Damage Resistance of a Co-cured Composite Wing Box to Low-Velocity Impact

1 Introduction

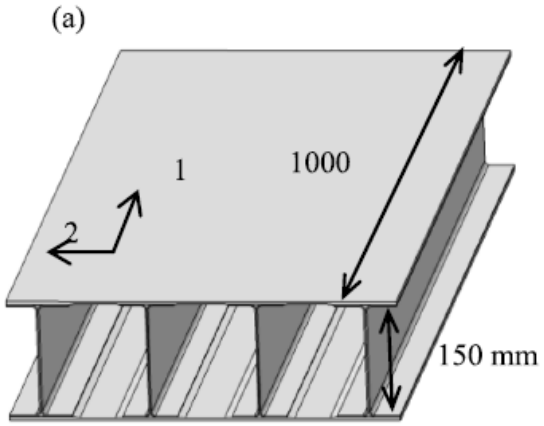
- Composite laminates have poor resistance to low-velocity impact
  - Caused by dropping tools
- Delamination is a serious damage
  - Hard to detect through visual inspection → Causes earlier buckling failure
- Impact on a small specimen
  - Regarded as quasi-static procedure → Contact force and plate response are in phase
  - The spring-mass model for simulating
- Low-velocity impacts were applied to an aircraft wing box fabricated by co-curing its spar and skin

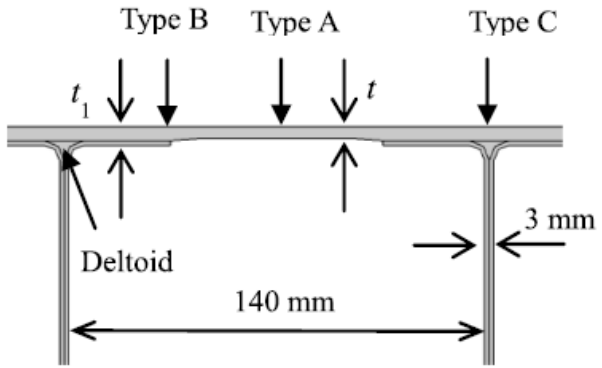
Delamination threshold load (DTL)
Energy absorbed
Permanent indentation

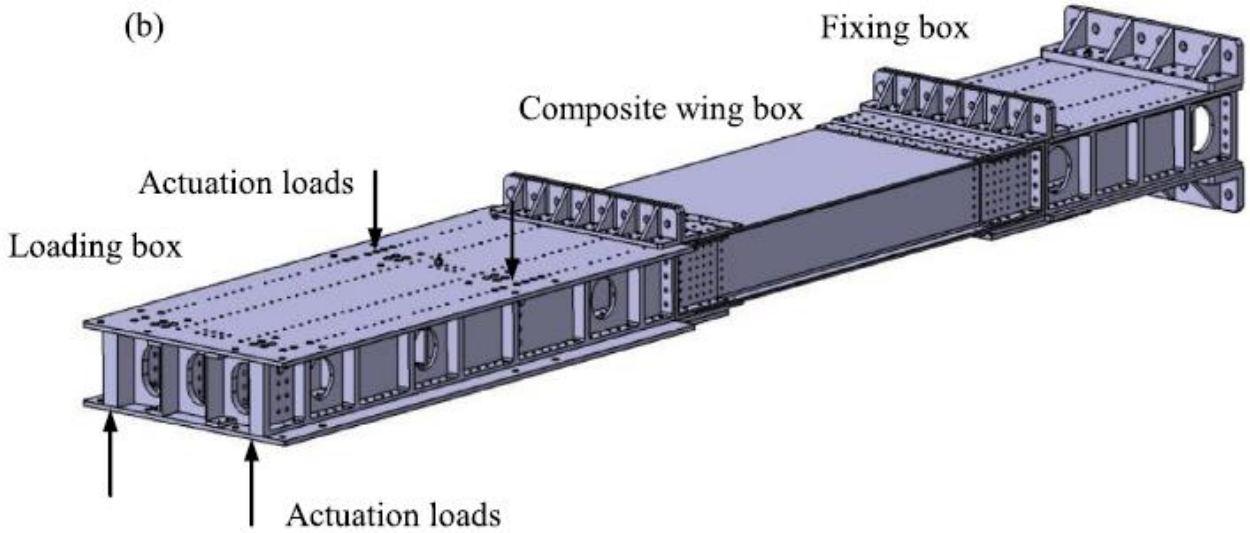
} Primary parameters for the damage resistance of composite laminates to low-velocity impact

2 Composite Wing Boxes & Experiment Setup

- Two wing boxes fabricated using carbon fibre-reinforced plastic composites:
  - First wing box is for the responses of the panel to low-velocity impacts
  - Second one is tested with the static bending load (five typical points) → Effect of the impact damage on structural strength





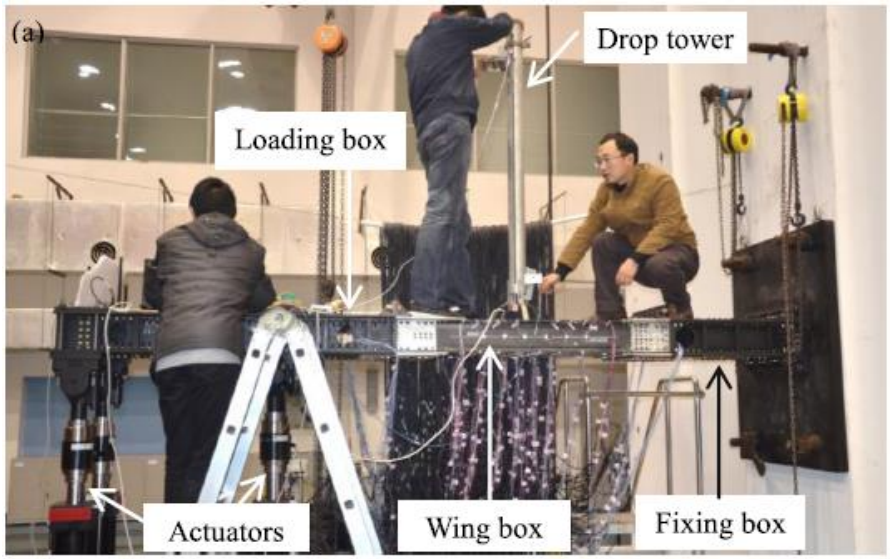


Wing Box: comprises skins and spars.

- Each spar consists of two beams with a channel cross-section.
- The deltoid region is formed by the two beams
- The skin was filled with the fibre bundle.
- Stacking sequence is [45/-45/02/(45/-45)290]s
- The thickness of the skin is 3.76mm
- The skin and the spar were co-cured.

- Three types of sites were subjected to the low-velocity impact:
  - **Type A:** at the bay between the spars
  - **Type B:** at the edge of the flange
  - **Type C:** exactly over the web.

- The wing box was connected to two steel boxes
  - Fixed at its two ends
- Four hydraulic actuators → To exert torsional and bending loading
- A drop tower → To produce the low-velocity impact
- The contact force was measured with the dynamic force sensor.
- The mass of the impactor can be adjusted by adding weights (10.4-5.3kg).



3 Results of Impact Tests

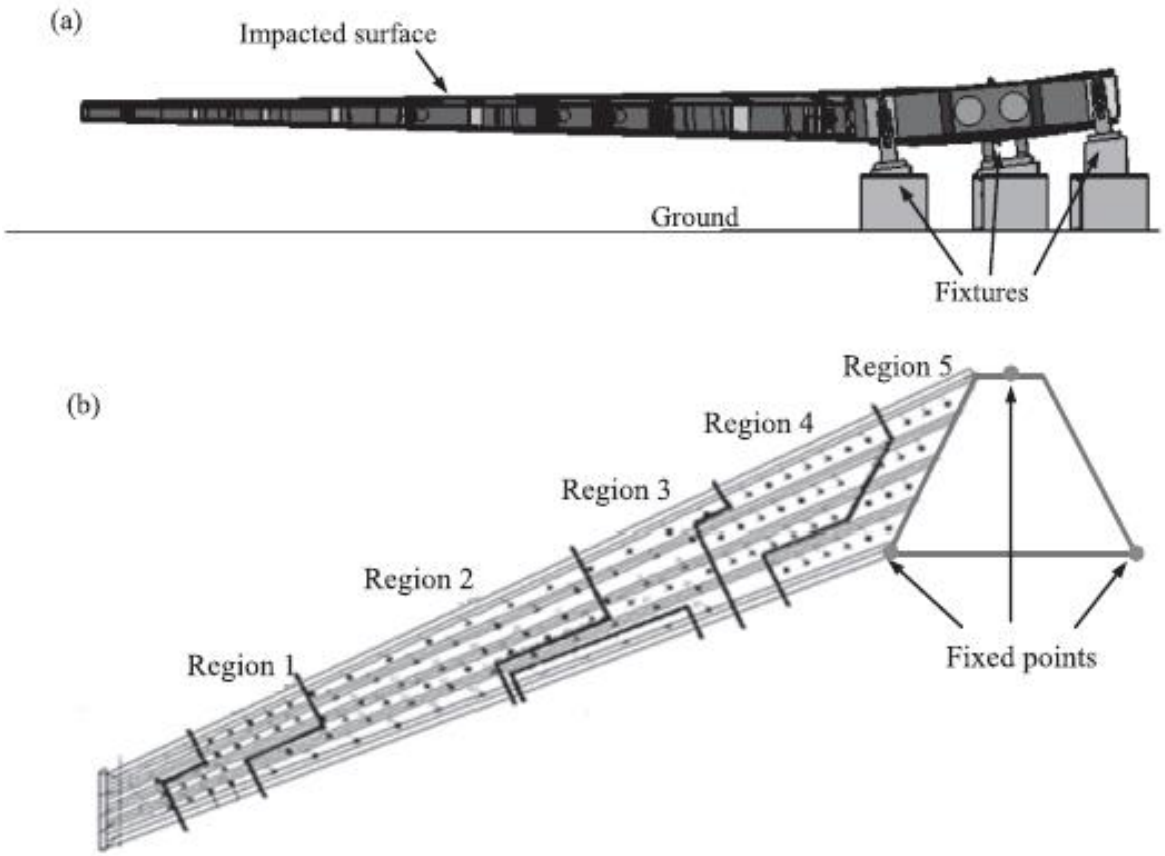


Table 1
Layup parameters of the regions of the composite horizontal tail.

Regions	Plies amount	t/mm	t_1/mm
Region 2	20	3.76	6.03
Region 3	24	4.51	7.22
Region 5	40	7.52	3.61

Composite horizontal tail: **(a)** fixtures setup **(b)** regions subjected to impact

3.1 Impact of Type A

- Energy ranging from 10 J to 60 J
- Peak force is lower than DTL of the 15J impact (~5290 N)
- Less than 5290 N → Significant damage does not ocur

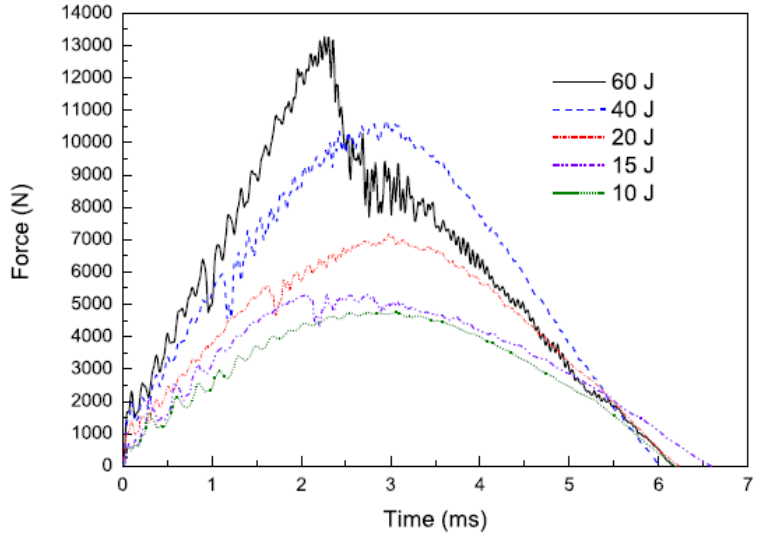


Fig. 4. Contact force histories of the type-A impact on the wing box.

- Sharp drop in each curve for the impact greater than 10 J
- The dramatic load drop at the peak in the 60-J curve :
  - Major portion of the delamination damage.
  - Crushing of the matrix and breakage of fibre at point
  - Significant indentation was then observed

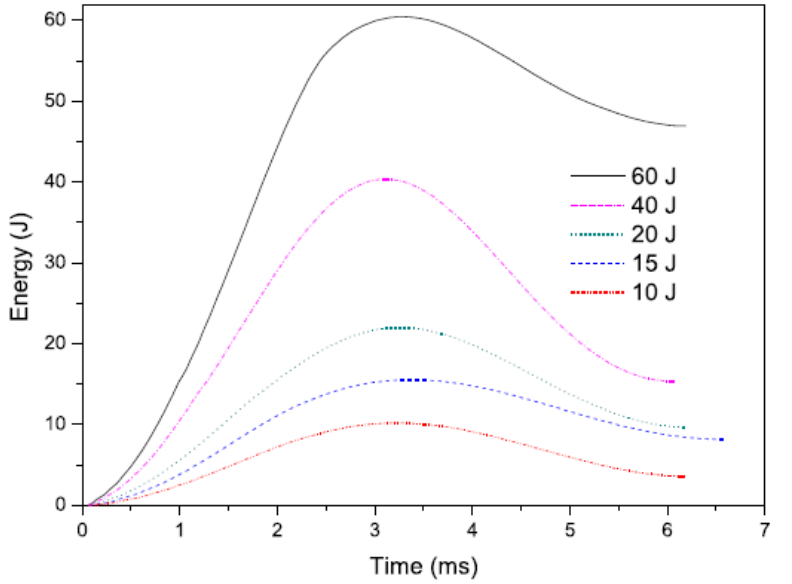


Fig. 7. Time histories of energy absorbed in the type-A impact on the wing box.

3.2. Impact of Type B

- Ranging from 10 J to 65 J
- Average DTL is equal to 6872 N
- A sharp drop appears when impact energy >10 J

3.3 Impact of Type C

- Ranging from 10 J to 60 J
- Secondary bump after the peak in the 40J & 60J
- No sharp drop occurs in the contact force
- The horizontal tail has lower stiffness than wing box → Impact energy was absorbed over structure

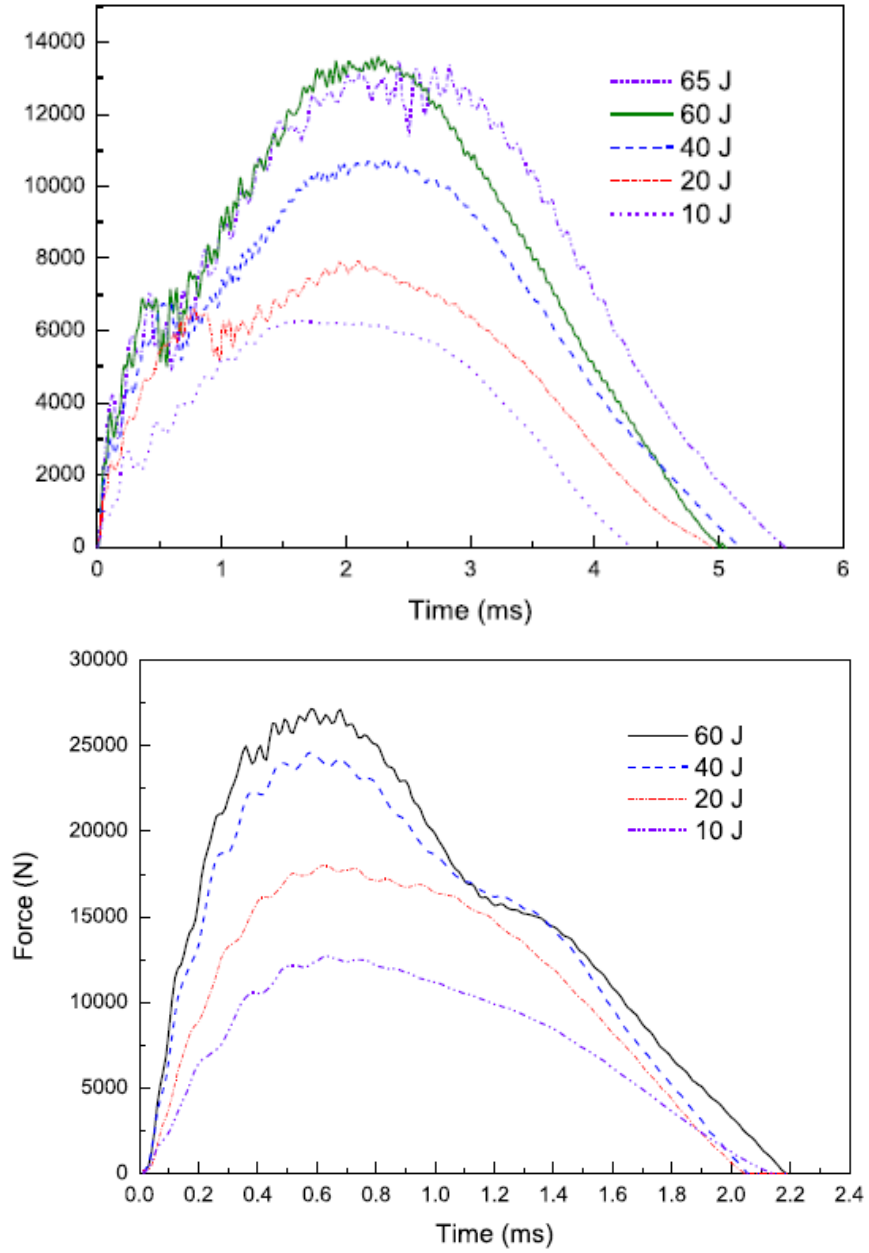


Fig. 14. Contact force histories of the type-C impact on the wing box.

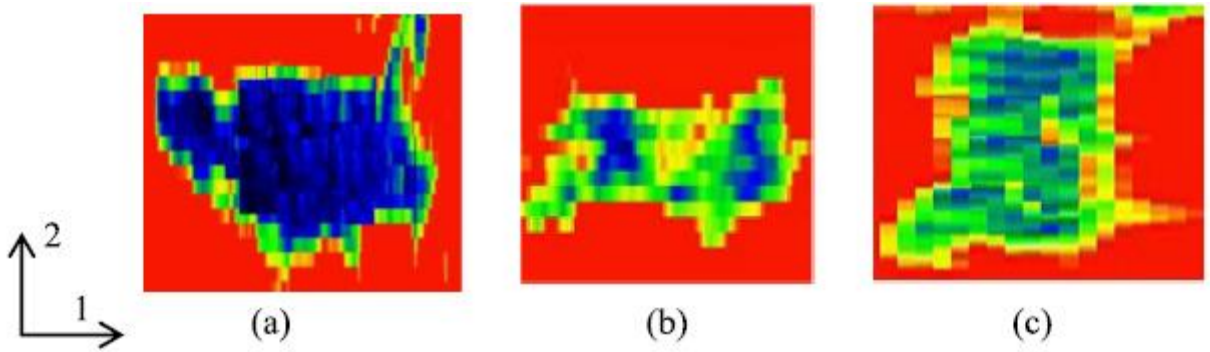


Fig. 5. Ultrasonic C-scans of the delaminations under the 40-J impacts: (a) type A, (b) type B, and (c) type C.

Table 2
Dimensions of the damage area of the wing box.

Impact type	Impact energy (J)	Dimensions of damage area along direction 1 and direction 2 (mm × mm)
A	15	27.8 × 16.5
	20	21.0 × 23.3
	40	38.3 × 27.1
	60	33.8 × 26.3
B	20	45.8 × 23.3
	40	30.8 × 12.8
	65	40.5 × 18.8
C	20	9.0 × 7.5
	40	13.5 × 11.3
	60	15.0 × 19.5

Table 3
DTL prediction for type B for the wing box.

Impact energy (J)	Experimental DTL for type A (N)	Experimental DTL for type B (N)	Predicted DTL for type B (N)	Prediction error/%
65	–	7059	–	–
60	6395	7049	7449	5.7
40	5946	6773	6926	2.3
20	5579	6608	6498	1.7
15	5290	–	6162	–
Average	5802	6872	6758	1.7

3.4. Prediction of DTL for Type-B Impact

- To predict the DTL of type-B location with the experimentally determined DTL of type-A location

3.5. The Impact Indentation

- General visible indentation occurs :
  - at 55 J for the Type-A impact
  - at 65 J for the Type-B impact.
    - Indentation is barely visible under 60 J
    - But cracks are generated on the surface
  - No indentation for the type-C impact
    - But a scar due to the high contact force

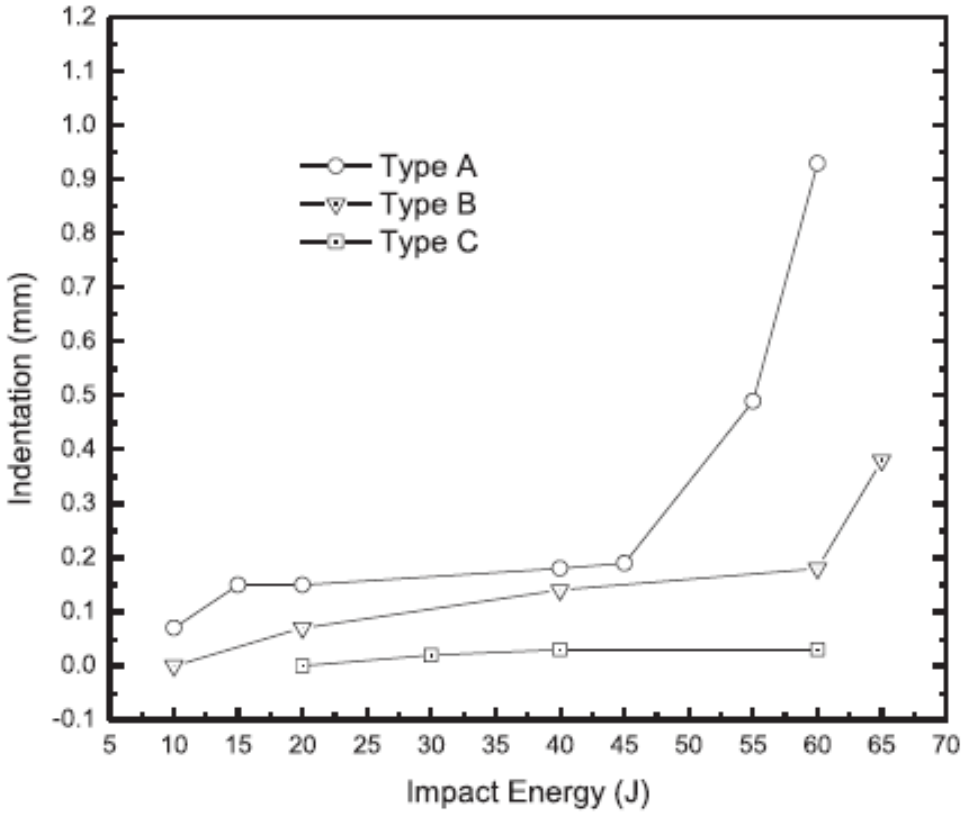


Fig. 19. Comparison of indentations of impacts on the wing box.

4 Ultimate Load Test After the Low-Velocity Impact

- A limited bending moment of 0.5x105 Nm is applied to second wing box without damage first.
- Five impact tests of 60 J is conducted on the upper surface of the wing box.
- Bending is applied to the wing box with impact damage
  - Breaks along the line at the bending moment of 1.1x105 Nm.

- Impact damage does not weaken the wing box to bear the limited load.
- The critical load of buckling of wing box is ~ 0.8x105 Nm.

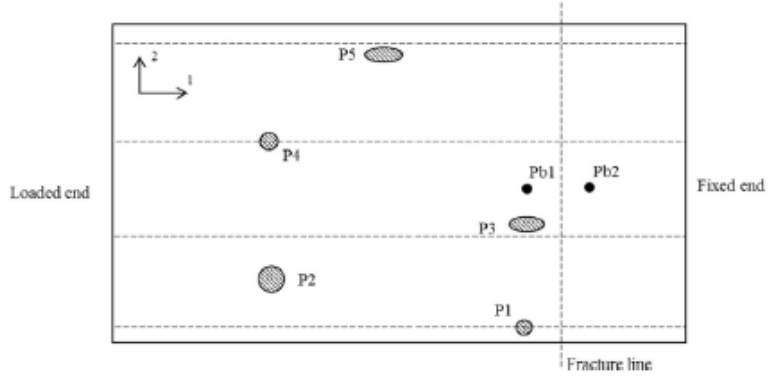


Fig. 20. Impact points and delamination regions of the wing box.

5 Conclusion

This study investigated:

- the contact force, energy absorption, delamination, and indentation due to low-velocity impact on the panel of a composite wing box.

- The characteristics of Type-A impact are consistent with the standard test on the specimen.

- The sharp drop in the F–t curve for the Type-A & Type-B impacts → Causes the delamination.

- Very high contact force is generated by the Type-C impact
  - Size of the delamination area is small
  - Shallow indentation is observed.

- The energy absorption is high for the impacts on the horizontal tail.
- The proposed model is effective in predicting the DTL of the Type-B impact with the experimentally determined DTL of Type-A
- To investigate the behavior of the damaged region under compressive load, impact damage is applied to the wing box.

- The wing box was broken after it began to buckle.
  - The strain response at the other impact points exhibited good damage resistance to Type-B and Type-C impacts.

- The failure position is close to the supporting end
  - Rather than the impact point where the delamination propagation occurs.
  - The impact point should be located in this region when investigating the effects of the impact damage on ultimate load of composite panel.

Co-Curing Process Combining Resin Film Infusion with Prepreg and Co-cured Interlaminar Properties of Carbon Fiber Composites

1 Introduction

- The carbon fiber/epoxy resin matrix composite laminates were fabricated using a co-curing process combining resin film infusion (RFI) process with prepreg-autoclave process (co-resin film infusion)
  - Low-cost for advanced composite structure
  - High mechanical performance

- Co-cured liquid composite molding (co-LCM) is an integral forming technique for combining liquid molding process with prepreg curing process.
  - The co-LCM technology improves the processability of complex structure
  - Achieves the purposes of time-saving and cost-saving by means of reducing fasteners, assembling procedures and simplifying mold.

- This papers:
  - Develops co-LCM in co-RTM → To fabricate aircraft structures
  - Proposes a new idea of co-RFI
    - Co-cures RFI part with prepreg stack simultaneously for taking advantages of cost-effectiveness of RFI and high properties of unidirectional prepreg.
- Two kinds of resins are used during co-LCM process:
  - Resin in prepreg stack
  - Resin for infusion
- Co-cured laminate was compared with RFI laminate and prepreg laminate:
  - Processing quality
  - Mode I and Mode II interlaminar fracture toughness

2 Experiment

2.1 Materials:

- A kind of epoxy resin film (MTM 44-1)
- T700SC (12k tow) unidirectional carbon fiber (for RFI process)
- HTS 5631 (12k tow)/MTM 44-1 unidirectional prepreg (for this study)
- An epoxy tackifier (for binding CFW-200 fabrics in RFI process and powder form)

2.2 Composite Manufacturing:

Prepreg-autoclave process:

- MTM 44-1 is cured with teflon film (To form pre-crack)
- Recommended cure cycle was applied in autoclave. Vacuum is applied.
- Temperature is increased:
  - Room temperature to 180°C at 2°C/min and maintained at 180°C for 2 h.

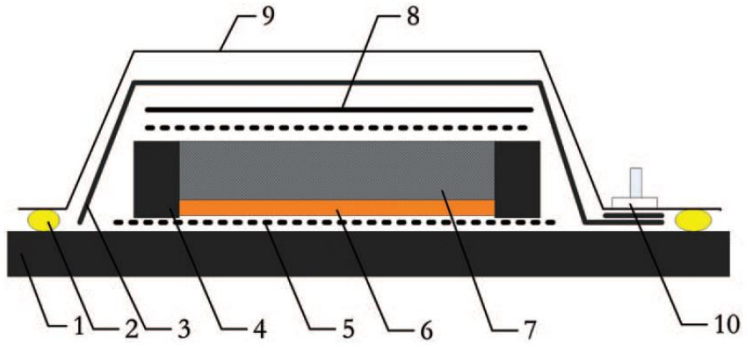


Figure 1. Schematic of the bagging procedure in RFI process.
1 – steel plate, 2 – sealant, 3 – breather, 4 – dam, 5 – peel ply, 6 – resin film, 7 – fiber fabric, 8 – release film, 9 – vacuum bag, 10 – vacuum valve.

RFI process:

- The stack contains 20 layers of CFW-200 (in 0 direction) and nine layers of resin film
- The release film was used → To ensure entrapped air to be released.
- Teflon film was placed in mid of the fiber stack.

1. Heat from 25°C to 180°C at 2°C/min and hold at 180°C for 120 min. (Recommended by manufacturer, ***Process A***)
2. Heat from 25°C to 130°C at 2°C/min and hold at 130°C for 30 min. Then, increase to 180°C at 2°C/min for 120 min. (***Process B***)
3. Disperse 8wt% tackifier on the surface of CFW-200 and maintain 5 min at 80°C. Then, the same cure cycle as Process B. (***Process C***)

Co-RFI process:

- 16 MTM 44-1 prepreg layers, 10 CFW-200 fabric plies and five layers of resin film (in 0 direction)
- Two kinds of lay-up types: Prepreg layers at the top of stack (prepreg/RFI) , Prepreg layers on bottom of stack (RFI/prepreg)
- Manufactured in an autoclave using Processes A, B and C.

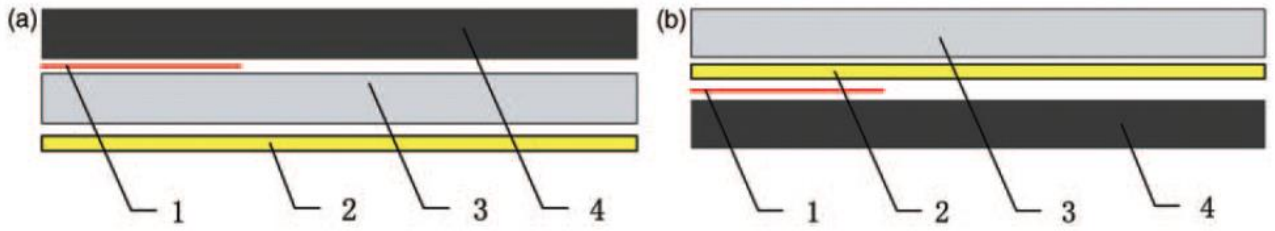


Figure 3. Schematic of two kinds of lay-up types: (a) prepreg/RFI stack and (b) RFI/prepreg stack.
1 – Teflon film, 2 – five layers of resin film, 3 – 10 carbon fiber fabric plies, 4 – 16 prepreg layers.

3 Testing

3.1 Resin Viscosity

- Using a Gemini rheometer

3.2 Mode I Interlaminar Fracture Toughness

- Using the double cantilever beam (DCB) specimen
- DCB specimen Width = 25mm and Length = 150mm
- The critical G_{IC} is calculated as average of G_{IC} values at beginning of delamination

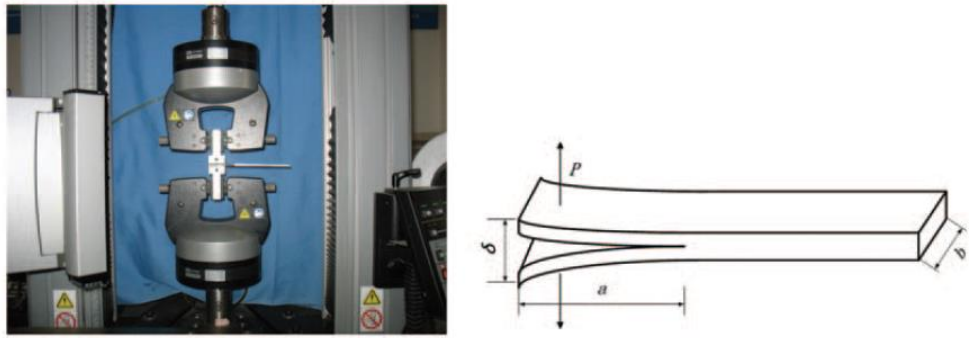


Figure 4. Schematic of DCB testing: a = crack length, p = Load, δ = displacement.
DCB: double cantilever beam.

3.3 Mode II Interlaminar Fracture Toughness

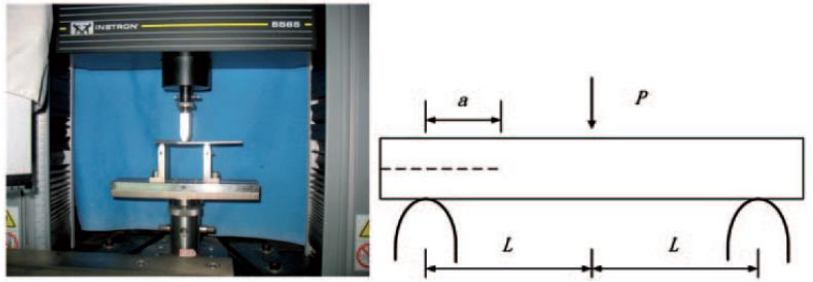


Figure 6. Schematic of ENF testing: a = the effective crack length, p = load, L = a half of the span length. ENF: end notched flexure.

- Using the end notched flexure (ENF) specimen.
- The ENF specimen; Width = 25mm and Length = 140mm
- Initial G_{IC} is calculated as average of G_{IC} values using the crack initiation loading for each specimen group

3.4 Processing Quality Observation

- Observation by
  - Optical micrograph → To observe defects inside laminates
  - Laminate thickness
- Using scanning electron microscopy → To observe crack surface of samples

4 Results and Discussion

Table 3. The void content of different laminates.

	Void content (%)		
	Process A	Process B	Process C
RFI laminate	0.03	0.02	0.01
RFI/prepreg laminate	0.03	0.01	0.01
Prepreg/RFI laminate	0.86 ± 0.03	0.63 ± 0.02	0.59 ± 0.01
Prepreg laminate	0	–	–

4.1 Processing Quality of Co-Curing Process

- Quality of prepreg laminate is perfect without void and the prepreg/RFI laminate cured by Process A gives the maximum value (about 0.86%)
- Void contents in co-cured interface are higher than integral laminates (especially for prepreg/RFI laminates)
- Isothermal dwell (in Process B) has great influence on decrease of voids at the laminate
- Addition of the tackifier almost has no influence on the flow and infiltration of the matrix resin
  - But makes the resin more redundant than the laminates without tackifier.

4.2 Evaluation Of Co-RFI Laminate Interface

- G_{IC} of RFI/prepreg laminate is 192 J/m2.
- G_{IC} of prepreg/RFI is 190 J/m2.
- Prepreg laminate has the maximum critical G_{IC}(222 J/m2).
- RFI processed laminate gives the minimum G_{IC} (168 J/m2).
- The cracks in the prepreg laminate runs along the centerline without deflection.

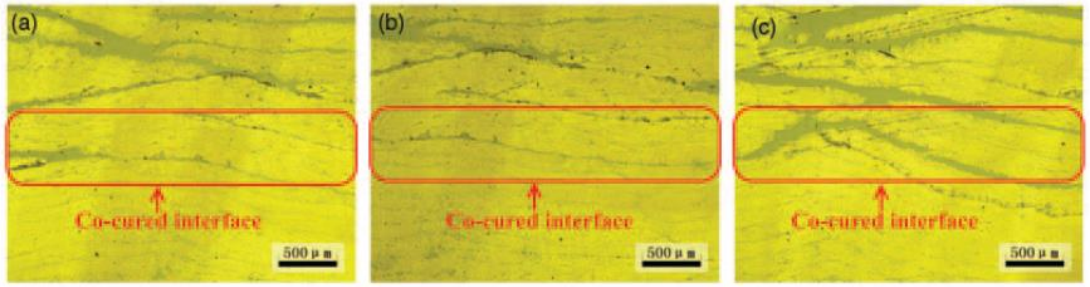


Figure 10. Micrographs of RFI/prepreg laminates cured by: (a) Process A, (b) Process B and (c) Process C. RFI: resin film infusion.

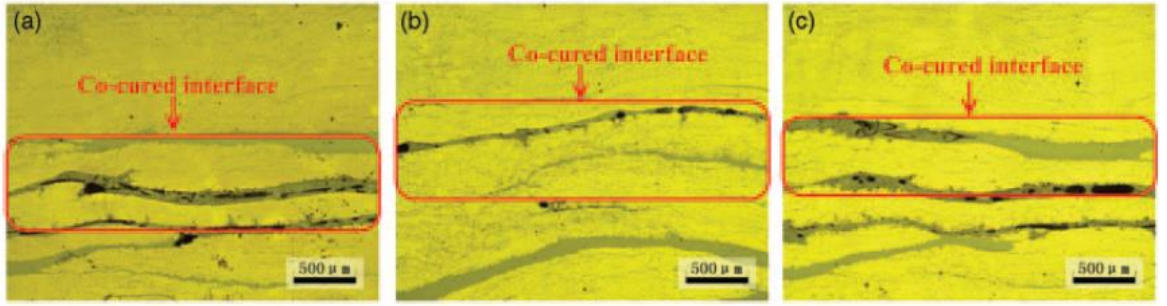


Figure 11. Micrographs of prepreg/RFI laminates cured by: (a) Process A, (b) Process B and (c) Process C.

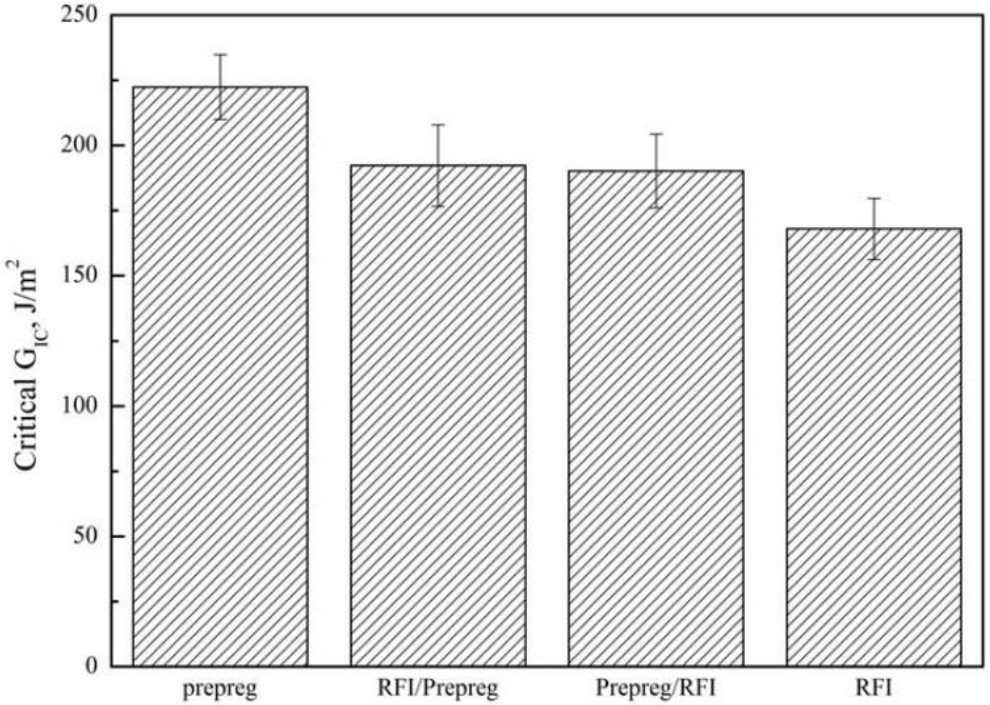


Figure 13. The critical G_{IC} values of different laminates fabricated using Process A.

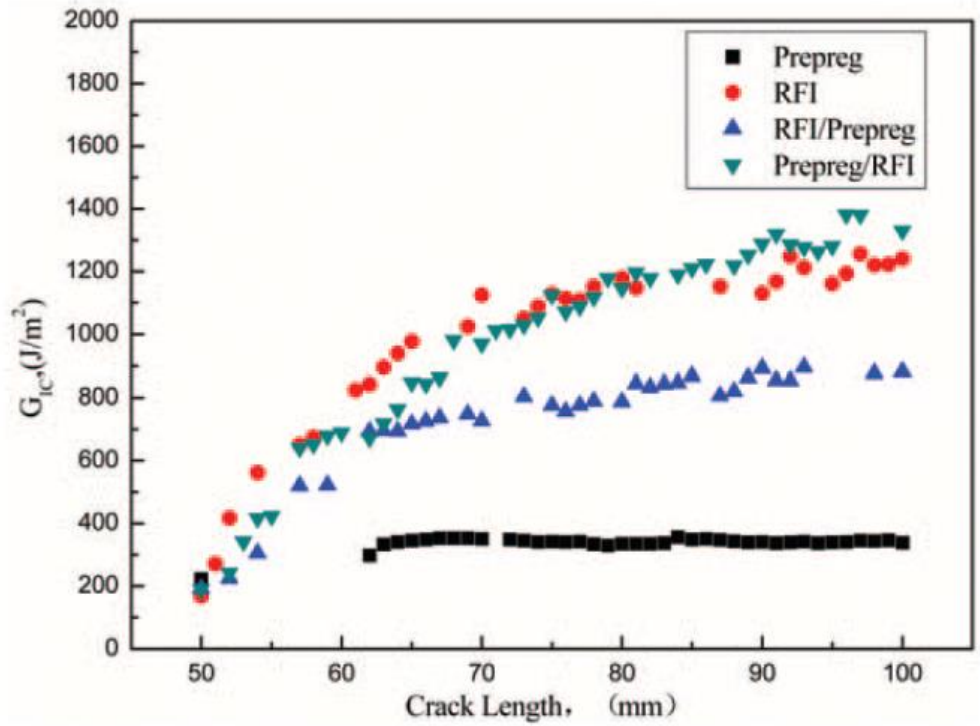


Figure 14. Mode I delamination resistance curves (R-curves) of laminates cured by Process A.

4.3 Influence Of Isothermal Dwell And Tackifier On The Interlaminar Properties

- The laminates co-cured under Processes B and C are tested through the Mode I and Mode II interlaminar fracture toughness

- The effects of the isothermal dwell and the tackifier on the interlaminar properties of co-cured interface are evaluated.

Influence Of Isothermal Dwell:

- Initial G_{IC} of co-RFI laminates fabricated using Process A and B.
- Significant increase in the initial G_{IC} for the composite laminates cured by Process B, compared to Process A.

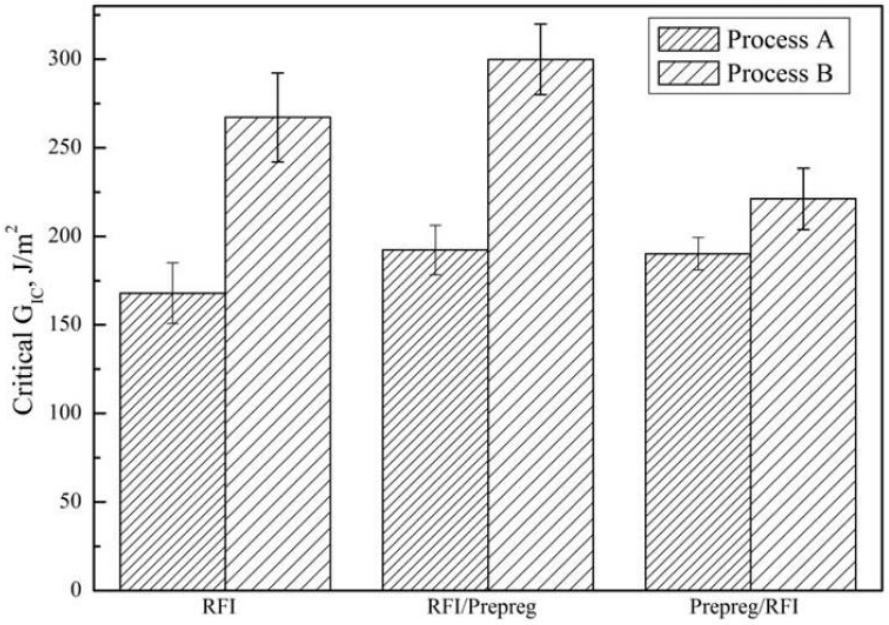


Figure 17. The initial G_{IC} values of laminates cured by Process A and Process B.

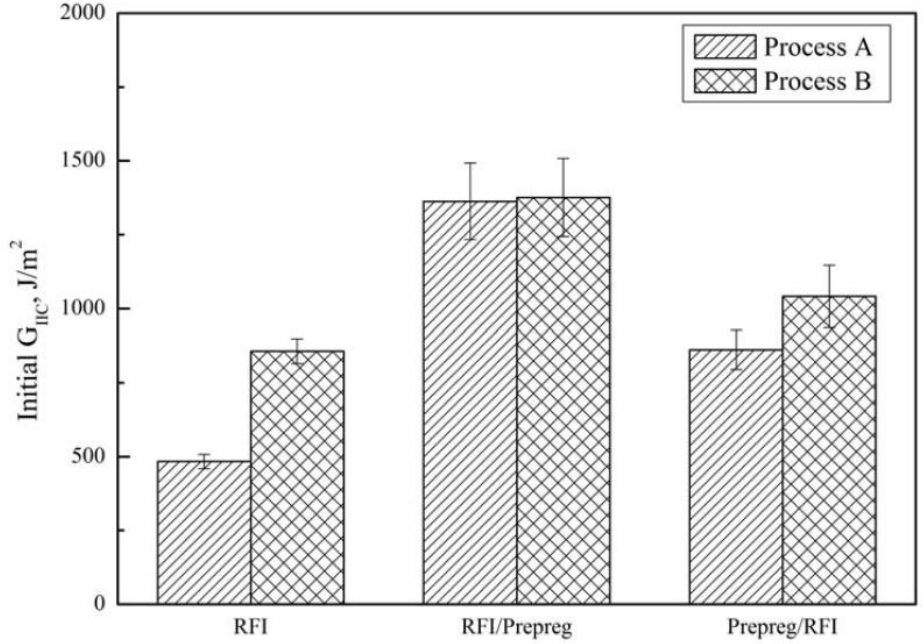


Figure 19. The initial G_{IIC} values of laminates cured by Process A and Process B.

Influence Of Tackifier:

- Tackifier has effect on the interlaminar fracture toughness of laminates.
- Initial G_{IC} of RFI laminate with tackifier is improved compared with the RFI without tackifier
- But initial G_{IC} values of co-RFI laminates with tackifier decrease in contrast with co-RFI without tackifier.

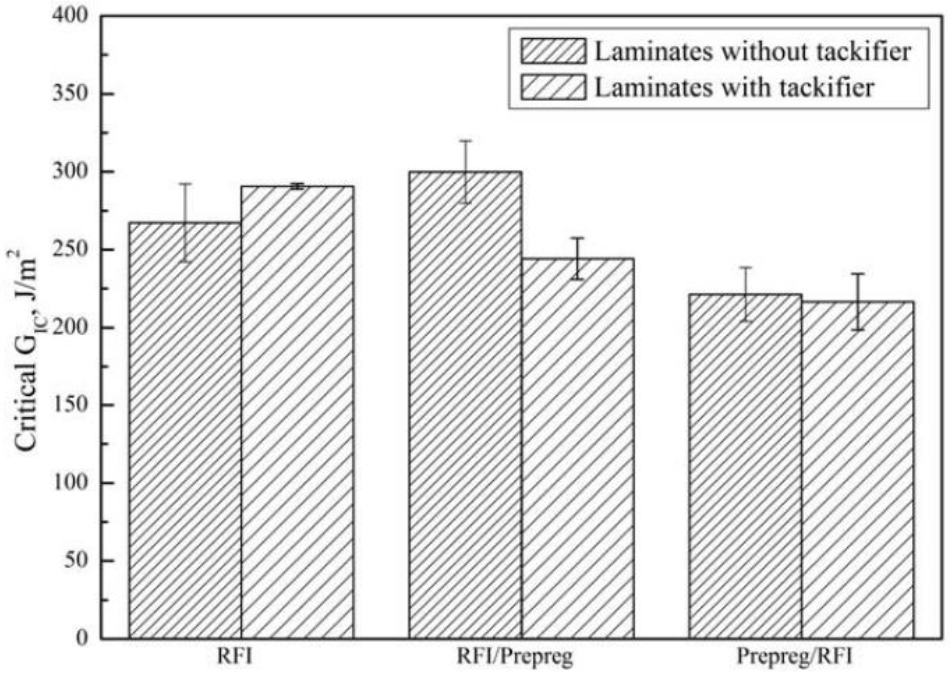


Figure 20. The critical G_{IC} values of laminates cured by Process B and Process C.

Table 5. The initial G_{IC} values of laminates cured by Processes A, B and C.

	The initial G_{IC} values		
	Process A	Process B	Process C
RFI laminate	167.96 ± 17.09	267.17 ± 25.09	290.59 ± 1.84
RFI/prepreg laminate	192.28 ± 14.01	299.87 ± 19.95	244.15 ± 13.21
Prepreg/RFI laminate	190.18 ± 9.10	221.17 ± 17.35	216.44 ± 17.93

RFI: resin film infusion.

Table 6. The initial G_{IIC} values of laminates cured by Process A, B and C.

	The initial G_{IIC} values		
	Process A	Process B	Process C
RFI laminate	547.96 ± 21.58	1159.90 ± 53.34	1838.77 ± 72.05
RFI/prepreg laminate	1414.77 ± 78.15	2031.17 ± 135.70	2553.02 ± 109.44
Prepreg/RFI laminate	1155.205 ± 46.37	1776.62 ± 169.335	984.44 ± 126.98

RFI: resin film infusion.

5 Conclusion

- Optical photographs of the laminates cured by co-RFI shows
  - Matrix-rich regions and voids mostly exist in RFI part and the interlaminar interface between the prepreg part and RFI part.
  - The matrix-rich regions and voids at the co-cured interface reduce the interlaminar properties of the co-RFI laminates, causing a lower delamination resistance

- Isothermal dwell before curing process has a great influence on the interlaminar fracture toughness of co-RFI laminates
  - Improves the interlaminar fracture toughness → Due to low resin viscosity and infusion time for improving the impregnation degree of the fiber preform.

- Epoxy tackifier is an important factor to make the resin redundant
  - Enlarges the matrix-rich region at the co-cured interface, and changes the interlaminar fracture toughness.

An Analytical Model For B-Stage Joining and Co-curing of Carbon Fibre Epoxy Composites

1 Introduction

- Paper develops cure kinetic models
  - To describe the B-stage curing
  - Co-curing assembly of **carbon fibre reinforced thermosetting polymer** (CFRP) composites
- **Problem** of using CFRP materials:
  - Inefficient joining procedures
  - Strict certification standards

  } Lost in efficiency

- **The solution**:
  - To partially cure two subassemblies, combine them and complete the cure cycle for both

- Co-cured joints also provide higher fracture toughness and joint strength than co-bonded joints

- Cure kinetic modelling of thermoset resins is widely used

- Most works focus on wide temperature ranges, model optimisation for a wide range of degree of cure
  - Such models are insufficent for B-Stage curing and co-curing (due to variance in a few degrees)

- A new approach is proposed to describe B-Stage curing and co-curing assembly by using the developed kinetic model

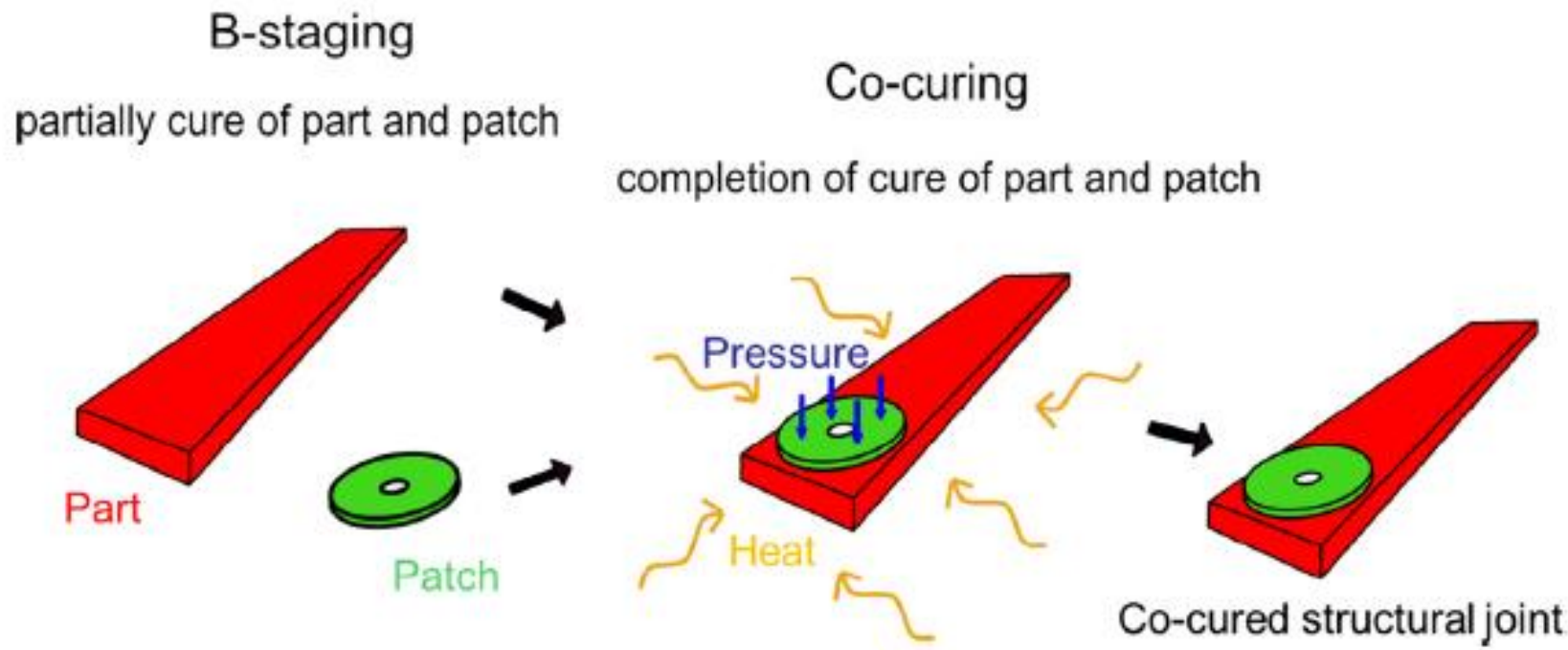


Fig. 1. Shows the concept of patch reinforcement of a structural part via co-curing of B-stage cured components. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2 Materials

- **Resin:** HexFlow RTM6
- **CFRP parts:** Manufactured by a RTM process
- **Reinforcing CFRP patches:** Manufactured from thin ply material
- **Nylon peel:** To prepare surfaces for co-curing

3 Experimental

- The differential scanning calorimetry (DSC) measurements were made

3.1 Resin Cure Kinetics

- Isothermal and dynamic DSC measurements of the uncured resin were made as reference data for the analytical modelling

3.2 B-stage Degree Of Cure

- The resin was heated to 80 C for one hour
- Transferred to a plate heated vacuum oven
- Degassed to 20 kPa for five minutes
- Circa 0.8 kPa vacuum pressure for a further 25 min

- The CFRP parts were cured at 400 kPa for varying times at 160°C
- Completely cured parts were cured at 180°C for 90 minutes in the RTM tool
- The B-stage cured CFRP parts were cured at 160°C in the RTM tool

3.4 Co-Curing Of the CFRP Part and Patch

- The CFRP patch and CFRP part were prepared by first removing peel plies (for adhesive)

4. Models and Methodology

- The curing reaction is applied using DSC of the pure resin at different temperatures and heating rates .
- Kinetics of the curing reaction of the resin are investigated.

4.1. Model For Evolution Of T_g and Resin Cure Kinetics

- DiBenedetto model is used to describe T_g as a function of α (degree of cure).

4.2. B-Stage Curing Cycle Of the CFRP Part and Patch

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4.3. Co-Curing Cycle Of the CFRP Part and Patch

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5 Result

- **5.1 DSC Measurements**

- **5.2 Comparison Of The Measured And Predicted B-Stage**

5.3 Co-curing Of The CFRP Part And Patch

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5.4 Discussion

6 Conculusion

- This work demonstrated an approach for using the developed kinetic model to describe the B-stage curing and co-curing assembly of local reinforcement.

- Described methodology to locally reinforce a partially cured structure has proved to be possible and presents techniques that are readily scalable, and cost effective.

- **Biggest challenge** for industrialisation is to the narrow window for the free standing cure of the CFRP part presented by the RTM6 resin system.