Rotationally Moulded Sandwich Composites in Small Marine Leisure Craft: Fracture Properties and Damage Analysis of The Composite Structure

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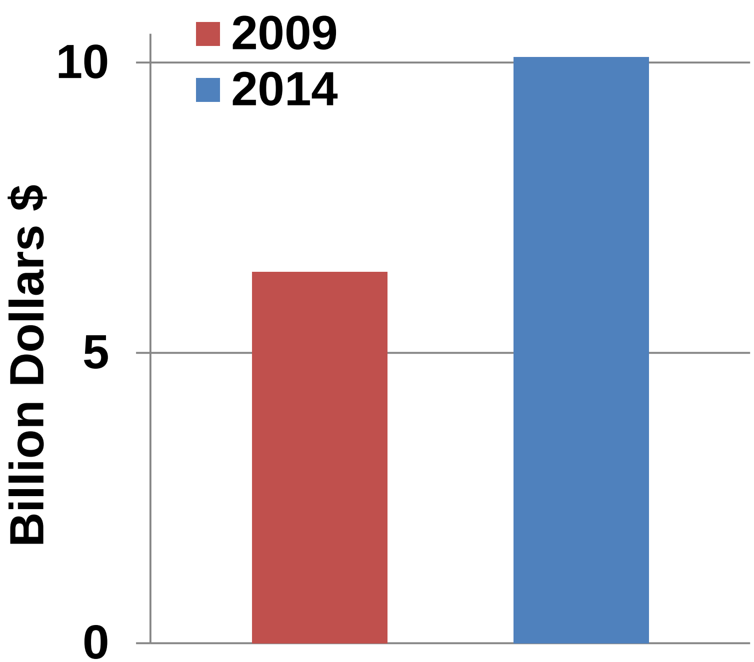
Contents

Recent Condition of Leisure Boat Industry

Europe and USA have the largest markets for leisure boats

6 million composite leisure crafts in Europe alone



End-of-life (EoL) disposal of composite leisure boats has become a major concern.

Current Disposal Method

Dumping into landfills

Abandoned in marine areas

Problems

Current Disposal Method

- Landfill dumping is already banned in Germany, Netherlands. UK is also going to implement this.
- BOATCYCLE project is done in Europe [1, 2].
- Recycling is not economical. 7m long boat- €800, 10 m boat- €1500, 15 m boat- €15000.
- Waste of material's potential.

Roto-moulded Thermoplastic Marine Leisure Craft

Rotational moulding

Rotational moulding is used to make large hollow shapes, one piece plastic parts in a single manufacturing step without any joints [3].

Rotational Moulding Process

Rotational Moulding Process

Uniqueness of Rotational Moulding

- Long processing cycles
- Slowest cooling rates
- Zero shear process
- Uniform thickness distribution
- Complex shapes, multiple layered and hollow plastic parts

Advantages of roto-moulded plastic boats over composite boats

- Cheap boats more than 10 m in length
- Reasonably durable
- Can be made from recycled materials
- Better EoL disposal – fully recyclable, zero waste concept (cradle to cradle philosophy)

Roto-moulded Leisure Boat Industry

Current Problems

- ❖ Rapid fracture of the structure after getting sharp cracks or scratches.
- ❖ This industry is based on trial-error basis not on scientific understanding [4].

Research so far

- ❖ Process parameter analysis [5].
- ❖ Limited understanding on material's properties.
- ❖ Tensile, flexural, impact properties are tested [6].
- ❖ Fracture behaviour and damage analysis are still absent.

Cracks & Scratches

Aim & Objectives of this research

Aim

Analysis of damage creation and propagation of rotationally moulded sandwich composite under low velocity impact condition.

Objectives

- ❖ Materials selection- fracture behaviour.
- ❖ Making sandwich composites.
- ❖ Low velocity impact testing and damage identification .
- ❖ Damage propagation analysis

Fracture Behaviour of the materials

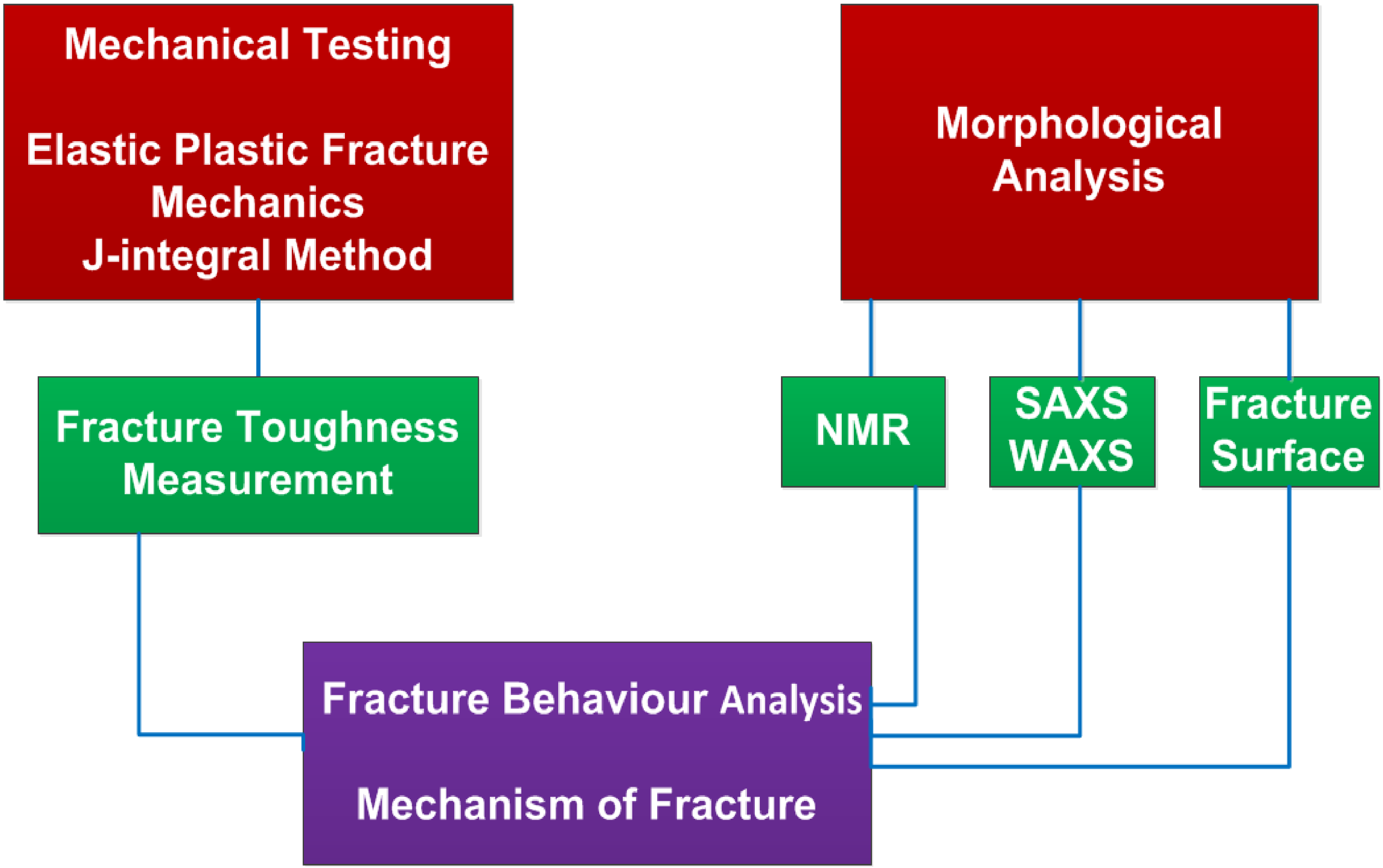
Fracture behaviour at slow loading rate

- Determination of fracture toughness properties.
- Investigation of microstructure arrangements of the materials.
- Identification of crack growth mechanism.

Fracture Toughness Provides

- Following fracture mechanics
- Crack initiation point
- Crack propagation resistance behaviour.
- Predict the progress of material damage subjected to external loads.
- One of the most important design parameters.

Methodology & Experimental Design



Testing Process

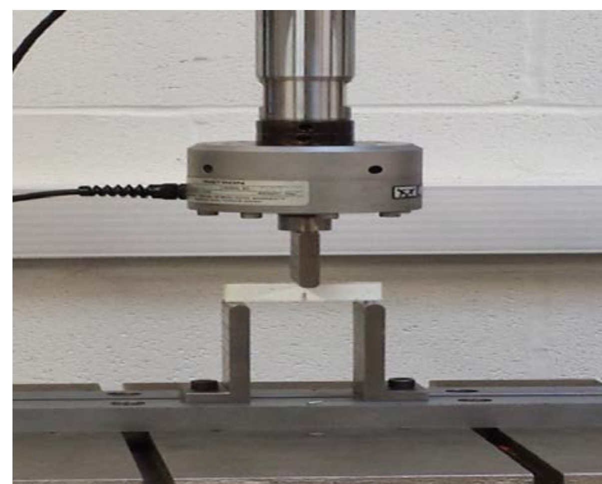
Sample Preparation

- ❖ Single edge notch sample.
- ❖ Initial notch & crack

Sample with Notch

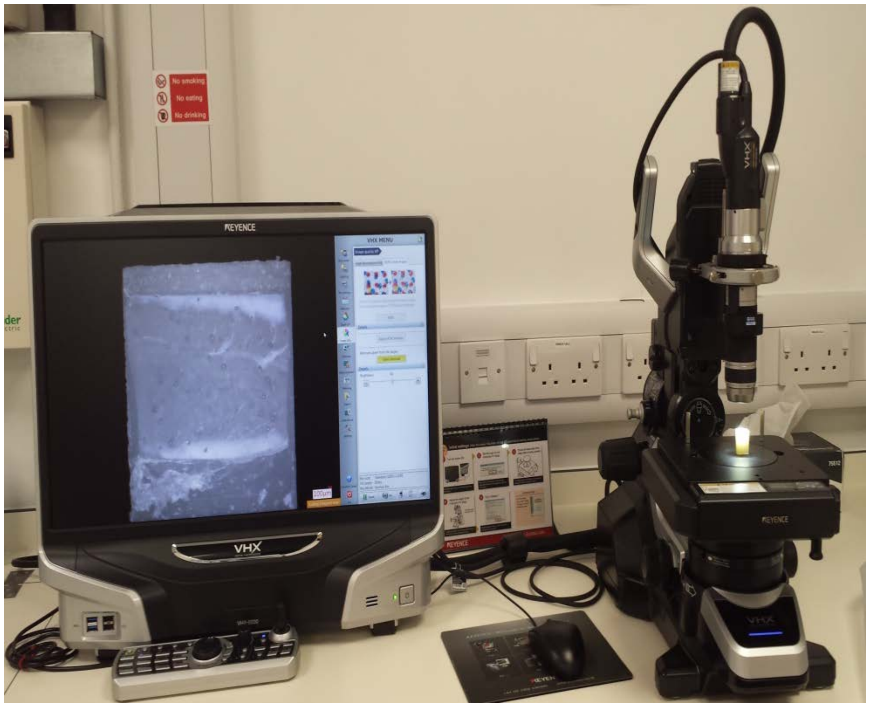
Testing in Instron

- ❖ Elastic-plastic fracture mechanics J-integral Method
- ❖ Multiple specimen process
- ❖ 3-point bending arrangement.
- ❖ 1mm/min loading rate, room temp.



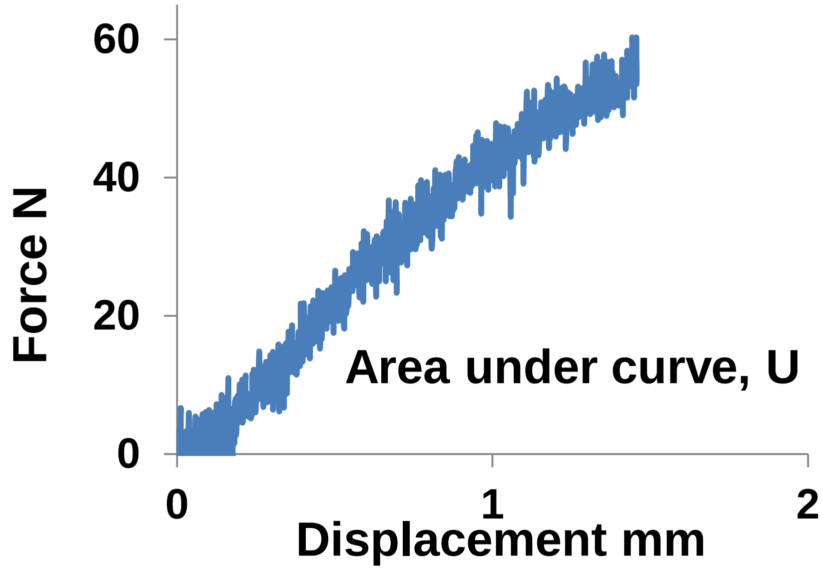
Testing Methodology

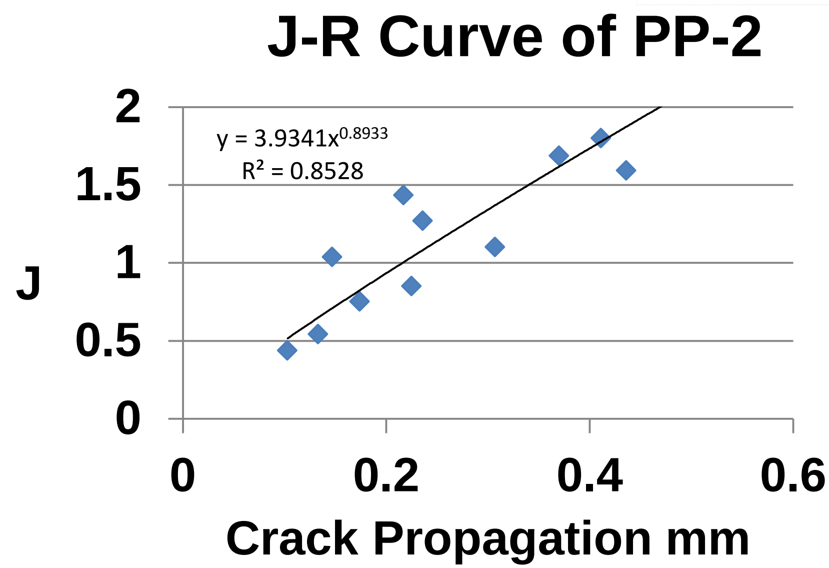
Measuring Crack Front with Optical Microscope



SEM for Higher Magnification Image

Polypropylene (PP)

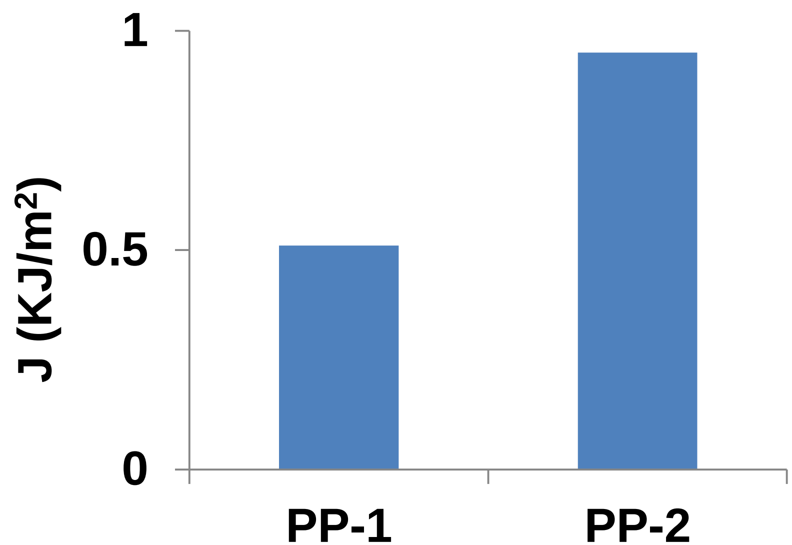




J-integral Fracture Toughness

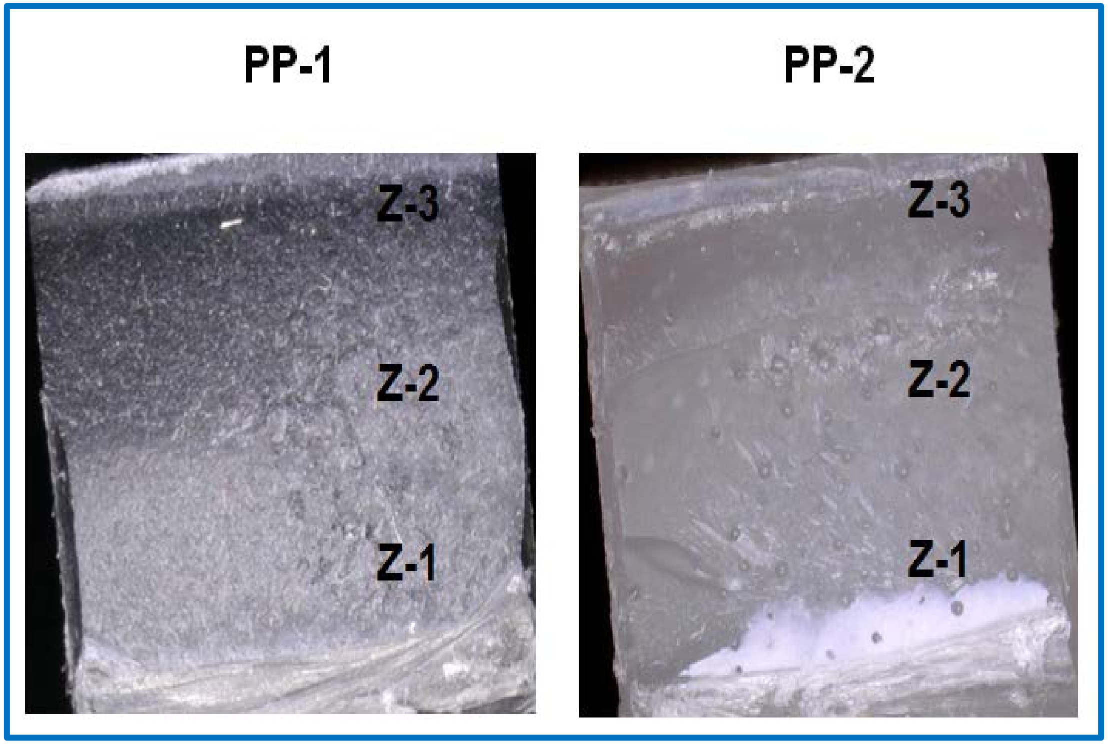
$$J = \frac{2U}{B\,(W - a)}$$

U= Total work to create crack
B= Sample Thickness, W= Width
a = length of initial notch and crack



Polypropylene (PP)

Fracture Surfaces



Z-1 = Stable crack growth.

Z-2 = Smooth wide, diffuse, lighter stress whitened area.

Z-3 = Brittle fracture.

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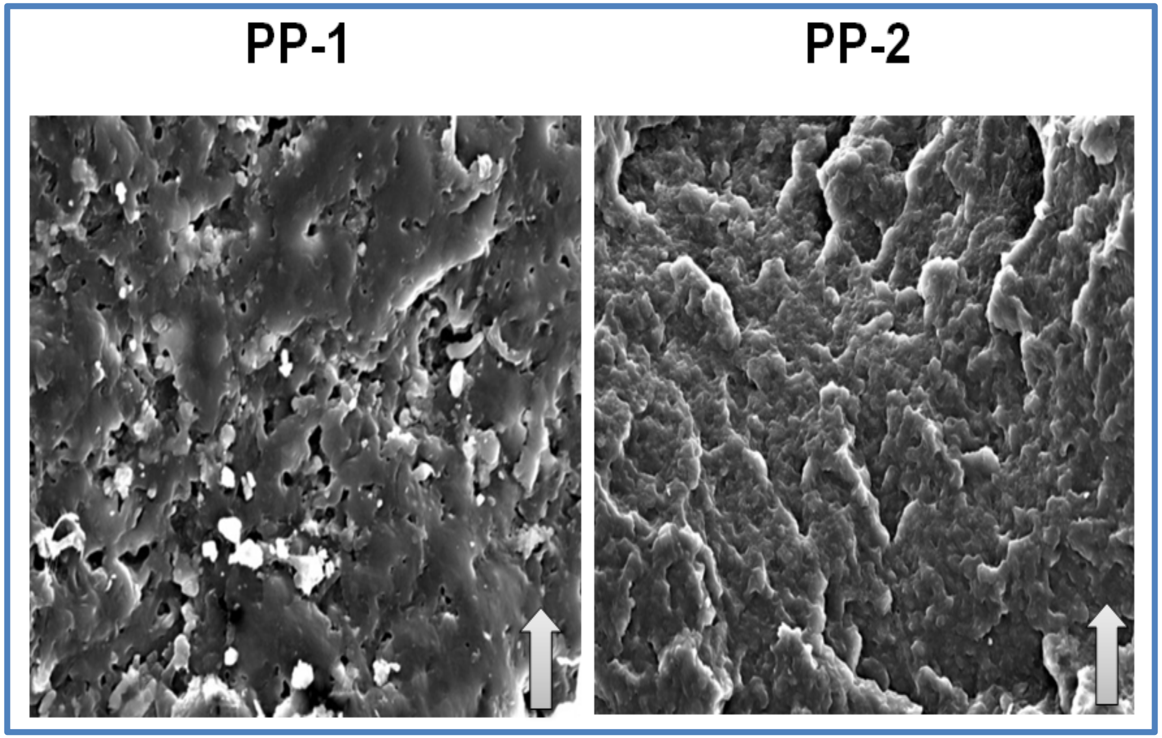
Polypropylene (PP)

SEM Images



Brittle fracture in PP-1.

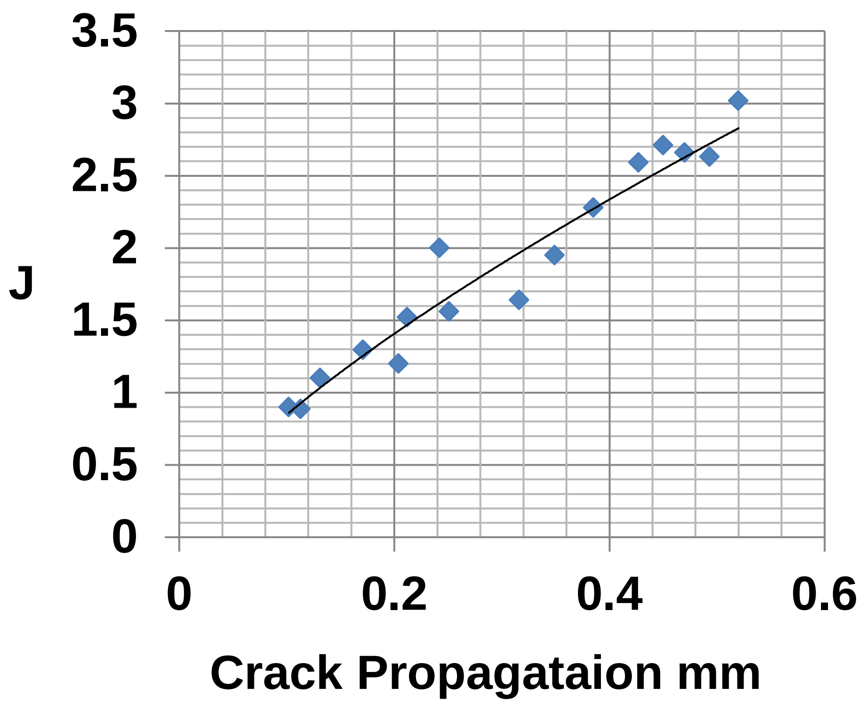
Patchy, wavy, more plastic deformation leads to higher toughness in PP-2.

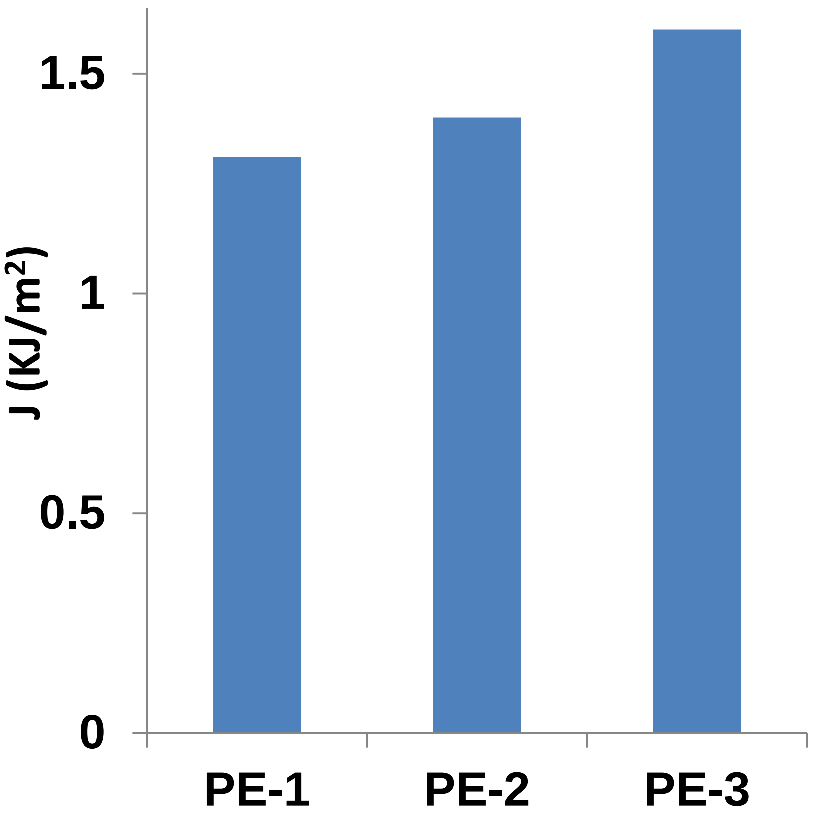
NMR, X-ray scattering, DSC analysis agree with this.

- ❖ PP copolymers.
- ❖ Cavitation in co-particles- transferred to PP main matrix- micro-voiding & shear yielding - crazing in PP matrix.

Polyethylene (PE)

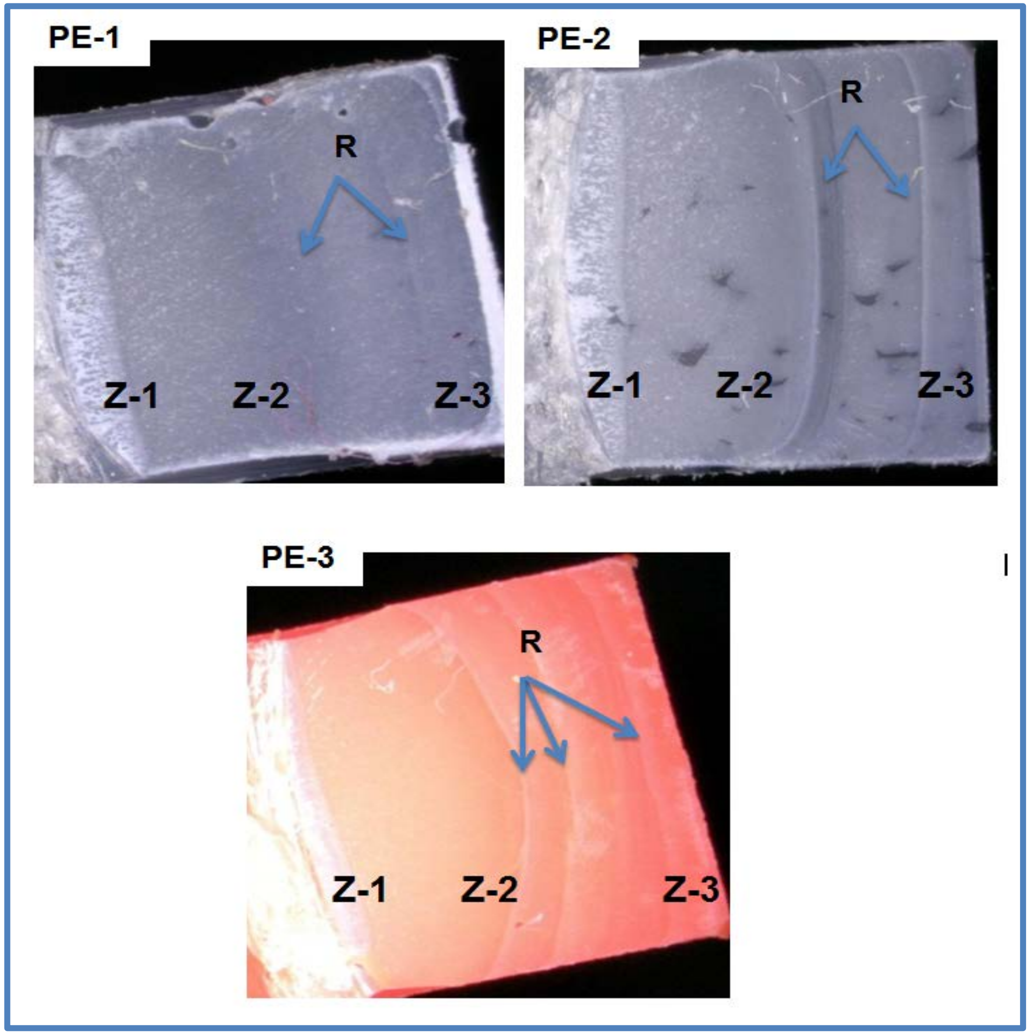
Crack Propagation Resistance Curve (J-R) of PE-3





Polyethylene (PE)

Fracture Surfaces



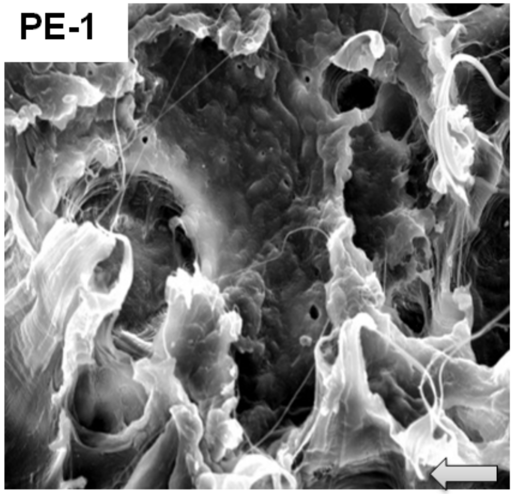
Three distinct regions.

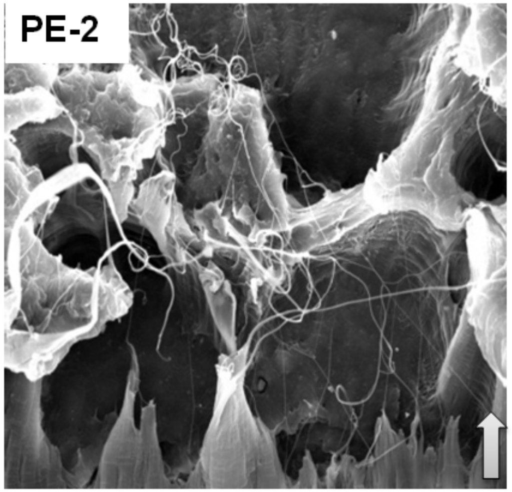
Ridges were noticed that mention stick-slip crack propagation.

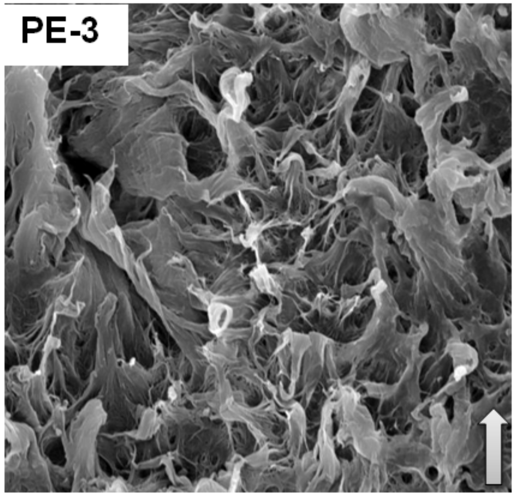
Ridges slows down the crack growth in rapid crack growth region.

Polyethylene (PE)

SEM Images







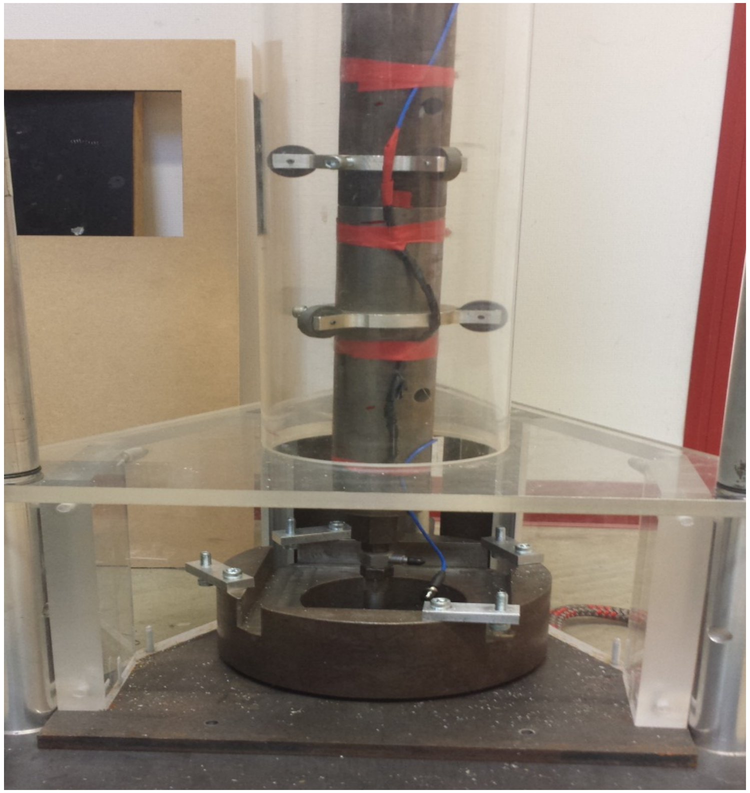
Voids formation- coalescence of voids - crazes - fibril formation - rapid crack propagation.

More fibrillar morphology was found for PE-3.

More fibrillar morphology creates higher plastic deformation that increase fracture toughness value.

Fracture behaviour of the materials at dynamic loading

- Drop weight Impact testing
- Impact properties
- Brittle or ductile fracture

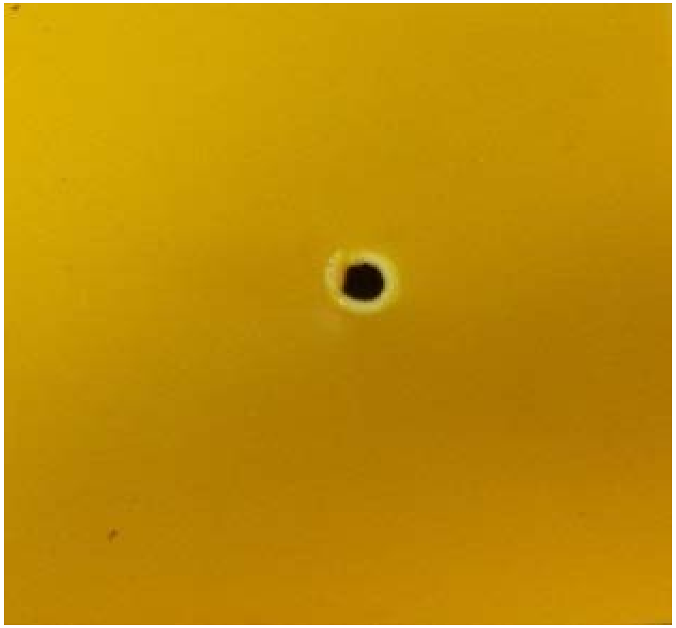


Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis

- ❖ Identification of the transition in the materials
- ❖ Explanation of the impact properties

Brittle Fracture



Ductile Fracture

Rotational moulding of the sandwich structure

Sandwich Composite

- Top and bottom layer –PE
- Middle layer PE foam
- Different skin-core thickness combination

Low velocity impact testing

- Testing at different energy level from 20 J to 50 J
- Identification of damages at different layers
- Measuring skin-core thickness effect on impact properties as well as damage creation

Rotational moulding of the sandwich structure

Materials

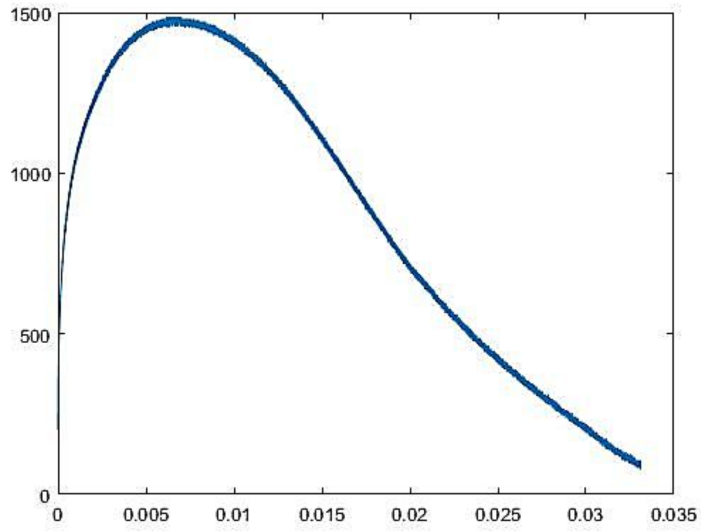
Materials Grade	Material Type	Layer	MFI (g/10 mins)	Density (g/cm³)
Revolve M-601	PE	Skin	3.50	0.949
M-56	PE	Core	3	0.310

Thickness Combinations

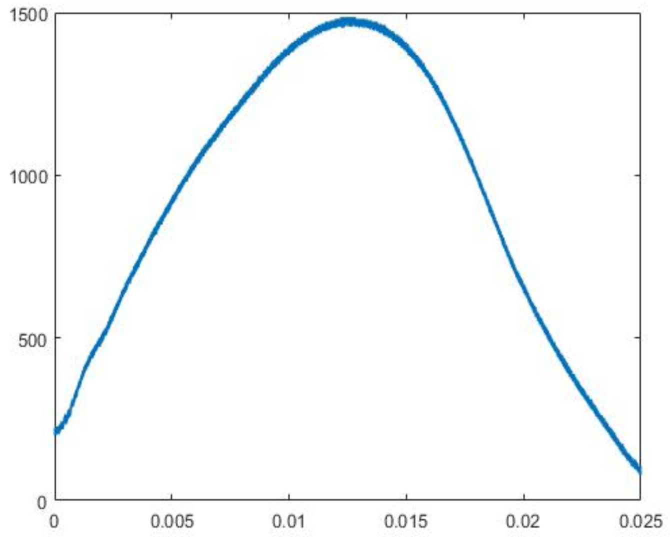
Sandwich Type	Thickness Combination (Skin + Core + Skin) (mm)
Sandwich-1	1+4+1
Sandwich-2	1+8+1
Sandwich-3	2+4+2
Sandwich-4	2+8+2

Low Velocity Impact Testing

- Energy level- 20 , 30 and 50 J.
- Tested four different sandwich samples- 1+4+1, 1+8+1, 2+4+2, 2+8+2.
- Force, deflection, time, absorbed energy were calculated.



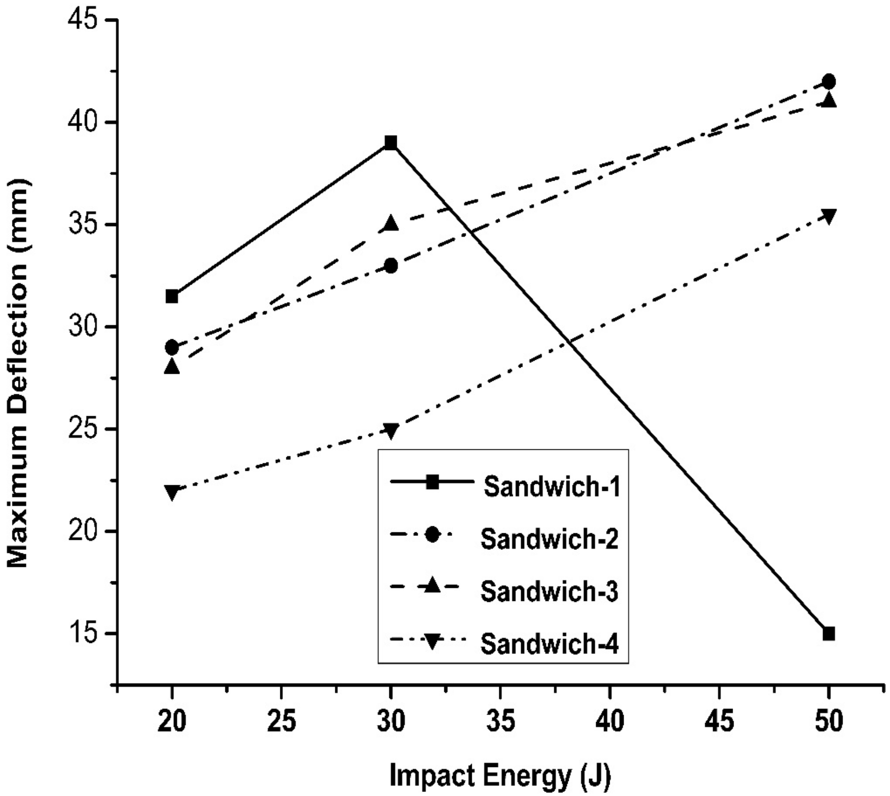
Force-Deflection Curve



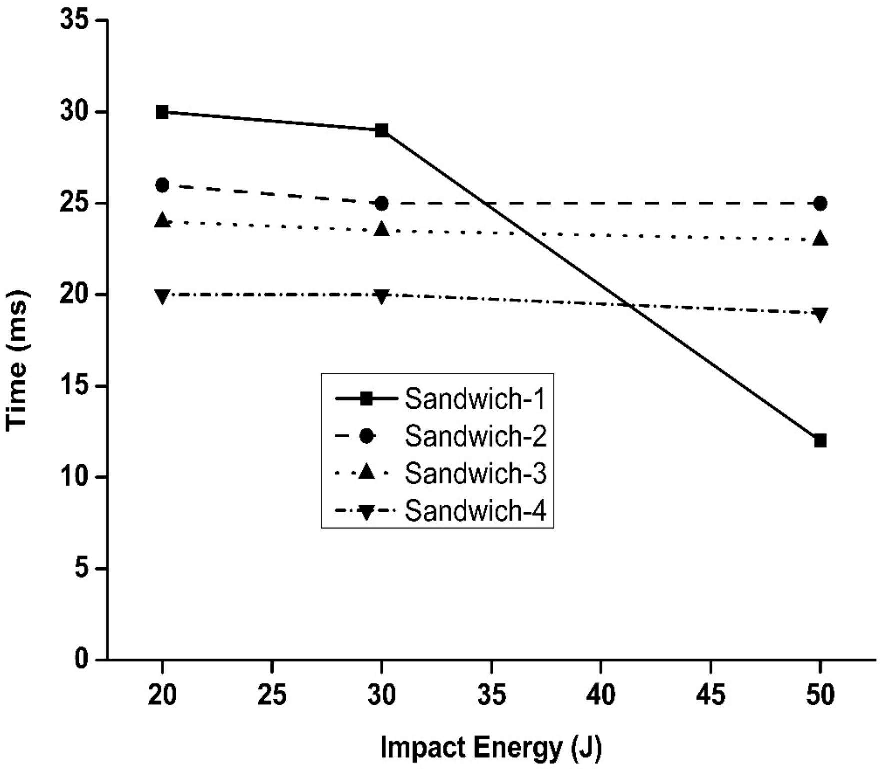
Force-Time Curve

Low Velocity Impact Testing

Deflection-impact energy Curve

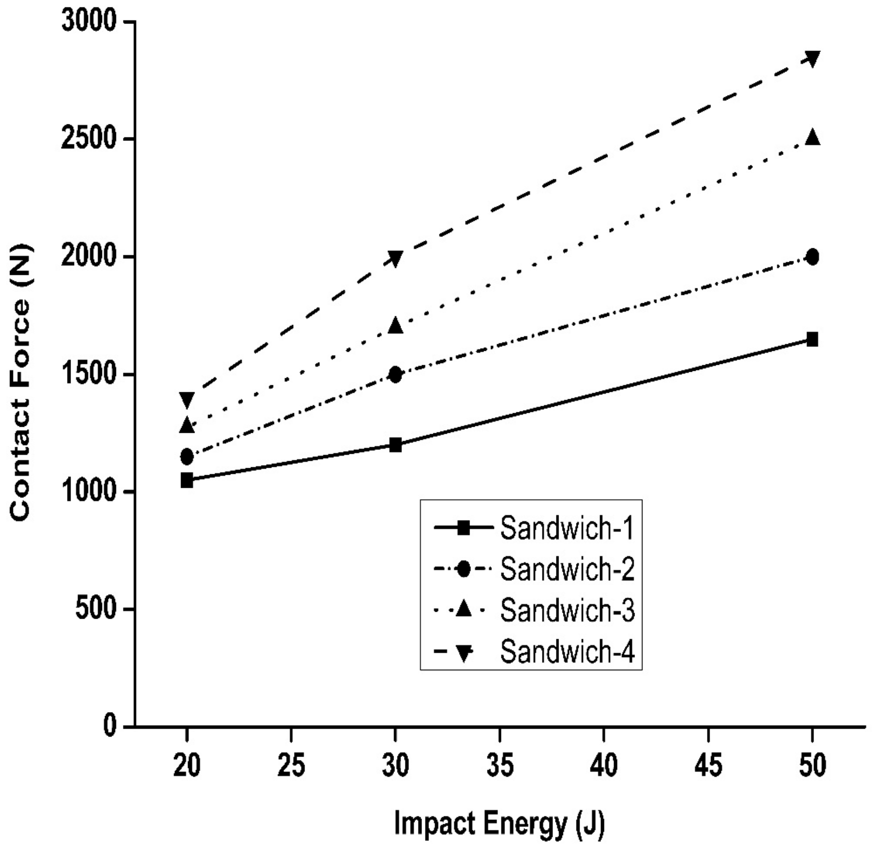


Time-impact energy Curve

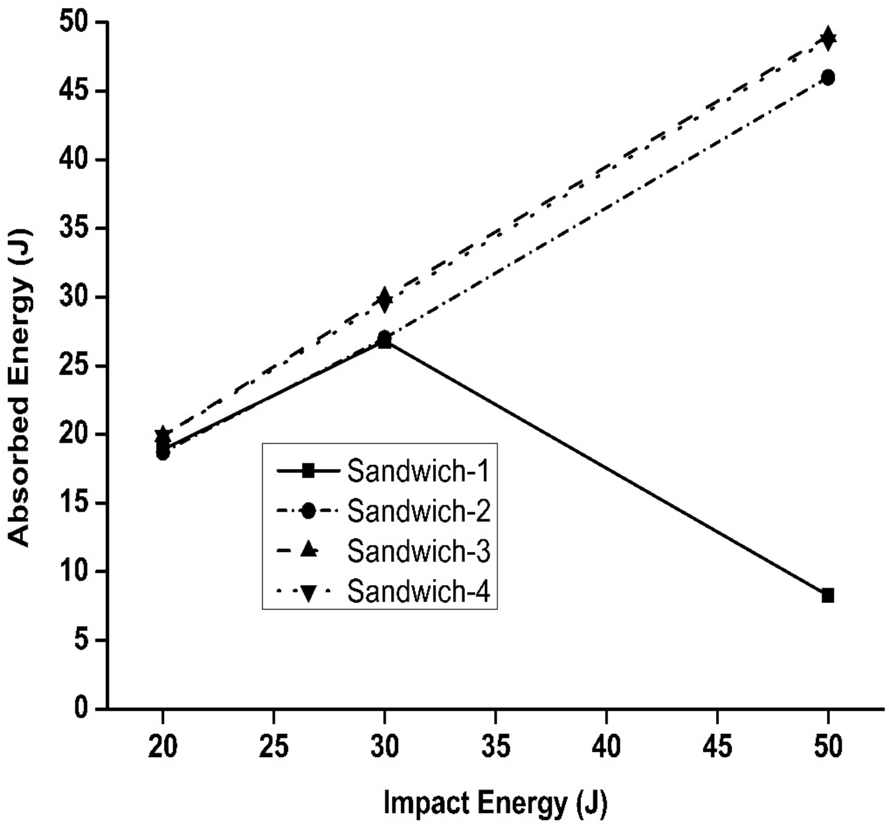


Low Velocity Impact Testing

Force-impact energy Curve



Absorbed energy –impact energy Curve

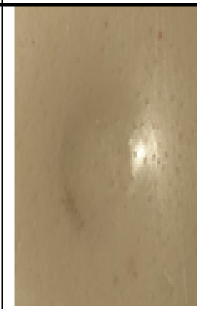
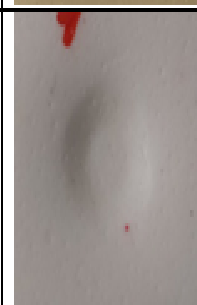
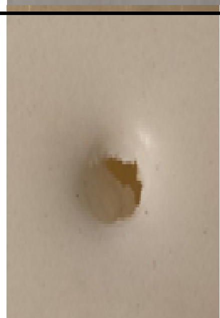
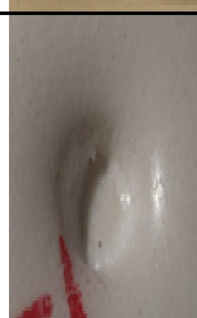
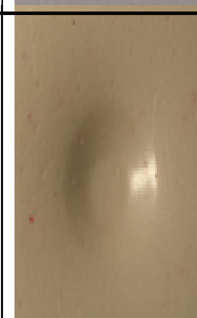


Low Velocity Impact Testing

- Force increase with core thickness as well as overall thickness.
- Deflection and time decrease with core thickness as well as overall thickness.
- It means the bending stiffness of the sandwich samples increase with core thickness as well as overall thickness.
- Core thickness is more responsible to increase the stiffness of the sandwich samples compared to core thickness.

Damages at Different Layers

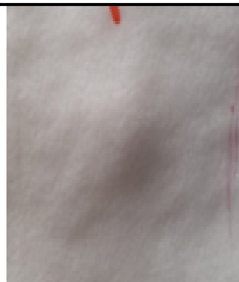
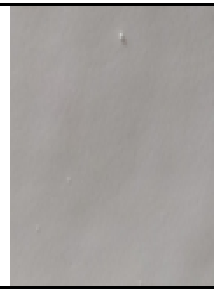
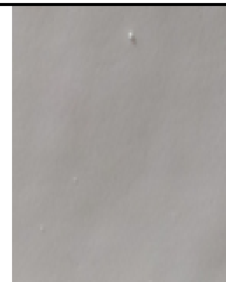
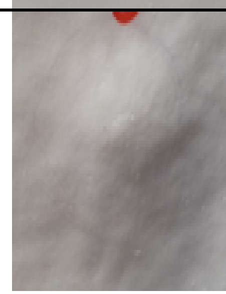
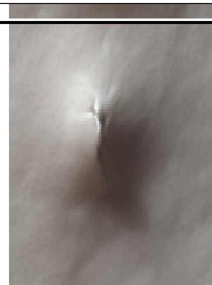
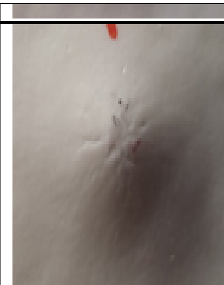
Damages- Outer skin

Energy J	1+4+1	1+8+1	2+4+2	2+8+2
20				
30				
50				

1. Local plastic deformation.
2. Depth of deformation increase with energy.
3. For 1+4+1 sample penetration happens at 50 J.
4. For 1+8+1 sample 50 J shows no penetration.
5. For 2+4+2 and 2+8+2 no penetration or crack observed in outer skin.

Damages at Different Layers

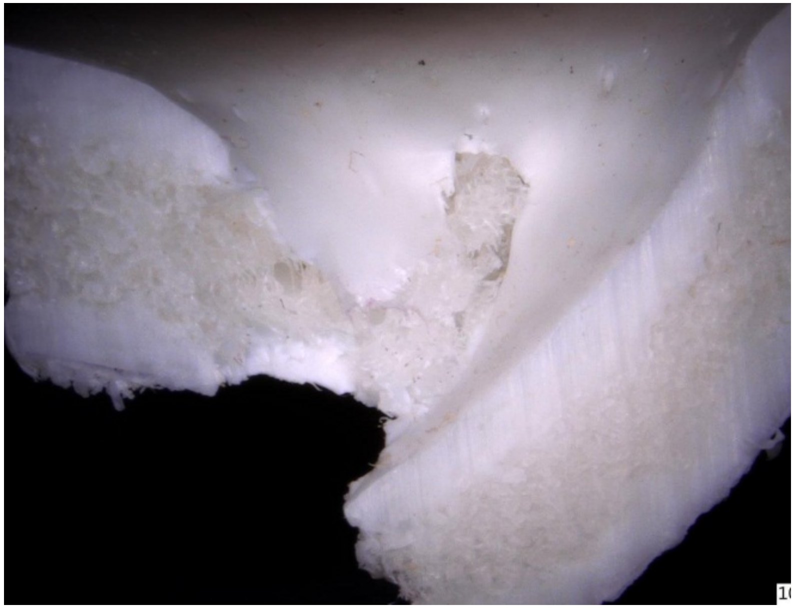
Damages- Lower skin

Energy	1+4+1	1+8+1	2+4+2	2+8+2
20				
30				
50				

1. For 1+4+1 sample crack starts at 30 J.
2. For 1+8+1 sample penetration happens at 50 J.
3. For 1+4+1 and 1+8+1 samples cracks start at first in bottom layer, then top layer.
4. For 2+4+2 and 2+8+2 no prominent scratch or cracks were observed.

Damages at Different Layers

Damages- Cross sectional views



Non penetration (non broken sample)

- Plastic deformation in outer skin
- No delamination in the skin-core interface.
- No cracking in the core.
- Thickness reduction in the core.

Penetrated sample (Broken sample)

- Full destruction
- Core layer doesn't provide any extra support when the outer layer gets penetrated.

Low Velocity Impact Testing

Major findings

1. 1+4+1 sample gets cracks in bottom layer at-----------------30 J
2. 1+8+1 sample gets cracks in bottom layer at-----------------50 J

(by increasing core thickness double it is possible to increase the damage resistance limit up-to two times)

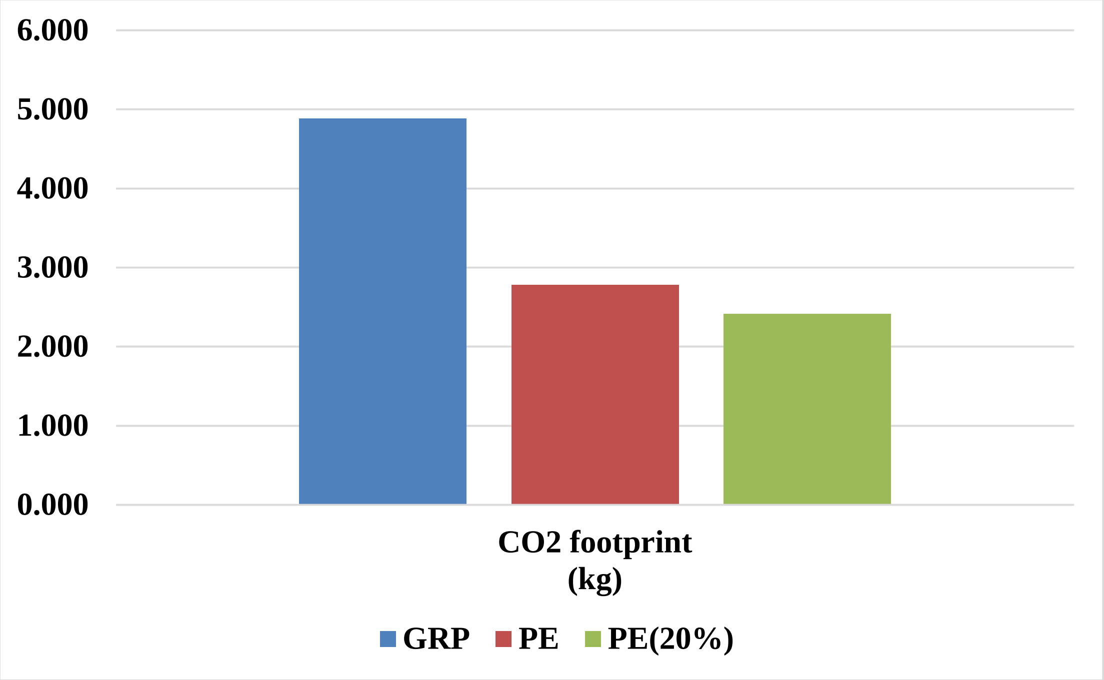
3. For 2+8+2 the damage tolerance is very high.

(For creating cracks it needs more energy, possibly 100 J. Therefore by increasing 1 mm skin thickness it is possible to increase the damage resistance limit up-to or more than three times compared to 1+4+1)

4. Between 1+8+1 and 2+4+2 , 2+4+2 has higher stiffness and damage resistance, but 1+8+1 has moderate damage resistance and lightweight.

Life cycle analysis

CO2 footprint per kg – Glass reinforce composite vs. PE and PE with 20% recycled content



Material	Energy (MJ)	CO2 footprint (kg)	CO2 footprint (kg) % vs. GRP
GRP	101.772	4.884	100%
PE	78.608	2.782	57%

Conclusion & Future Work

Conclusion & Remarks

- Material was selected based fracture behaviour analysis
- Low velocity impact properties of sandwich structure were studied.
- Damages at different layers were identified.

Future Work

- Compression after impact test
- FEA analysis of CAI properties.
- Detail life cycle analysis.

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Question Answer

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