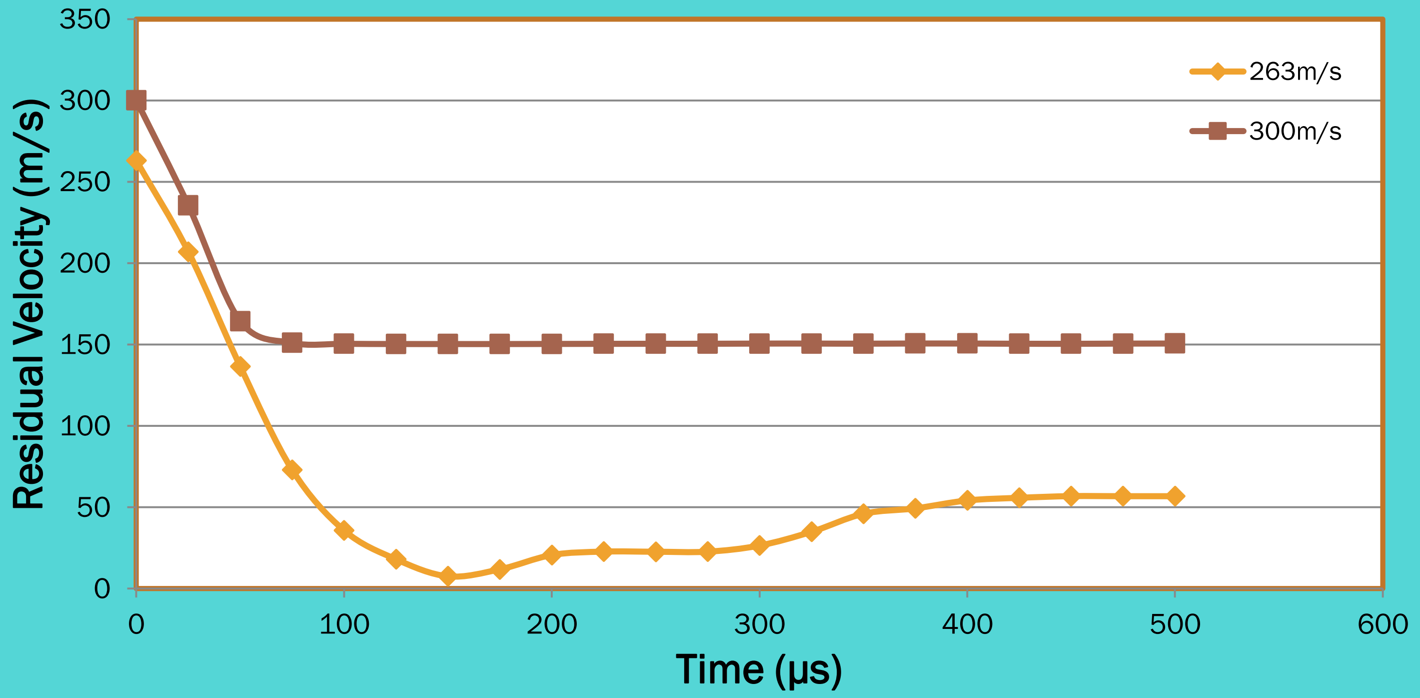
ANSYS/Explicit Dynamic compared with Abaqus/Explicit and Experiment result

Good agreement between each other

Numerical setting of the ANSYS/Explicit Dynamic consider acceptable with certain accuracy

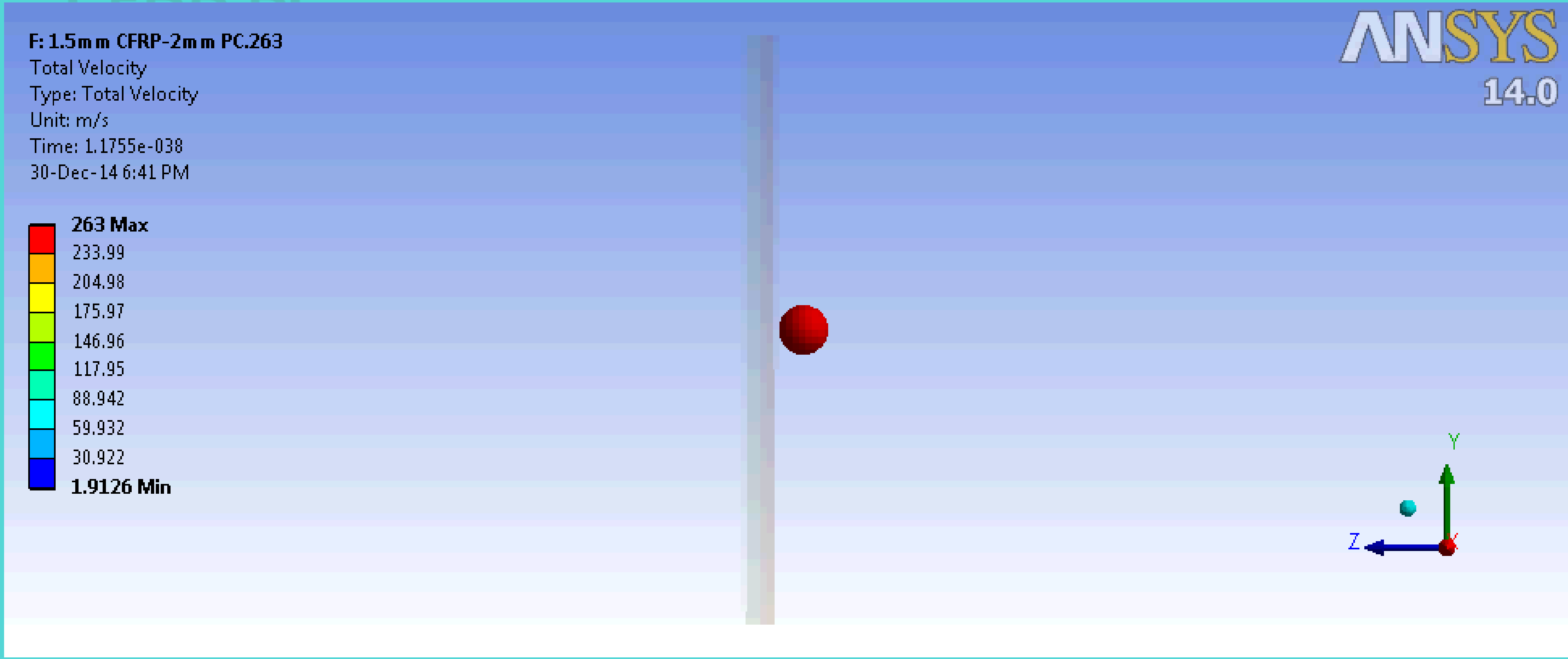
Reference: Bing Wang, Jian Xiong, Xiaojun Wang et al. Energy absorption efficiency of carbon fiber reinforced polymer laminates under high velocity impact. *Materials and Design,* 2013. 50: 140-148.

RESIDUAL VELOCITY VERSUS TIME



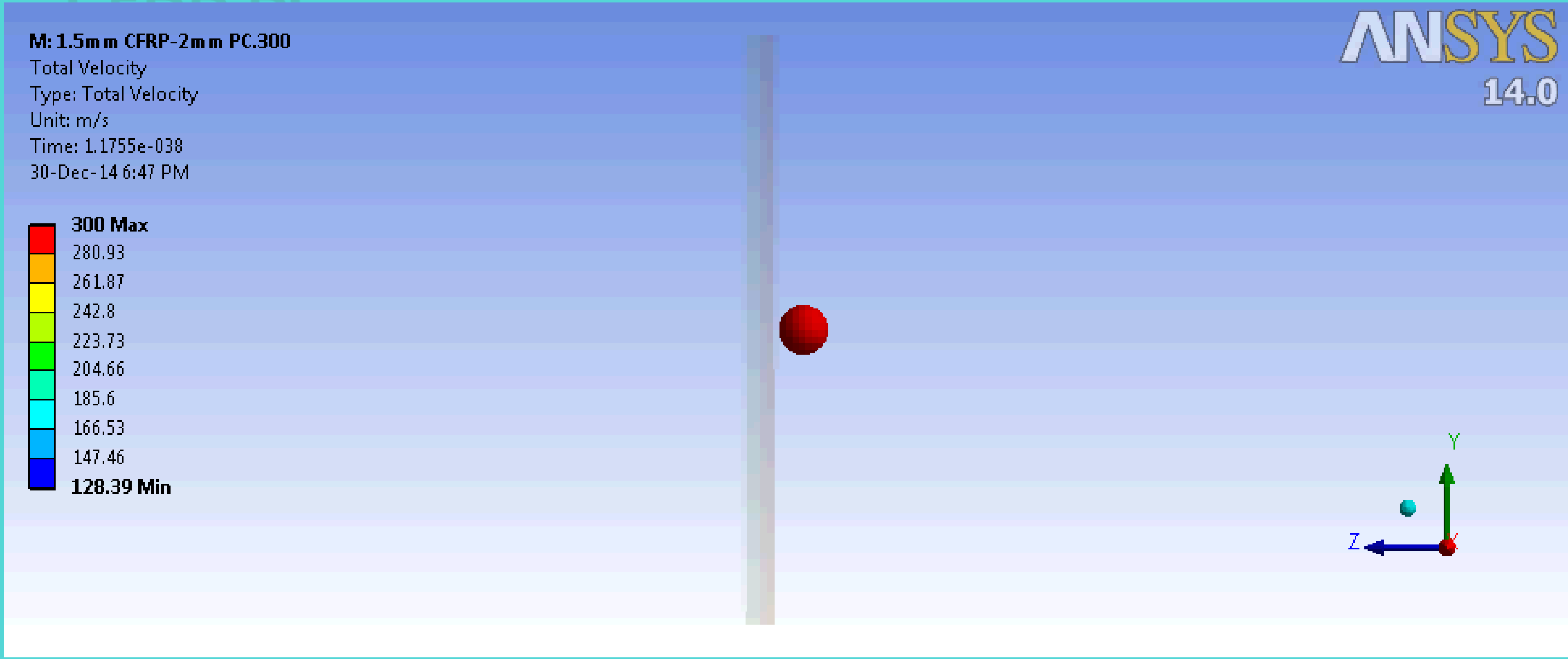
Graph of residual velocity versus time. Stacking sequence: CFRP-PC, Thickness CFRP = 1.5mm, Thickness PC = 2mm

CFRP-PC

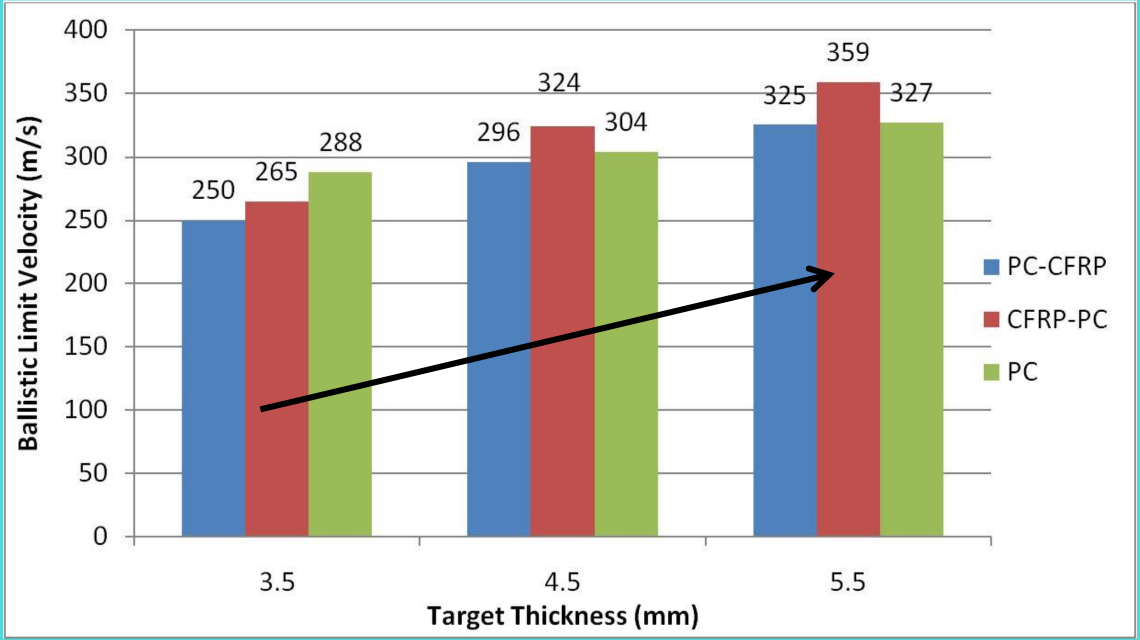


F: 1.5mm CFRP-2mm PC.263
Total Velocity
Type: Total Velocity
Unit: m/s
Time: 1.1755e-038
30-Dec-14 6:41 PM
263 Max
233.99
204.98
175.97
146.96
117.95
88.942
59.932
30.922
1.9126 Min
ANSYS
14.0
Y
Z
X

CFRP-PC


M: 1.5mm CFRP-2mm PC.300
Total Velocity
Type: Total Velocity
Unit: m/s
Time: 1.1755e-038
30-Dec-14 6:47 PM
300 Max
280.93
261.87
242.8
223.73
204.66
185.6
166.53
147.46
128.39 Min
ANSYS
14.0
Y
Z
X

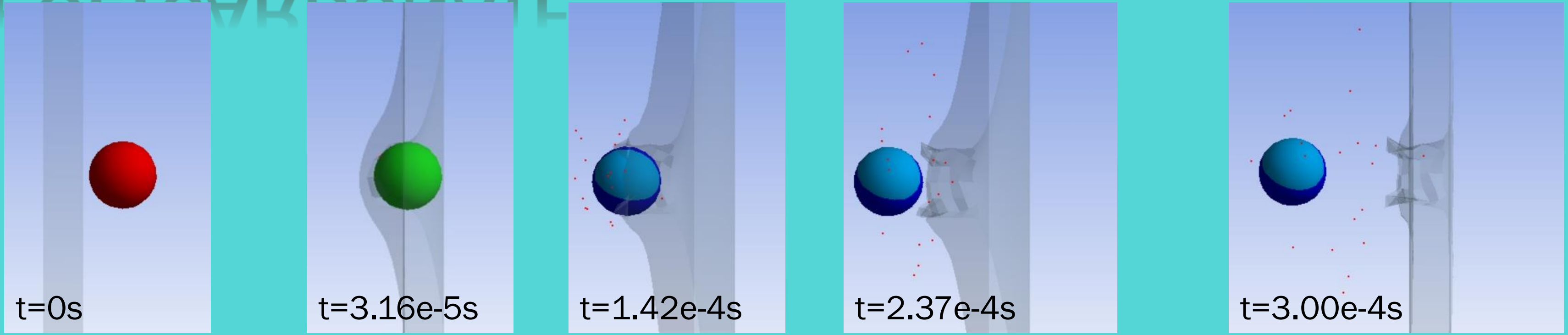
BALLISTIC LIMIT VELOCITY



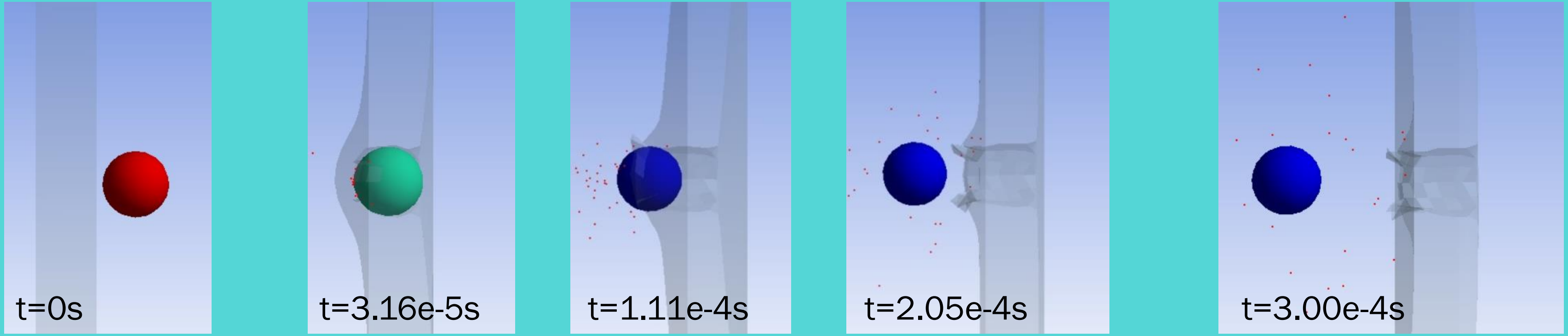
PC better than CFRP-PC and PC-CFRP at thin thickness

CFRP-PC better than PC-CFRP

POLYCARBONATE

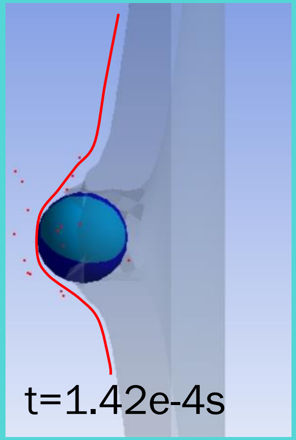


Thickness=3.5mm

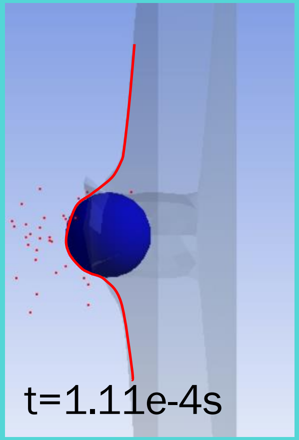


Thickness=5.5mm

DEFORMATION BEHAVIOUR



3.5mm



5.5mm

Different response between thin and thick PC

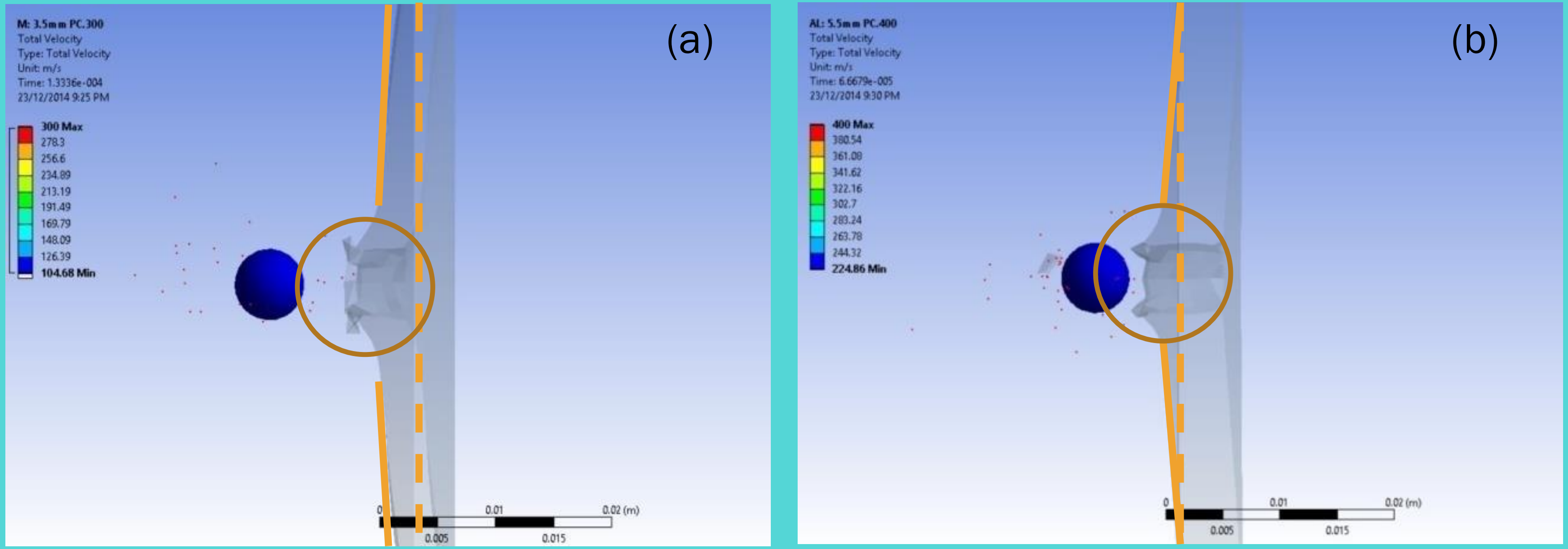
Elastic deformation-Dishing

Large dishing on thin PC plate

Small dishing on thick PC plate

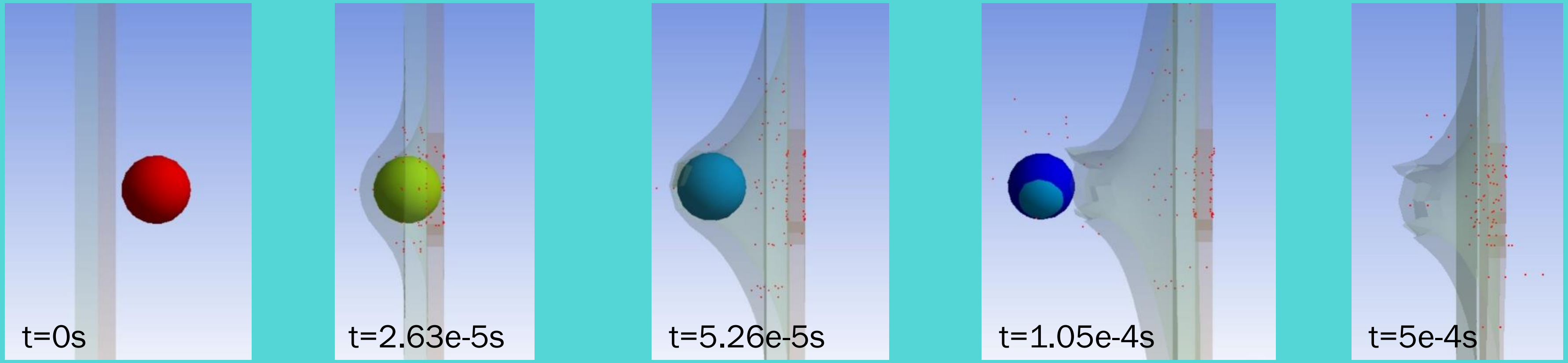
Reference: S.C.Wright, N.A. Fleck and W.J. Stronge. Ballistic impact of polycarbonate-an experiment investigation. International Journal of Impact Engineering, 1993. 13(1) : 1-20.

DEFORMATION BEHAVIOUR

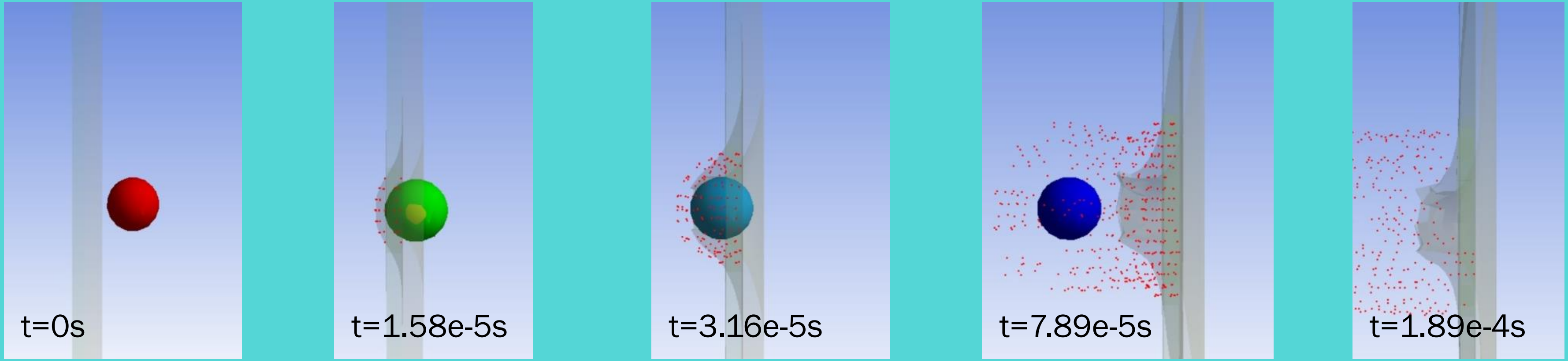


Impact behaviour of PC. (a) 3.5 mm PC (b) 5.5 mm PC

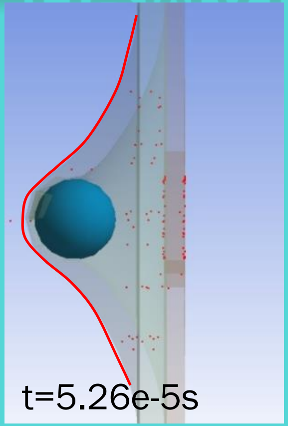
CFRP-PC



PC-CFRP



DEFORMATION BEHAVIOUR

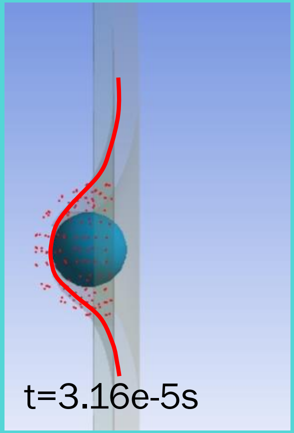


<u>CFRP-PC</u>

PC plate suffers stretching deformation

Dishing – Deformation on circular region of plate surrounding projectile.

Large Dishing = Large elastic deformation



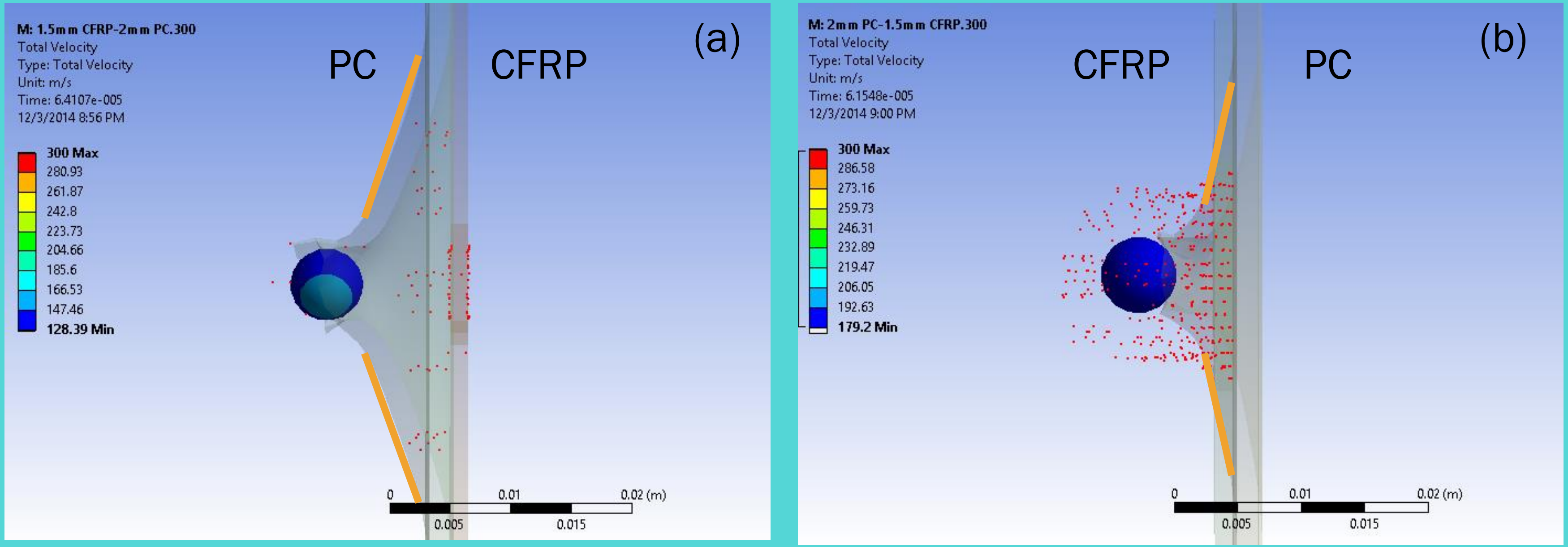
<u>PC-CFRP</u>

PC plate suffers stretching deformation

Restricted by CFRP plate

Small Dishing = Small Elastic Deformation

DEFORMATION BEHAVIOUR



Impact response of hybrid material. (a) CFRP-PC; (b) PC-CFRP

PDS . Function Decompose . Concept Development . Numerical Simulation

5.0 BULLET PROOF SHIELD DESIGN ANALYSIS

PRODUCT DESIGN SPECIFICATIONS

Overall weight must less than 4.5kg

Area of protection must cover the human torso

Must come with baton holders

Do not block the view of user when in use

Must achieve the ballistic limit velocity of 300m/s

FUNCTION DECOMPOSE

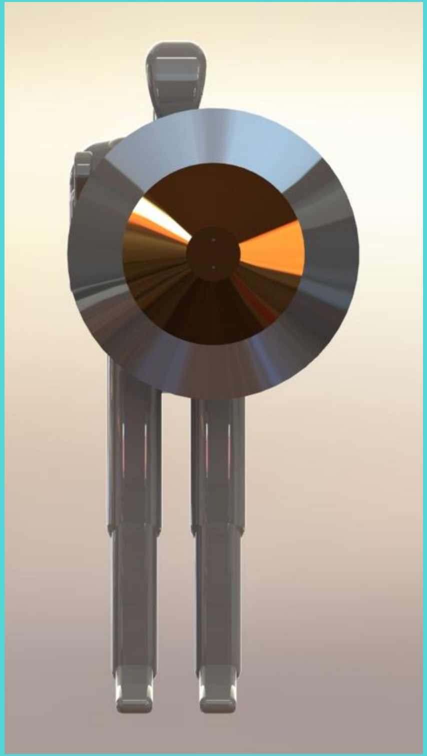
Strike Face

Baton Holder

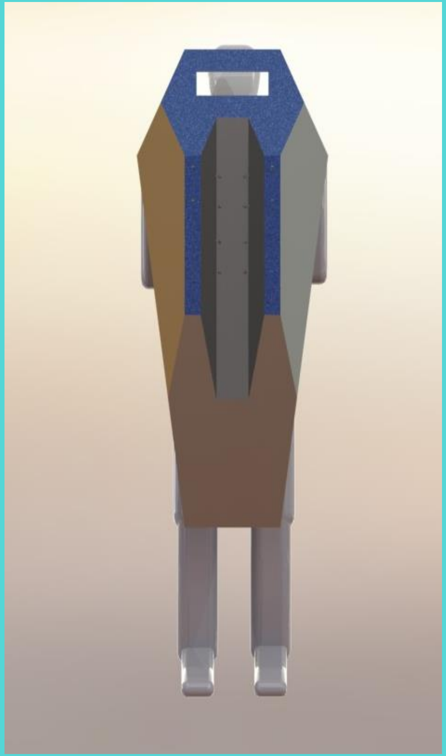
Hand Grip

View Window

DESIGN CONCEPTS



Concept 1



Concept 2

Concept 3

EVALUATION CRITERIA

RATING

Relative Performance	Rating
Very Bad	1
Bad	2
Normal	3
Good	4
Very Good	5

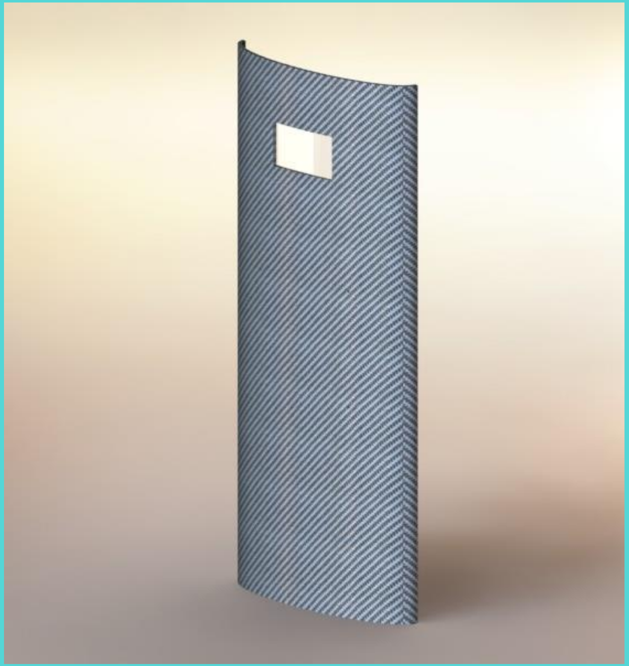
CONCEPT SCORING MATRIX

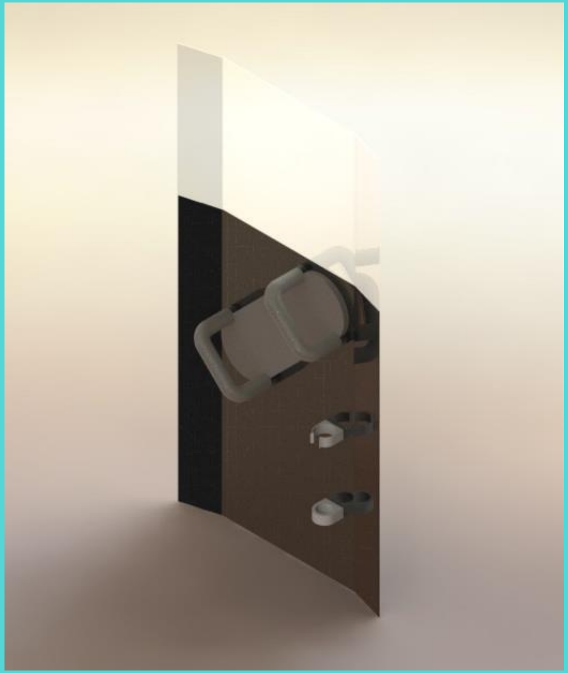
No.	Criteria	Weight	Concept 1	Concept 2	Concept 3
1	Ease of Manufacture	20%	3	2	4
2	Ease of Maintenance*	15%	2.8	2.4	3.2
3	Aesthetic*	5%	2	3.4	3.8
4	Area of Protection*	20%	1.6	2.8	4.4
5	Ease of Handling*	10%	2.4	2.6	3.4
6	Portability*	25%	3	3	3.6
7	Storage*	5%	3	3	3.4
		Total Weighted Score	2.58	2.65	3.76
		Rank	3	2	1
		Continue?	No	No	Yes

* Marks based on average value given by the potential end users.

FINAL CONCEPT DEVELOPMENT

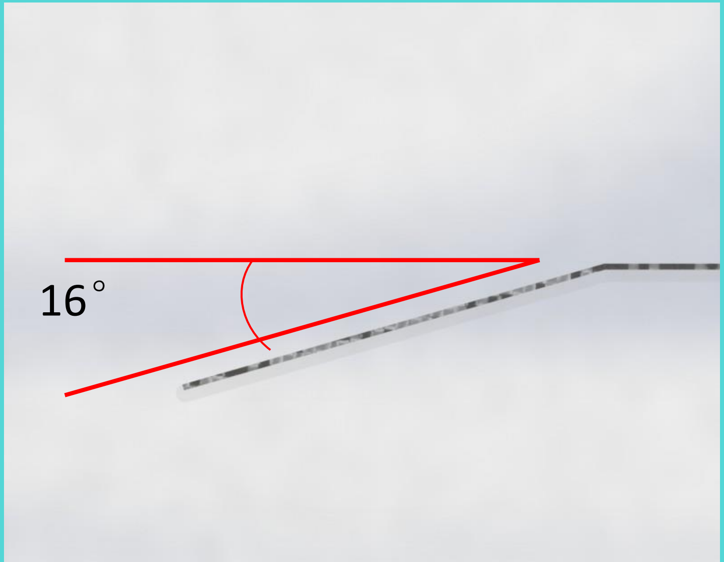
- Strike Face





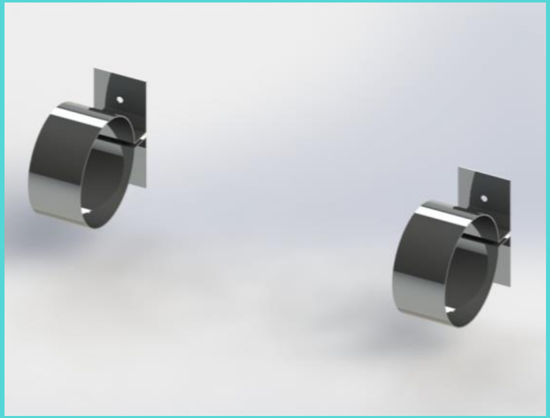
FINAL CONCEPT DEVELOPMENT

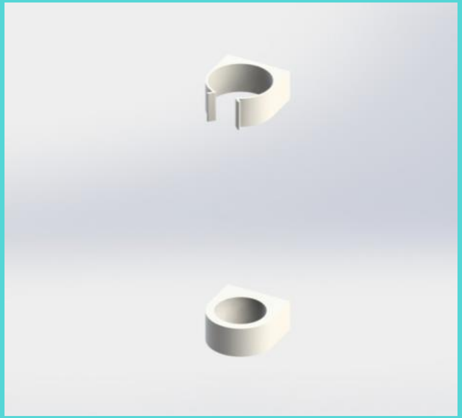
- Strike Face

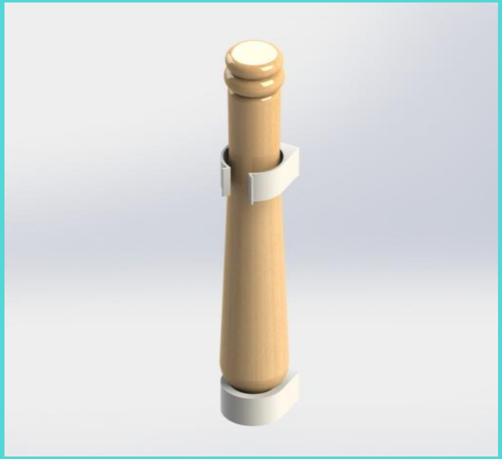


FINAL CONCEPT DEVELOPMENT

- Baton Holder

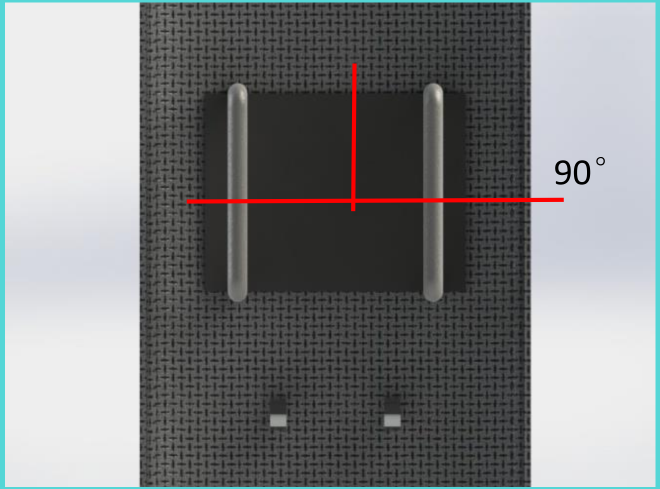


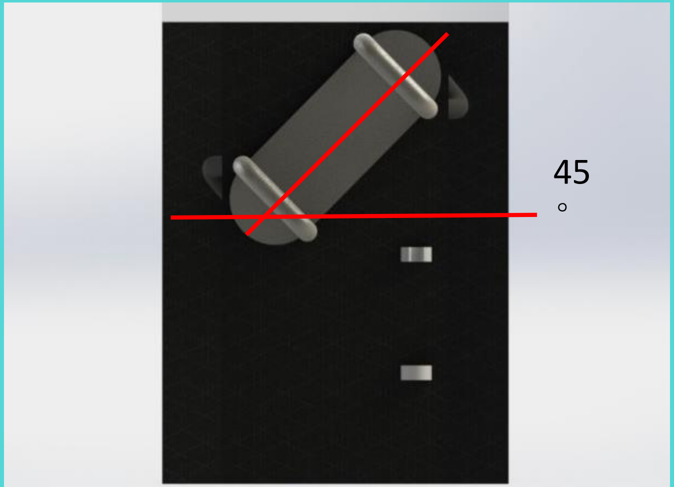




FINAL CONCEPT DEVELOPMENT

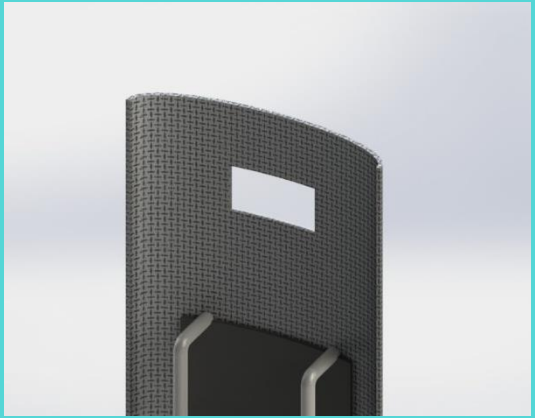
- Hand Grip



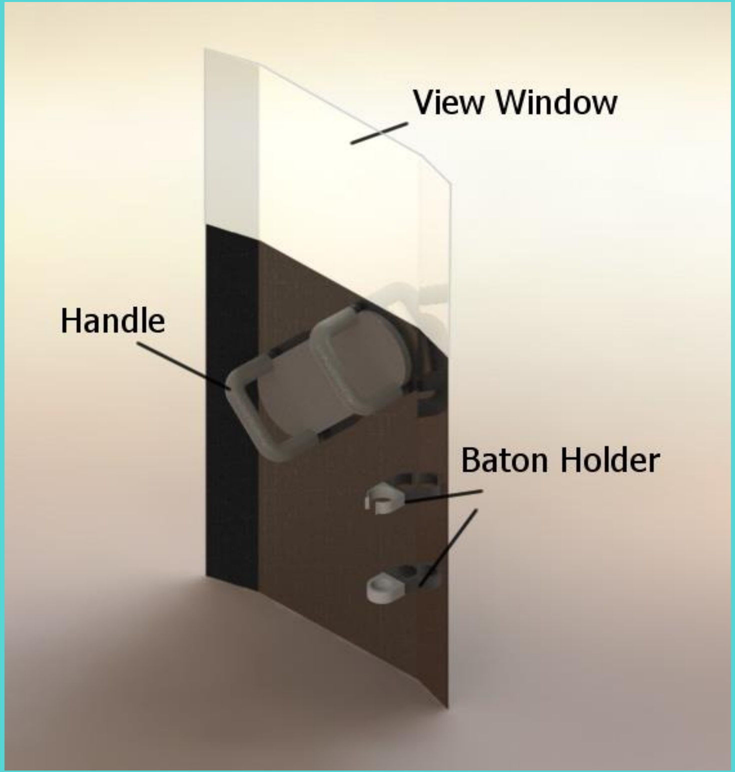


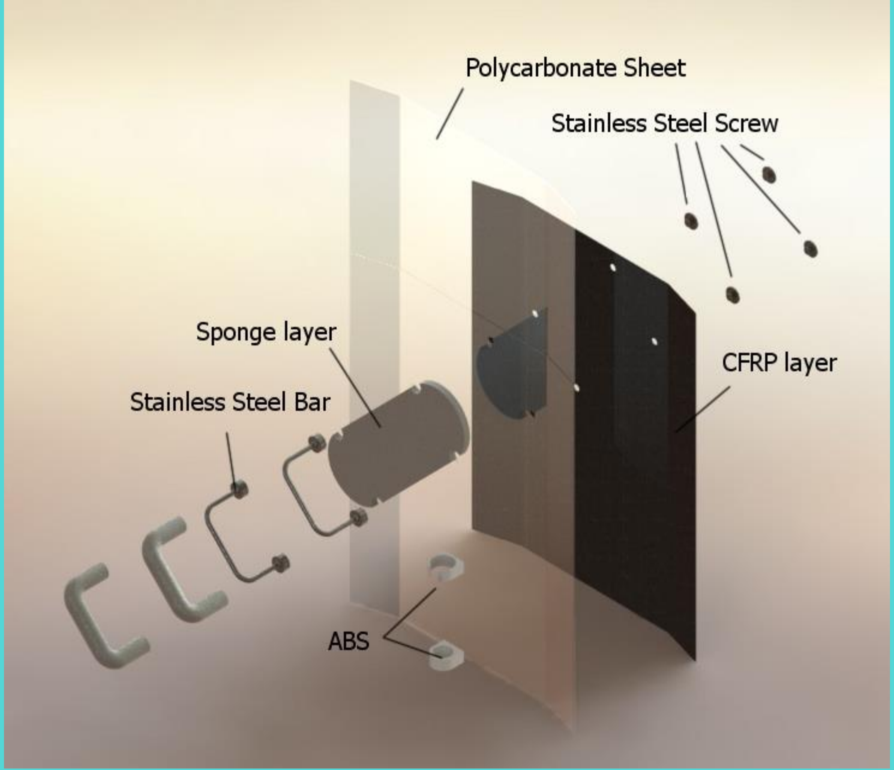
FINAL CONCEPT DEVELOPMENT

- View Window

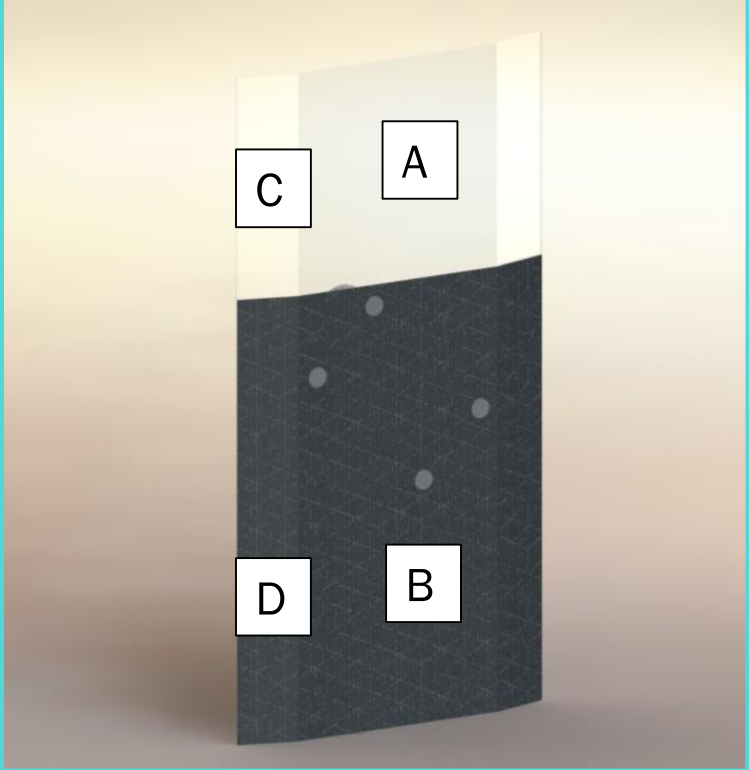


FINAL CONCEPT



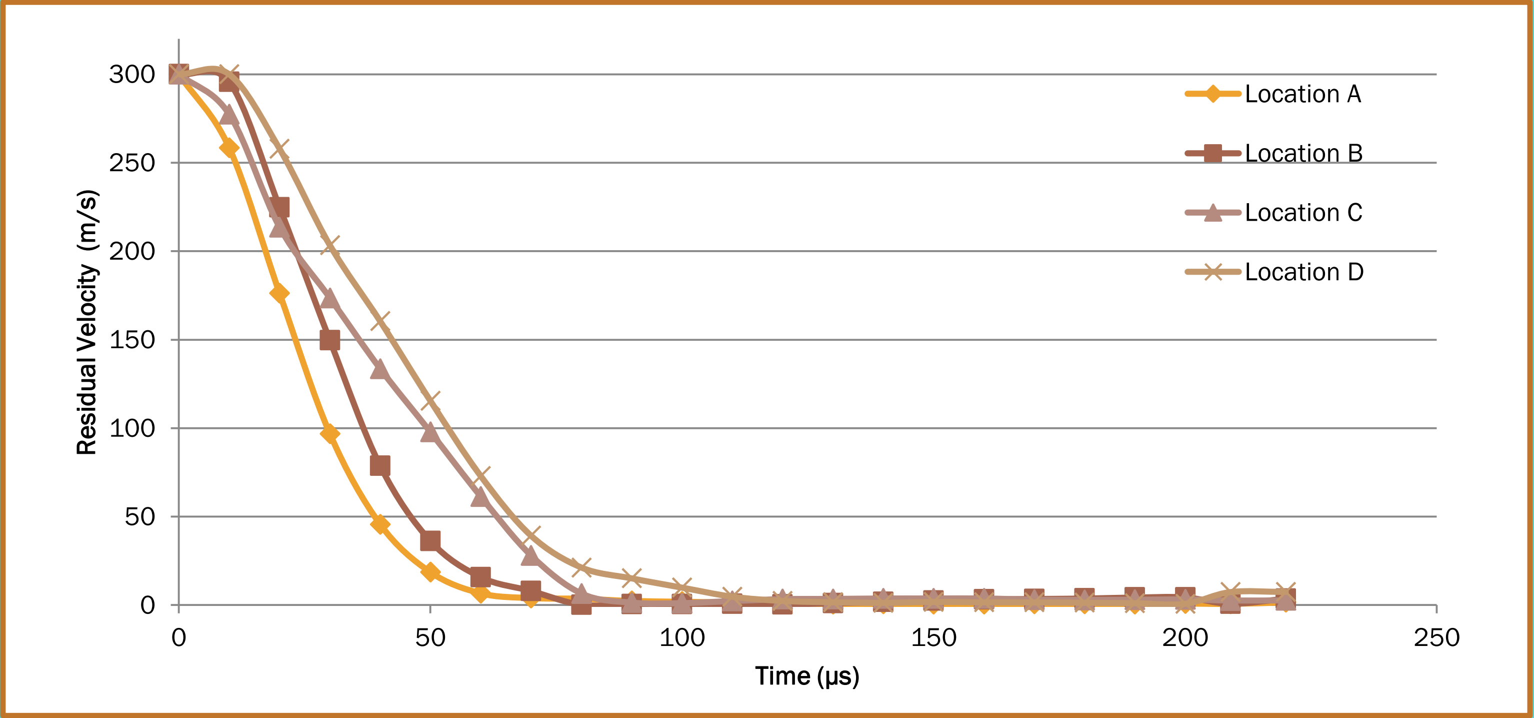


NUMERICAL ANALYSIS



Location	Description
A	200mm from Top, 254mm from left
B	250mm from top, 55mm from left
C	300mm from bottom, 254mm from left
D	400mm from bottom, 35mm from left

RESULT



Graph of residual velocity versus time. Impact velocity = 300m/s.

6.0 CONCLUSION AND RECOMMENDATION

CONCLUSION

- Biomimetics approach is embedding with product design process
- Conceptual design of bullet proof shield was proposed
- Principles from two biological model were extracted and transferred.

CONCLUSION

- CFRP-PC have 6.57% higher ballistic limit velocity compared to PC for thickness 4.5mm
- CFRP-PC showed 9.78% higher ballistic limit velocity compared to PC for thickness 5.5mm
- Hybrid material of CFRP-PC is most suitable when thickness is a constraint

CONCLUSION

- Shield is design for higher ballistic limit velocity, longer service life and proper weight
- Shield is 1200mm height x 609.6mm width
- Weight : 4.27kg
- Thickness : 4.5mm

CONCLUSION

- Impact behaviour of materials been demonstrated by numerical analysis and analytical analysis
- Experiment and empirical studies are required

RECOMMENDATION

- Future direction: Biomimetics approach enhancement and hybrid material optimization
- Biomimetics - Solution-based approach
- Hybrid Material – To achieve cost-performance balance
- Hybrid Material – introduce filler

ACKNOWLEDGEMENT

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Thank you

THE END

REFERENCES

REFERENCE

1. N.K. Naik and A.V. Doshi. Ballistic impact behaviour of thick composites: Parametric studies. *Composite Structures*, 2008. 82: 447-464.
2. N.K. Naik, P. Shrirao and B.C.K. Reddy. Ballistic impact behaviour of woven fabric composites: Parametric studies. *Materials Science and Engineering A*, 2005. 412: 104-116.
3. N.K. Naik and P. Shrirao. Composite structures under ballistic impact. *Composite Structures*, 2004. 66: 579-590.
4. A.J. Kinloch, S.J. Shaw, D. A. Tod and D.L. Hunston. Deformation and fracture behaviour of a rubber-toughened epoxy: 1. Microstructure and fracture studies. *Polymer*, 1983. 24: 1341-1354.
5. D.J. Carr. Failure mechanisms of yarns subjected to ballistic impact. *Journal of Materials Science Letters*, 1999. 18: 585-588.
6. H. Harel, G. Marom and S. Kenig. (2002). Delamination Controlled Ballistic Resistance of Polyethylene/Polyethylene Composite Materials. *Applied Composite Materials*, 2002. 9: 33-42.
7. Zhu Shengqing and Chai Gin Boay. Damage and failure mode maps of composite sandwich panel subjected to quasi-static indentation and low velocity impact. *Composite Structures*, 2013. 101: 204-214.

REFERENCE

8. Schmitt O. H. Some interesting and useful biomimetics transforms. *Proc. 3rd Int. Biophysics Congress.* 29 August to 3 September, 1969. Boston, MA, p297.
9. W. Brain Arthur. The structure of invention. *Research Policy*, 2007. 36: 247-287.
10. H. Welling. Invention. In: Mark A. Runco and Steven R. Pritzker. *Encyclopaedia of Creativity*. Elsevier. 689-695; 2011
11. Gary B. Magee. Rethinking invention: cognition and the economics of technological creativity. *Journal of Economic Behaviour & Organization*, 2005. 57: 29-48.
12. Abd. Rahim Abu Talib and Nadia Abdullah. *Innovation Methodology*. Malaysia: Universiti Putra Malaysia Press. 2013
13. William Wilmot and Curtis R. Carlson . *Innovation: The Five Disciplines for Creating what Customers Want*. United States: Crown Business. 2006
14. V. Sivapalan and Renuka Sena. Fostering the creation of the next generation of innovative technology enterprises in Malaysia. Unpublished note, Prime Minister's Office, Malaysia. 2011

REFERENCE

15. Benyus, J.. *Biomimicry - Innovation Inspired by Nature*. New York, Harper Collins Publishers. 1997

16. L.H. Shu, K. Ueda, I. Chiu et al.. Biologically inspired design. *CIRP Annals- Manufacturing Technology*, 2011. 60: 673-693.

17. Sinan Korkmaz. A review of active structural control: challenges for engineering informatics. *Computers and structures*, 2011. 89: 2113-2132.

18. Rasha Mahmoud Ali El-Zeiny. Biomimicry as a problem solving methodology in interior architecture. *Procedia Social and Behavioral Sciences*, 2012. 50: 502-512.

19. It is Beijing <http://itisbeijing.wordpress.com/2012/06/30/beijing-bird-nest-hotel/>, (Retrieved April 10, 2014)

20. Ask Nature <http://www.asknature.org/product/6273d963ef015b9>, (Retrieved April 10, 2014)

21. Daily Mail Online < http://www.dailymail.co.uk/home/index.html>, (Retrieved April 10, 2014)

REFERENCE

22. The Shinkansen-Japan's Bullet Train <http://www.theworldisnotflat.com/shinkansen>,(Retrieved April 10, 2014)
23. L. Feng, S.H. Li et al. Super-hydrophobic Surfaces: From Natural to Artificial. *Advanced Materials*, 2002. 14: 1857-1860.
24. W. Barthlott and C. Neinhuis. Purity of the scared lotus, or escape from contamination in biological surfaces. *Planta*, 1997. 202:1-8.
25. C. Neinhuis, W. Barthlott. Seasonal changes of leaf surface contamination in beech, oak, and ginkgo in relation to leaf micromorphology and wettability. *New Phytologist*, 1998. 138: 91-98.
26. Kesong Liu and Lei Jiang. Bio-inspired design of multiscale structures for function integration. *Nanotoday*, 2011. 6: 155-175.
27. Helms M, Vattam S, Goel A. Biologically Inspired Design: Process and Products. *Design Studies*, 2009. 30(5): 606-622.
28. U. Lindemann, J. Gramann. Engineering Design Using Biological Principles. *International Design Conference*. 18 May -21 May. Dubronik. 2004.1-6.

REFERENCE

29. Marc Andre Meyers, Po-Yu Chen et al. Biological materials: Structure and mechanical properties. *Progress in Materials Science*, 2008. 53: 1-206.
30. Kodera, H et al. *Jurassic Fishes: Selection, Care, Behavior*. Tfh Pubns. Inc. 1994
31. Edwin H. Colbert, Michael Morales, Eli C. Minkoff. *Evolution of the Vertebrates: A History of Backboned Animals Through Time*. New York: Wiley. 2001
32. Gisela M Luz and Joao F Mano. Biomimetics design of materials and biomaterials inspired by the structure of nacre. *Philosophical Transactions of Royal Society A*, 2009. 367: 1587-1605.
33. Francois Barthelat. Biomimetics for next generation materials. *Philosophical Transaction of Royal Society A*, 2007. 365: 2907-2919.
34. Francois Barthelat. Nacre from mollusk shells: a model for high performance structural materials. *Bioinspiration & Biomimetics*, 2010. 5: 1-8.
35. Benjamin J.F. Bruet, Juha Song et al. Materials design principles of ancient fish armour. *Nature Materials*, 2008. 7: 748-756.
36. J.D. Currey, A. Nash, W. Bonfield (1982). Calcified cuticle in the stomatopod smashing limb. *Journal of Materials Science*, 1982. 17: 1939-1944.

REFERENCE

37. Wadley Research Group <http://www.virginia.edu/ms/research/wadley/ballistic-impact.html>, (Retrieved April 14, 2014)
38. S.C. Wright, N.A. Fleck and W.J. Stronge. Ballistic Impact of Polycarbonate- An Experimental Investigation. International Journal of Impact Engineering, 1993. 13(1): 1-20.
39. Karl T. Ulrich. Steven D. Eppinger. *Product Design and Development*. (3rd Edition). New York: McGraw-Hill. 2003
40. Kromm FX, Quenisset JM, Harry R, Lorriot T. An example of multimaterial design. *Advanced Engineering Materials*, 2002. 4:371-4
41. M.F. Ashby, Y.J.M. Brechet. Designing hybrid materials. *Acta Meterialia*, 2003. 51:5801-5821.
42. K.V. Rijswijk. *Application of Natural Fibre Composites in the Dvelopment of Rural Societies*. Master Thesis. Delft University of Technology. 2001.
43. James C. Gerdeen, Harold W. Lord, Ronald A.L. Rorrer. *Engineering Design with Polymers and Composites*. Florida: CRC Press. 2006.
44. Bryan Harris. *Engineering Composite Materials*. London: IOM Communications Ltd. 1999.
45. L.J. Hart-Smith. *Simple methods for predicting the strength of cross-plied fibrous composite laminates*. California: McDonnell Douglas Corporation. 1989.

REFERENCE

46. Wen HM. Predicting the penetration and perforation of FRP laminates struck normally by projectiles with different nose shapes. *Composite structures*, 2000.49: 321-329.
47. N.K. Gupta, M.A. Iqbal, G.S. Sekhon. Effect of projectile nose shape, impact velocity and target thickness on deformation behaviour of aluminium plates. *International Journal of Solids and Structures*, 2007. 44: 3411-3439.
48. C.T. Lim, V.B.C. Tan, C.H. Cheong. Perforation of high-strength double-ply fabric system by varying shaped projectiles. *International Journal of Impact Engineering*, 2002. 27(6): 577-591.
49. T. Mitrevski, I.H. Marshall, R. Thomson, R. Jones, B. Whittingham. The effect of impactor shape on the impact response of composite laminates. *Composites Structures, 2005.* 67(2): 139-148.
50. V.B.C. Tan, K.J.L. Khoo. Perforation of flexible laminates by projectiles of different geometry. *International Journal of Impact Engineering*, 2005. 31(7): 793-810.
51. Lingyu Sun, Ronald F. Gibson et al. Energy absorption capability of nanocomposites: A review. *Composites Science and Technology*, 2009. 69: 2392-2409.

REFERENCE

52. Brenda L. Buitrago, Shirley K. et al. Influence of shear plugging in the energy absorbed by thin carbon-fibre laminates subjected to high velocity impacts. *Composites: Part B*, 2013. 49: 86-92.
53. S.S. Morye, P.J. Hine, R.A. Duckett, D.J. Carr, and I.M. Ward. Modelling of the Energy Absorption by Polymer Composites upon Ballistic Impact. *Composites Science and Technology*, 2000. 60(14): 2631-2642.
54. Chiara Colombo, Laura Vergani. Influence of delamination on fatigue properties of a fibreglass composite. *Composite Structures*, 2014. 107: 325-333.
55. S.A. Taylor, D.J. Carr. Post failure analysis of 0°/90° ultra high molecular weight polyethylene composite after ballistic testing. *Journal of Microscopy*, 1999. 196(2): 249-256.
56. C.F. Li, N. Hu, Y.J. Yin, H. Sekine, H. Fukunaga. Low-velocity impact-induced damage of continuous fibre-reinforced composite laminates. Part 1. An FEM numerical model. *Composites Part A: Applied Science and Manufacturing*, 2002.33(8): 1055-1062.
57. Shirley K Garcia-Castillo, Sonia Sanches-Saez, Enrique Barbero. Influence of areal density on the energy absorbed by thin composite plates subjected to high-velocity impacts. *J. Strain Analysis*,2012. 47(7): 444-452.
58. G. Sadeghi, H. Hosseini-Toudeshky, B. Mohammadi. An investigation of matrix cracking damage evolution in composite laminates- Development of an advanced numerical tool. *Composite Structures*, 2014. 108:937-950.
59. Hideaki Kasano. Impact perforation of orthotropic and quasi-isotropic CFRP laminates by a steel ball projectile. *Advanced Composite Materials*, 2001. 10(4):309-318.

REFERENCE

60. National Institute of Justice. Ballistic Resistant Protective Materials. United State: Department of Justice. NIJ Standard 0108.01. 1985
61. Gupta BP, Davids N. Penetration experiments with fiberglass-reinforced plastics. *Experimental Mechanics*, 1966. 6(9): 445-450.
62. M.J. Iremonger, A.C. Went AC. Ballistic impact of fibre composite armours by fragment-simulating projectiles. *Composites Part A: Applied Science and Manufacturing*, 1996. 27(7): 575-581.
63. Bartus SD, Vaidya UK. Performance of long fiber reinforced thermoplastics subjected to transverse intermediate velocity blunt object impact. *Composite Structures*, 2005. 67(3): 263-277.
64. Jacobs M.J.N., Van Dingenen J.L.J. Ballistic protection mechanisms in personal armour. *Journal of Materials Science*, 2001. 36(13): 3137-3142.
65. Bhatnagar A, Lin LC, Lang DC, Chang HW. Comparison of ballistic performance of composites. *Proceedings of 34th International SAMPE Symposium and Exhibition*. 1989. 1529-1537.
66. Jeng ST, Wang SB, Sheu LT. A model for predicting the residual strength of GFRP laminates subject to ballistic impact. *Journal of Reinforced Plastics and Composites*, 1992. 11(10): 1127-1141.
67. D.G. Lee. Impact properties of glass fiber composites with respect to surface treatment and fibre volume fraction. Doctor Philosophy, Mechanical Engineering, Korea Advanced Institute of Science and Technology; 2000
68. Hazall PJ, Kister G, Stennett C, et al. Normal and oblique penetration of woven CFRP laminates by a high velocity steel sphere. *Composites Part A: Applied Science and Manufacturing,* 2008. 39(5): 866-874.

REFERENCE

69. J. Lopez-Puente, R. Zaera, C. Navarro. Experimental and numerical analysis of normal and oblique ballistic impacts on thin carbon/epoxy woven laminates. *Composites Part A: applied science and manufacturing,* 2008. 39(2):374-387.
70. Chu C.K., Chen Y.L., Hseu G.C., Hwang D.G. The study of obliquity on the ballistic performance of basket fabric composite materials. *Journal of Composite Materials,* 2007. 41(13): 1539-1558.
71. G.J. Czarnecki. Estimation of the V50 using semi-empirical (1-point) procedures. *Composites Part B: Engineering,* 1998. 29(3): 321-329.
72. Czarnecki G.J. The significance of laminate spallation generated by high velocity spherical metallic impactors. *Composites Engineering,* 1994. 4(3): 287-297.
73. Von Hippel, Eric. *The source of Innovation*. New York: Oxford University Press. 1988
74. W.J. Cantwell, J. Morton. Impact perforation of carbon fibre reinforced plastic. *Composites Science and Technology*, 1990. 38(2): 119-141.

REFERENCE

75. Bing Wang, Jian Xiong, Xiaojun Wang et al. Energy absorption efficiency of carbon fiber reinforced polymer laminates under high velocity impact. *Materials and Design,* 2013. 50: 140-148.

76. J.G. Hetherington. The optimization of two component composite armors. *International Journal of Impact Engineering,* 1992. 12:229-59.

77. Bullet Proof Shield

<http://www.chinaypages.com/sampleroom/onesample/51549729/Bulletproof_Shield.html>, (Retrieved December 1, 2014)

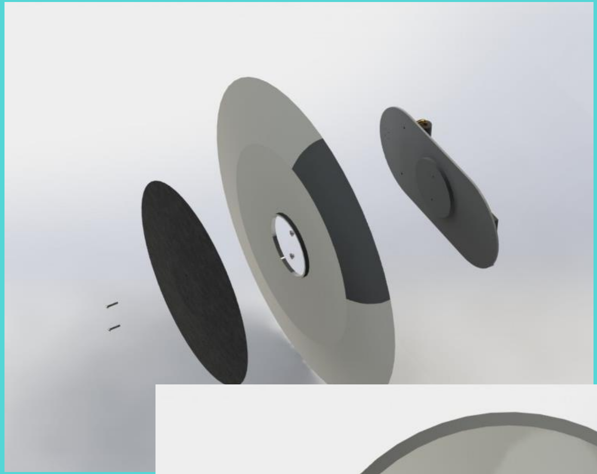
78. Police Baton

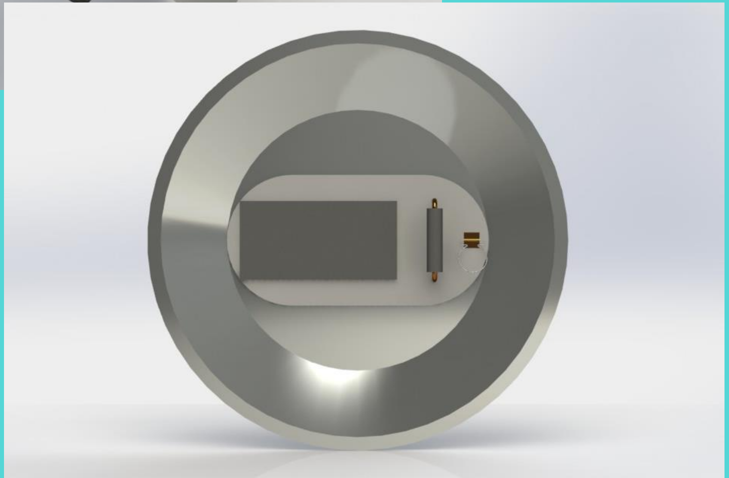
<http://www.costumecraze.com/ACC526.html>, (Retrieved December 1, 2014)

BIOMIMETICS DESIGN

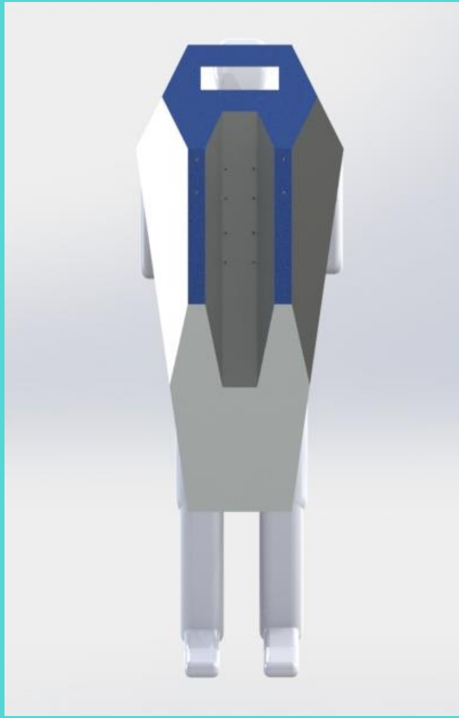
Source:The Shinkansen-Japan's Bullet Train
<http://www.theworldisnotflat.com/shinkansen>,(Retrieved April 10, 2014）

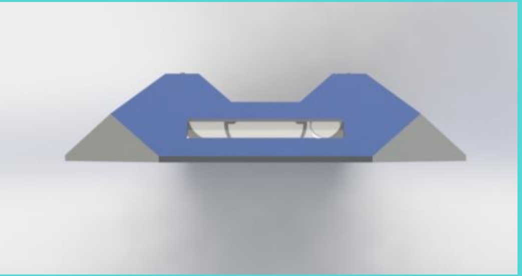
PROPOSED CONCEPT 1

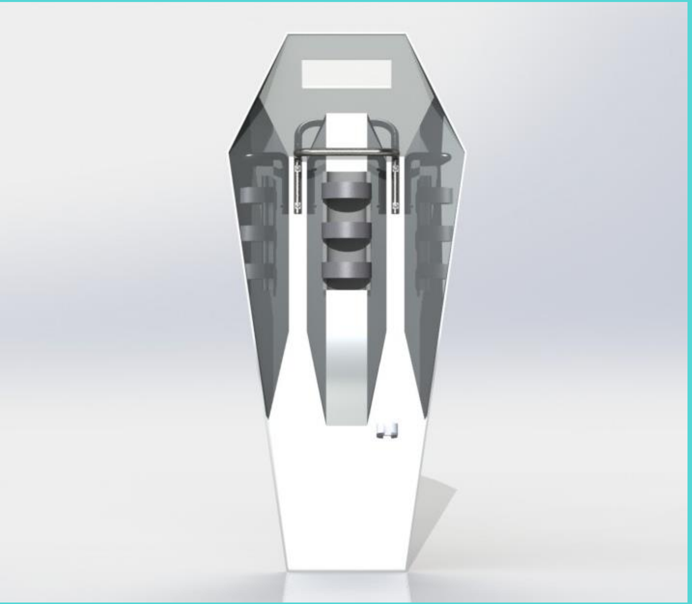




PROPOSED CONCEPT 2

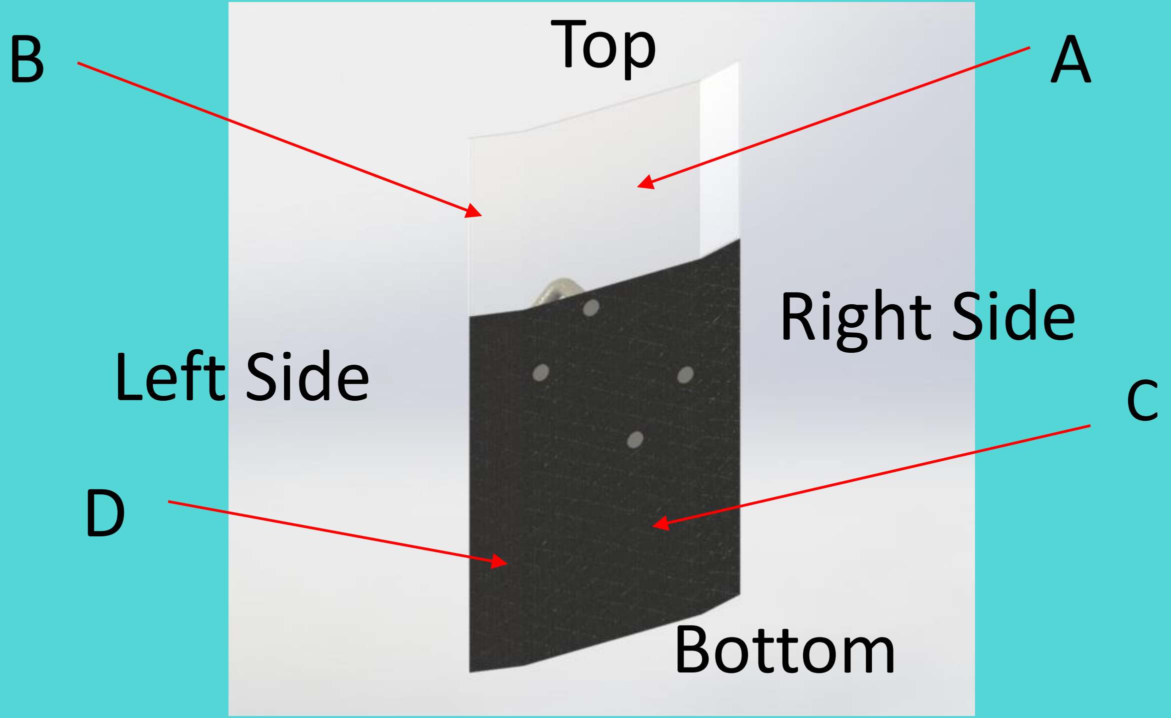






PROPOSED CONCEPT 3

NUMERICAL SIMULATION



Biomimetics Approach

1. Problem Definition
2. Reframe the problem
3. Biological solution search
4. Define Biological Solution
5. Principle Extraction
6. Principle Application

1. Biological solution identification
2. Define biological solution
3. Principle extraction
4. Reframe the solution
5. Problem search
6. Problem Definition
7. Principle Application