TECHNICAL PAPER

PERFORMANCE AND SIMULATION OF A THERMOPLASTIC PAEK HYBRID COMPOSITE SYSTEM

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INTRODUCTION

With more than 35,000 new aircraft needed over the next 20 years, the entire Aerospace industry supply chain faces the pressure of delivering planes at a much more cost-effective and rapid pace. The replacement of metal and thermoset composites with next-generation thermoplastic composite solutions has the potential to reduce cost though lower cycle time and net shape molding.

A recently developed thermoplastic PAEK polymer-based hybrid composite system (Figure 1) enables a part to have the strength of a continuous fiber structure, the flexibility of injection molded design and the short cycle time of thermoplastic processing. The system consists of a continuous carbon-reinforced VICTREX AE™ 250 composite laminate (Figure 2) and an injection over-molded VICTREX™ PEEK component (Figure 3). The continuous carbon fiber laminate can be thermoformed and/or cut into shapes using standard industrial equipment. The formed shapes are then inserted into a standard injection mold and over-molded with a short carbon fiber reinforced VICTREX PEEK resin using standard injection molding processing methods.

The paper presents the results of a commissioned study with Materials Sciences Corporation (MSC) that looks at material behavior and the development of simulation methods for modeling the hybrid system.

The study focuses on the behavior and simulation of the interface between the injection molded material and the continuous composite laminate. The results present test data and simulation results for both plaques and a bracket constructed using the hybrid technology.

Materials Sciences Corporation

MSC is headquartered in Horsham, Pennsylvania and has provided engineering services to the composites industry since 1970. MSC also operates a specialty textile manufacturing facility in Greenville, South Carolina. As a recognized leader in the design, analysis and testing of composite materials and structures, MSC is committed to excellence in all stages of the engineering development cycle: research, design, analysis, manufacturing and testing. MSC's corporate mission has expanded beyond basic research and development to include transitioning of advanced material technologies from the laboratory into innovative new products and applications.

Figure 1: Hybrid bracket manufactured for primary and secondary structural applications

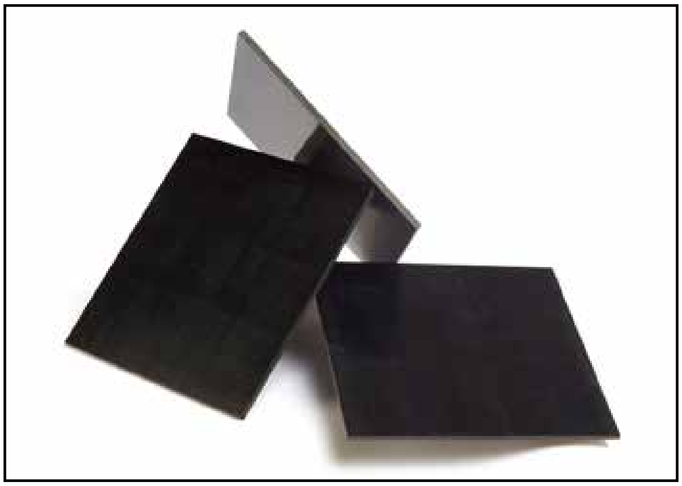


Figure 2: VICTREX AE 250 continuous carbon-reinforced, low-melt PAEK thermoplastic composite laminate

Figure 3: Short carbon fiber injection molded VICTREX PEEK polymer

1.1 Hybrid Molding Concept

The continuous carbon fiber VICTREX AE™ 250 UDT tape is fabricated into the desired laminate structure. The layup is heated and compressed into a laminated composite panel with multiple layers of continuous fiber. The composite panels are then thermoformed into shapes using standard industrial equipment. The final mold blank form is then cut using standard equipment such as a water jet.

The formed shapes are then inserted into a standard injection mold and over-molded with a short carbon fiber reinforced VICTREX™ PEEK resin using standard injection molding processing methods. Additional inserts, such as threaded metal inserts can also be placed into the injection molding tool. Once the inserts are properly loaded thermoplastic injection molding is used to create the net shape part.

When the PAEK composite insert is overmolded with the short-fiber injection-molding PEEK resin a bond develops at the interface of the two components. The bond is a result of the differential in melt temperature. The molten PEEK melts and fuses with the low-melt PAEK matrix composite laminate.

The system does not require preheating of the composite insert. The resulting hybrid component is a continuous structure that has the three-dimensional shape of an injection molded part and the structural backbone of a continuous composite laminate. The entire matrix material is a PAEK family resin having the benefits of PEEK such as chemical resistance and high temperature capability.

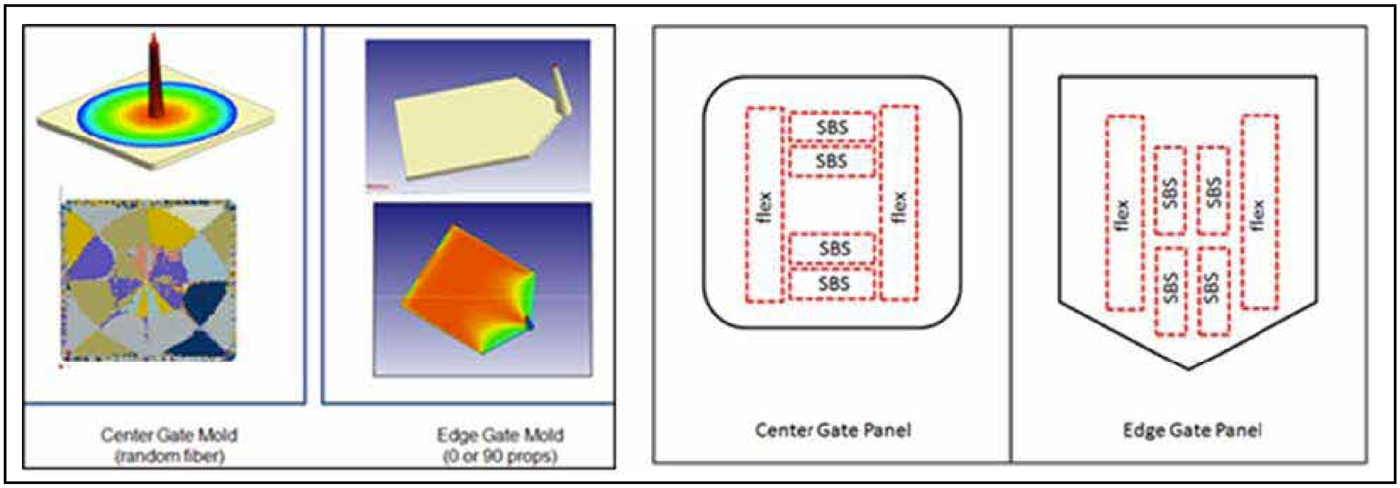
1.2 Project Scope

Materials Sciences Corporation was contracted by Victrex plc to characterize the mechanical performance of the hybrid composite structures. The focus of the study is placed on the development of a methodology to quantify the bond strength between the injection molded and continuous fiber composite components of the hybrid structure. The goal of the initial effort is the generation of preliminary data necessary to provide a basic understanding of the overmolded composite structure performance. Results from the study are discussed in this paper. The work includes:

- Coupon fabrication
- Mechanical testing
- Modeling to characterize the performance of the overmolded hybrid composite structure

A building block approach is utilized such that coupon fabrication and testing was first performed to gather the fundamental properties of the structure, with a focus on model development to assess bond strength. The study looks at various processing parameters such as injection temperature, tool temperature, and hold times. While processing parameters effect performance, it will not be discussed in detail in this paper as we are focusing on parts that are properly processed. The process study is to determine processing windows and is outside the scope of this discussion.

The paper focuses on structural performance of the hybrid sample; in particular results are presented for overmolding of a woven composite panel molded with a random-oriented injection-molded layer, and an uni-directional composite panel over-molded with a direction fiber injection-molded layer.



Center Gate Mold (random fiber)

Edge Gate Mold (0 or 90 props)

Center Gate Panel

Edge Gate Panel

Figure 4: Injection mold configurations and Flex coupon locations

2. EXPERIMENTATION

2.1 Panel fabrication

Hybrid panels were fabricated at MSC using in-house molds to produce the overmolded configurations. Two different molds are used as shown in Figure 4, both have a total wall thickness of 6.35 mm (0.25 in) and are 152 mm x 152 mm (6 in x 6 in). One mold uses a center sprue, resulting in a more random-fiber orientation in the molded layer. The other mold uses a fan gate on one edge of the part resulting in high orientation of the short-fiber molded layer.

The following constituent materials are used for fabrication:

- VICTREX™ PEEK 150CA30 polymer -30% wt carbon filled PEEK molding compound
- Plain Weave Panel - 10 ply weave panel with VICTREX AE™ 250 polymer matrix
- Unidirectional (UNI) Panel - 20 plies unidirectional carbon fiber constructed from VICTREX AE 250 UDT composite tape

Using the provided materials and MSC molds, 152 mm x 152 mm x 6.35 mm (6 in x 6 in x 0.25 in) overmolded panels were fabricated according to Table 1.

Table 1. Hybrid configurations

CONFIGURATION	MOLDED LAYER ~ 3.2 mm (0.125 in)	CONTINUOUS COMPOSITE LAYER ~ 3.2 mm (0.125 in)
1	Center Gate	Plain Weave Panel
2	Edge Gate	Unidirectional Panel

Configurations 1 and 2 are designed to be representative of actual composite structures under nominal processing and design conditions. Configuration 1 uses a weave panel and the center gate mold. Configuration 1 represents a more isotopic type of product. Configuration 2 is designed to maximize properties of both the highly-oriented molded layer created by the fan gate and the unidirectional layup composite panel.

Mold cavities are set to 6.35 mm (0.25 in) thick; where the base panel and molded section are both approximately 3.2 mm (0.125 in). The continuous carbon fiber plaques are water jet cut to size 152 mm x 152 mm x 6.35 mm (6 in x 6 in x 0.25 in) prior to overmolding. After the injection overmolding molding process, each hybrid panel is used to fabricate the test coupons. Water jet cutting is used to fabricate two flex bar specimens for 3-point flex tests and four samples for short-beam shear tests from each panel. Flex specimens are 152.4 mm (6 in) long x 19.05 (0.75 in) wide and short-beam shear specimens were 50.8 mm (2 in) long and 12.7 mm (0.5 in) wide, as guided by ASTM D790 [1]. The cut patterns for specimens made from the center gate mold and edge gate mold are shown in Figure 4. Note that the specimens for the edge gate panel are designed to align with the 0° direction of the continuous fibers as well as the flow of the fiber filled molding compound.

2.2 Coupon Testing

The paper reports results of standard 3-point flex tests. Flex tests are performed according to ASTM D790 [1] where a test span of 127 mm (5 in) is used, and a compressive load was applied at the midpoint at a constant crosshead rate of 2.8 mm/min (0 .11 in/min) until failure occurred. Specimens are evaluated with both the injection side facing up (IU) and the continuous composite facing up (CU).

2.3 Modeling

An approach for modeling an overmolded composite structure is presented; the approach includes potential interface effects at the bond. The initial effort combines limited, existing data on constituent properties of the molding compound and continuous fiber reinforced panel composed of UD-tape lay-up, along with the coupon test results.

2.4 Part Testing

A hybrid demonstrator bracket consisting of UD-tape composite form with an injection overmold as described in Figure 1 is tested to fracture load.

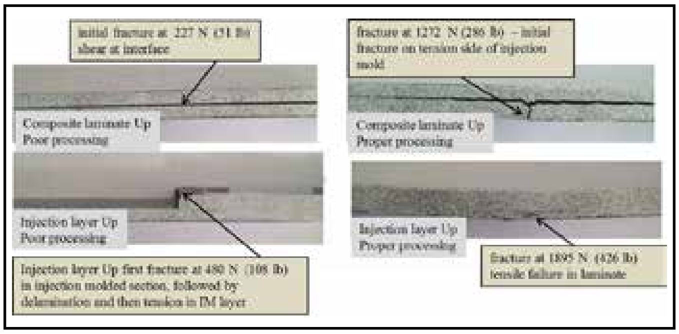


Figure 5. Illustration of improper processing and proper processing

3. RESULTS

3.1 Flexural Bending

The parameters of the injection molding can play an important role in the performance of the hybrid system. In this paper, we are limiting the processing discussion other than to illustrate it can affect performance if not properly done. As with any process, an improperly processed part results in reduced performance. In the case of the hybrid process, incorrect processing parameters results in poor bond strength between the injection molded layer and the continuous composite panel. Using poorly processed panels from the center gate mold (configuration 1 as described in Table 1) shows the fracture starts at the interface. Figure 5 illustrates the difference between a properly processed panel and one that is processed incorrectly. The load to failure is 4 times or more when the part is constructed and processed correctly. There are premature stiffness changes and premature fractures at the interface.

Flexural bending results for the center gate panels are shown in Table 2. With IU (Injection side Up) test set-up, failure occurred at the composite due to tension (plus some delamination between composite plies). The interface appeared fully intact. The failure load was 1895 N (426 lb), relating to a 551 MPa (79.9 ksi) tensile stress on the tension side. With the continuous composite side up, failure occurred due to tension of the molding compound and eventually propagated up towards the interface as shown in Figure 5. The molded compound failed at a higher stress level than a random orientated injection molded bar, 233 MPa (33.8 ksi) per Victrex allowable data at 45° using a fan gated plaque.

The next set of data presented is for Configuration 2, which uses a unidirectional composite panel overmolded in the fan gate tool. The injection direction is aligned with the unidirectional composite orientation. Flex tests are run with the fibers aligned with the direction of bending. Results are shown in Table 3.

Similar to the Configuration 1 specimens, flex strengths were overall higher when tested with IU (Injection side Up). All specimens here showed good bond strength, where initial and final failure occurred at the same time. Under IU test set-up, failure occurred at the composite due to tension near the surface (the interface appeared fully intact). Under a CU (Continuous side Up) test set-up, failure occurred due to tension of the molding compound and eventually propagated up towards the interface. Fractures are shown in Figure 6. As in Configuration 1 the molding compound failed at higher load than a random orientated injection molded property, 473 MPa (68.6 ksi) compared to 364 MPa (52.8 ksi) per Victrex allowable data at 0° using a fan gated plaque.

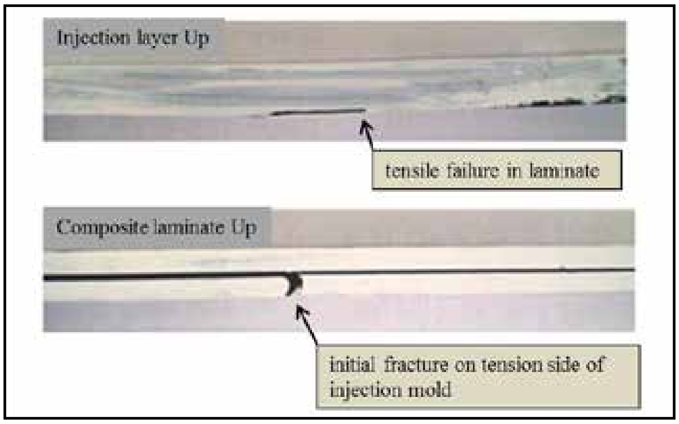


Figure 6. Flex test results - Configuration 2 (unidirectional panel with fan gate mold)

Table 2. Flex test results - Configuration 1 (weave panel - center gate)

TEST ORIENTATION	SPAN		SPECIMEN WIDTH		SPECIMEN THICKNESS		ULTIMATE LOAD		ULTIMATE STRENGTH	
	(mm)	(in)	(mm)	(in)	(mm)	(in)	(N)	(lb)	(MPa)	(ksi)
Injection Side Up	127	5.0	19.4	0.764	5.82	0.229	1895	426	551	79.9
Continuous SIde Up	127	5.0	19.4	0.753	5.79	0.228	1272	286	378	54.8

Table 3. Flex test results - Configuration 2 (unidirectional panel with fan gate mold)

TEST ORIENTATION	SPAN		SPECIMEN WIDTH		SPECIMEN THICKNESS		ULTIMATE LOAD		ULTIMATE STRENGTH	
	(mm)	(in)	(mm)	(in)	(mm)	(in)	(N)	(lb)	(MPa)	(ksi)
Injection Side Up	127	5.0	19.3	0.760	5.99	0.236	3326	748	916	132.8
Continuous SIde Up	127	5.0	19.4	0.753	5.79	0.228	1272	286	378	54.8

3.2 Modeling

The initial effort is focused on the modeling of Configuration 2 – unidirectional laminate overmolded using the fan gate mold. The first step in modeling is to determine the constituent properties. Properties of the unidirectional continuous fiber material are based on tensile and compression data. Additional parameters needed for the model, such as shear stiffness and Poison's ratio are estimated using classical micro-mechanics models. The populated model parameters for the unidirectional composite are presented in in Table 4.

For the molded layer, key stiffness/strength values are primarily based on molded tensile test specimens. Additional parameters, such as shear stiffness and Poison's ratio, are computed using classical micro-mechanics models. The models assume 73% of the fibers are aligned along the length of the specimen, and 13.5% of the fibers through the thickness and transverse to the specimen as determined by micrographs of the tensile bar cross sections. Populated data is provided in Table 5.

In order to account for variable fiber distributions, MSC utilizes a series of in-house, analytical tools to reduce test data and predict the average response of the heterogeneous, discrete microstructure of the material as a homogeneous continuum. The approach employs two regimes of modeling: short fiber models based on Eshelby's solution of an ellipsoidal inclusion in an infinite body [2, 3] and a generalized three-dimensional (3D) assemblage model based on average energy principles [4]. The model allows for assessment of linear, directionally dependent strengths for conservative analysis that is consistent with continuous fiber reinforced composite design methodologies. It should be noted that within this framework a polymer phase failure criteria could be employed if desired, but isotropic metrics for failure, e.g. Von Mises stress, are not totally capable of accounting for the discrepancy between the tensile and compressive strength of molded specimen with relatively uniform distributions of fiber orientations.

The material model incorporates the typical "skin/core/skin" effect. Based on a microphotograph of the fan gate sample, shown in Figure 7, a roughly 60% skin and 40% core was observed in the injection molded edge gated samples. Table 6 shows the estimated stiffness and strength of the edge gated material as compared to experimental values. The results indicate the modeling approach can be used to extend material models from molded tensile specimen to panels with more complex fiber distributions with reasonable accuracy.

Table 4. Constituent properties for unidirectional panel

Experimental Strength			Material Model		
Parameter	**(MPa)**	**(ksi)**	**Parameter**	**(GPa)**	**(Msi)**
S1 Tension	1717	249	E1	127.5	18.5
S1 Compression	1096	159	E2	10.0	1.45
			E3	10.0	1.45
			NU 12	.335	
			NU 13	.335	
			NU 23	.445	
			G12	5.76	.836
			G13	5.76	.836
			G23	3.47	.503

Table 5. Constituent properties for carbon filled PEEK (injection molded tensile specimen)

Experimental Dogbone Properties			Dogbone Material Model		
Parameter	**(MPa)**	**(ksi)**	**Parameter**	**(GPa)**	**(Msi)**
E1 Tension	27.6	4.0	E1	27.6	4.0
E1 Compression	26.9	3.9	E2	10.3	1.49
			E3	10.3	1.49
Parameter	**(MPa)**	**(ksi)**	NU 12	0.23	
S1 Tension	**274**	**39.7**	NU 13	0.23	
S1 Compression	**352**	**51**	NU 23	0.23	
			G12	2.48	0.359
			G13	2.48	0.359
			G23	2.16	0.314

Table 6. Predicted Properties of overmolded material

	E2		E2		S1 Tension		S1 Tension	
	(GPa)	(Msi)	(GPa)	(Msi)	(MPa)	(ksi)	(MPa)	(ksi)
Victrex Exp.	21.4	3.1	17.2	2.5	206	29.9	153	22.2
E1 Compression	26.9	3.9	E2	10.3	1.49			
Model	**20.7**	**3.0**	17.2	2.5	198	28.7	166	24.1
Failure Mode					Core		Skin	

With constituent material models in place, a half symmetry, solid model with discrete thickness layers was generated to represent the composite laminate, and the skin and core regions of the overmolded part for a flex specimen as shown in Figure 8. The skin and core of the molded layer is modeled with the same unidirectional properties (i.e., tensile specimen data) but different orientations (0° and 90°). Properties of the composite and molding material are switched depending on the composite side up or injection molding side up tests.

The goal of these preliminary simulations is to attempt to provide insight into certain key features observed in the experimental tests; with an understanding that the current state of the material models and assumed fiber distributions are approximate and require additional data for refinement and validation.

Specifically, under a composite side up test set-up, observed failure was noted in the molding material due to tension. Failure was seen as a linear, brittle response. In contrast, under an injection molding material side up set-up, tensile failure of the composite was noted where failure was seen as a nonlinear, ductile response, as seen in Figure 9. Average data indicates the specimens exhibit a nonlinear response around 1780 N (400 lb), and that the specimens' effective stiffness is about 75% of the linear value at failure. It is assumed that this reduction can be attributed to the nonlinear response of the injection-molding material under compression.

Computed stresses of a 3-point flex specimen of the unidirectional panel overmolded in the fan gate tool with a composite side up test configuration are shown in Figure 10. Axial stresses (in respect to the fiber direction, S11 or S22) are plotted in the composite, the core region of the injection molding material, and the skin region of the molding material. Analysis indicates a tensile failure of around 269 MPa (39 ksi) occurs in the lower skin of the molding material at an applied load of around 1560 N (350 lb) which correlates well with the experimental results.

Computed stresses of a 3-point flex specimen of the unidirectional panel overmolded in the fan gate tool with the injection side up test configuration are shown in Figure 11. Axial stresses (in respect to the fiber direction, S11 or S22) are plotted in the composite, the core region of the injection molding material, and the skin region of the molding material. Analysis indicates an onset of nonlinearity around 345 MPa (50 ksi) occurs in the upper skin of the molding material at an applied load of around 1780 N (400 lb) which correlates well with the experimental results.

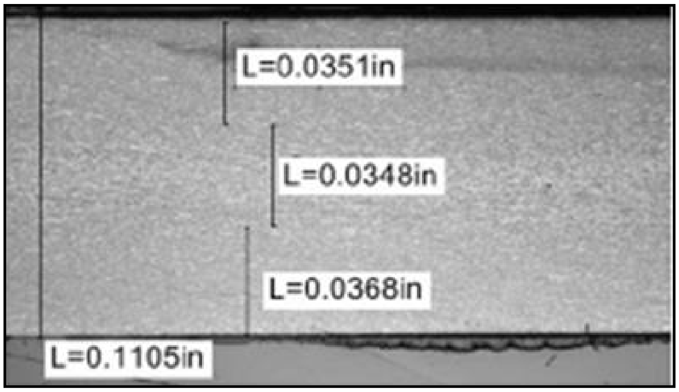


Figure 7. Photo of typical skin core fiber alignment

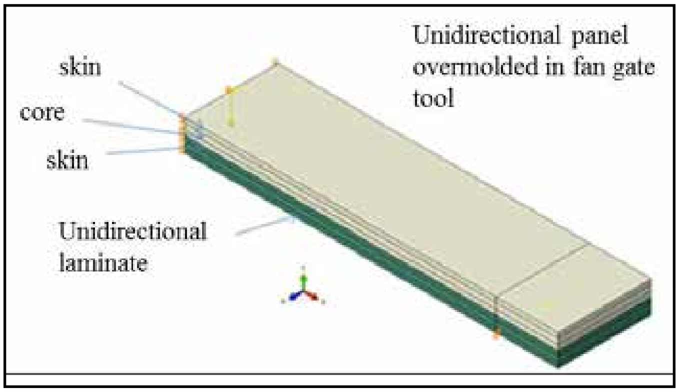


Figure 8. 3-pt bend (half) model for overmolded specimen

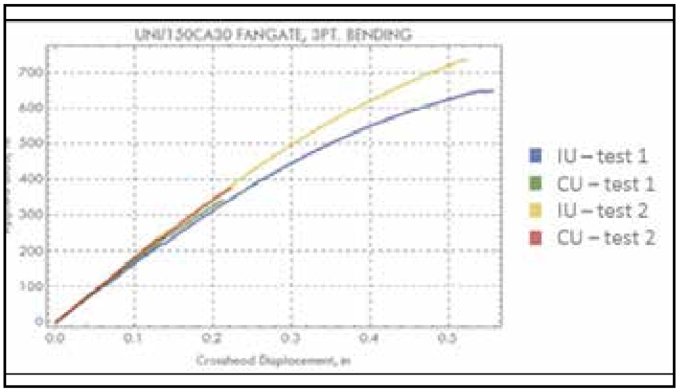


Figure 9. Test data showing linear response when tested Composite side Up (CU) and nonlinear when tested Injected side Up (IU)

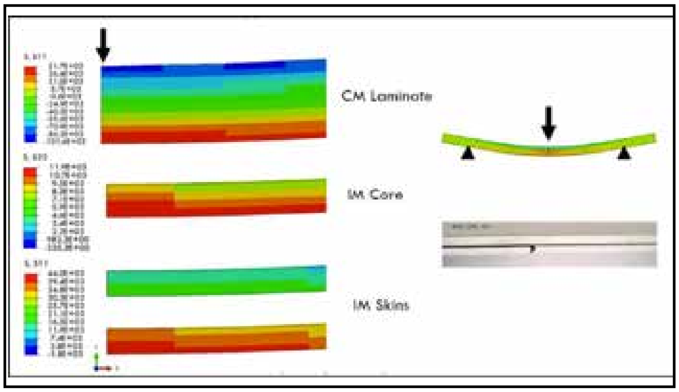


Figure 10. Predicted stress (psi) of overmolded specimen when tested Composite side Up (CU)

To approximate nonlinearity, the overmolded material stiffness is reduced by 50%, which corresponds to a 70-75% reduction in the 3-point bending stiffness, as seen in Figure 12. Analysis suggests that a ductile, nonlinear response of the overmolded material in compression results in a redistribution of the load that causes ultimate failure in the laminate. A nonlinear material model could be employed in future efforts to verify the accuracy of the simple, uniform stiffness reduction applied in this initial effort.

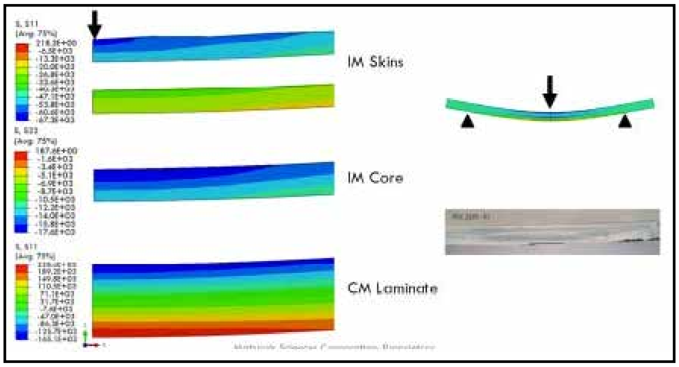


Figure 11. Predicted stresses (psi) of overmolded specimen when tested Injection side Up (IU)

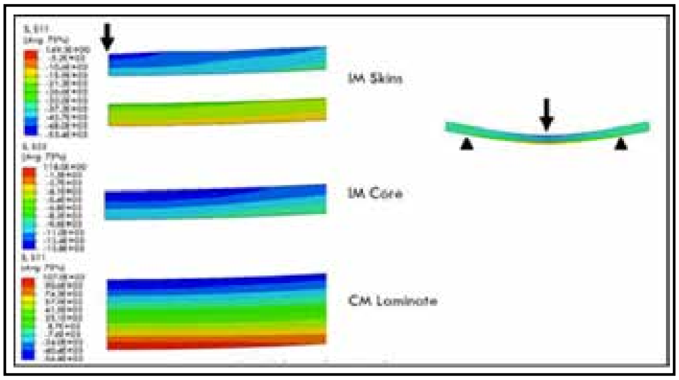


Figure 12. Predicted stresses (psi) of overmolded specimen when tested Injection side Up with reduced stiffness of molded material to capture nonlinearity

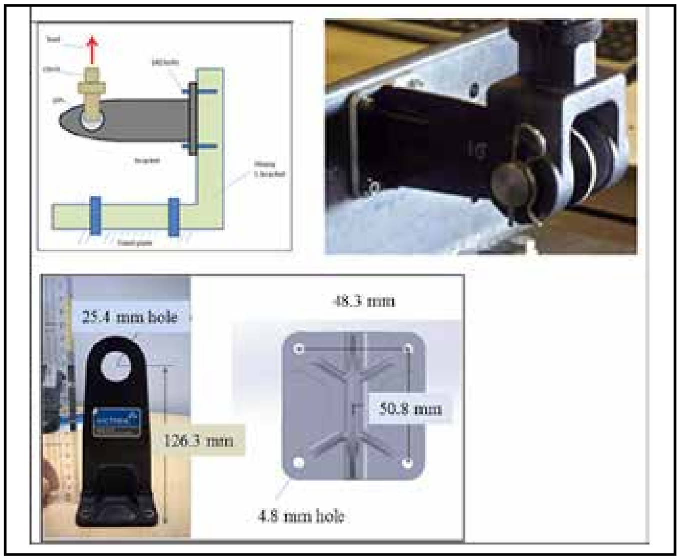


Figure 13. Load description and part dimensions.

3.3 Part Testing: Lateral Load Test Results

A lateral load is applied to the bracket as shown in Figure 13. The load-displacement curve for the bracket under the applied load is shown in Figure 14. A minor drop is seen in the load-displacement curve around 978 N (220 lb) although no damage was seen or detected. A subsequent load drop was seen at 1348 N (303 lb) possibly due to some dislocation of the molded material at the interface. At 1468 N (330 lb), a significant load change is seen where cracks were visually seen forming around the interface of the molded material. This was confirmed in the DIC measurements, shown in Figure 15. Subsequent loading beyond this point yielded distinct progressive failure events that resulted in unloading and reduced stiffness, as seen in Figure 15.

The failed bracket is shown in Figure 15. Highest load reached was around 1690 N (380 lb). The test demonstrates a very stable failure progression; the highest load capability is well beyond the initial load drop. It is assumed the initial load drop (first fracture) would be the design limit of the bracket. It is assumed this is desirable in that it provides some level of warning of failure if used in actual application.

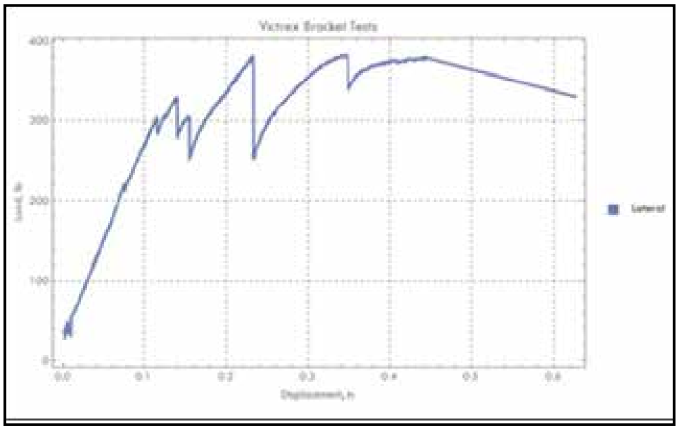


Figure 14. Load-displacement curve for bracket

4.CONCLUSIONS

- Flex strength is higher when tested with IU compared to CU. This suggests stress transfer from the molding material to the continuous composite layer is occurring.
- Under 3-point flex, failure of the injection molding layer is higher than published data, which supports the assumption that stress transfer is occurring through the interface bond.
- Under 3-point flex and IU test set-up, failure occurred at the composite due to tension. The interface appeared fully intact. Under a CU test set-up, failure occurred due to tension of the molding compound and eventually propagated up towards the interface. The behavior suggests the limiting factor is not the interface bond.
- Simulations of the 3-point flex of overmolded samples were able to capture certain key features as observed in the experimental tests. Specifically, under a CU test set-up, observed failure was noted in the molding material due to tension. Failure was seen as a linear, brittle response. In contrast, under an injection molding material side up set-up, tensile failure of the composite was noted where failure was seen as a nonlinear, ductile response.
- Under 3-point flex simulation, nonlinearity was represented by a 50% reduction in stiffness of the molded layer, resulting in an approximately 75% reduction in the stiffness seen at initial failure. Analysis suggests that a stable ductile nonlinear response of the overmolded material in compression results in a redistribution of the load that causes ultimate failure in the laminate.
- For conservative design methodology, a standard, linear analysis approach is applicable to an overmolded composite system without special consideration of the overmolded interface. Both the experimental observation and linear analysis indicate that the strength of the overmolded material is the limiting factor in the 3-point flexural strength of the hybrid specimen.
- Recommendation is to perform additional testing to achieve more statistical meaningful data.

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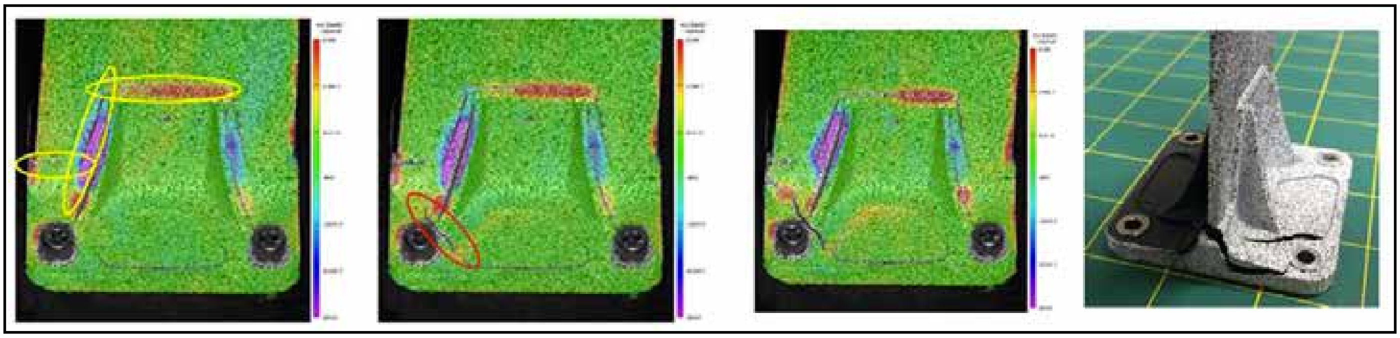

Figure 15. DIC Images of bracket under load, showing high strain locations and damage at increasing load and final fracture

SUMMARY

For more than three decades, Victrex has collaborated with customers to understand their challenges and deliver high-performance solutions and unmatched expertise. As the industry continues to increasingly use PAEK-based hybrid systems, it becomes even more critical to understand component performance to improve confidence in service life. Please consult with Victrex should there be any specific questions or concerns.

A company with cutting-edge polymeric solutions, streamlined production facilities, application development expertise, unmatched technical support and a presence across the globe—that's a future performance partner.

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