AN INTEGRATED SYSTEM FOR IMPROVED DAMAGE RESISTANCE AND LIGHTNING STRIKE PROTECTION IN COMPOSITE STRUCTURES

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Abstract

This paper summarises findings from research at QinetiQ, targeted primarily at improving the relatively poor impact performance of polymer matrix composites (PMC) via the use of shape memory alloys (SMA). The paper describes the evolution of manufacturing technology to produce SMA-reinforced PMCs, impact test results and findings from simulated lightning strike trials.

Impact results demonstrated a step change increase of up to 227% in the energy absorbed by 4-ply PMC laminates. In addition, tests on the lightning strike protection capability of the material produced excellent results, culminating in the conclusion that the SMA material is superior in preventing structural degradation due to lightning strike (compared to commercially available systems).

The results confirm that the SMA-reinforced PMC technology can be considered a truly integrated, multi-functional material system, capable of delivering both improved impact performance and lightning strike protection to future composite structures.

1 Introduction

The relatively poor impact performance of polymer matrix composite (PMC) materials, compared to their high specific strength and stiffness, often necessitates the development of more conservative, heavier designs than would otherwise be needed to carry simple design loads. Despite these safety measures, the tendency of bulk composites to damage when subjected to local impact threats still presents a serious problem for composite structures, particularly as damage may remain undetected within the structure. Poor impact performance, therefore, remains one of the most significant factors restricting the more efficient (and widespread) use of PMCs, particularly in safety critical load-bearing applications. As a consequence, significant research effort has been targeted at this problem for many years.

The emergence of techniques such as stitching and z-pinning, and the development of resin systems with improved toughness, has led to some incremental improvement in the impact performance of PMCs. However, further developments are still required.

Current research at QinetiQ has sought to address the above issues through the development of a highly novel, shape memory alloy (SMA) reinforced polymer composite system, whose primary function is to deliver a step change in impact performance.

This is made possible due to the unique properties of SMA materials; a special class of metallics that have lower density than other high strength metals, whilst also possessing the ability to undergo large amounts of elastic and plastic deformation, at moderately high stresses. Thus, they are tough and can absorb very high levels of energy before failure. These attributes render SMA an ideal reinforcing material for improving the impact resistance of PMC materials and structures. Unsurprisingly, therefore, several researchers have investigated the use of SMA materials to enhance the impact properties of PMCs.

Kiesling et al studied the performance of carbon/bismaleimide laminates after embedding uni-directional and bi-directional Ti-Ni (Nitinol) SMA wires, at levels between 3 and 6% by volume [1]. The effect was to increase the impact energy absorbed by 23% and 41%, respectively, without any change in the stiffness or strength of the bulk material.

Paine and Rogers studied the low velocity impact properties of carbon/bismaleimide composites, embedded with Nitinol wires at 2.8% by volume, demonstrating an increase of 25% in the maximum force during impact [2]. Further work by the same group also revealed that the impact perforation of carbon and glass epoxy PMCs could be increased by 100% and 67%, respectively, via the introduction of surface layered Nitinol wires [3].

Importantly, the approach taken by researchers in the published literature utilises SMA wires which are 'discretely' added to the bulk PMC, either by placing the SMA at the surface, or by placing SMA reinforcement at the laminate inter-layer during the manufacturing process. The approach taken throughout the research at QinetiQ has been to incorporate modest volumes of SMA reinforcement into the bulk composite in an entirely integrated manner, using advanced weaving techniques, to ensure the materials specific properties are optimised.

Although the primary performance attribute addressed during this study has been improved impact performance, the SMA materials investigated also have the potential to offer multi-functionality in PMC structures because of their interesting, and, in some cases, unique mechanical, thermal and electrical properties. Current research at QinetiQ is investigating the use of the embedded SMA materials as actuators and sensors. However, for the purposes of this paper, we also focus on the potential ability of SMA to act as a media for the protection of PMC structures in the event of lightning strikes.

2 Manufacturing development

2.1 Techniques for introducing SMA reinforcement

The primary focus of early work completed on the development of a cost-effective method for introducing SMA reinforcement into PMCs investigated the manufacture of hand-woven SMA meshes which were introduced during laminate lay-up. Whilst this was useful in demonstrating the potential performance attributes of different SMA materials, it was quickly dismissed on the grounds of cost and complexity.

Two further approaches were suggested; filament winding and advanced weaving technology. The filament winding method developed produced good quality resin films, reinforced with controllable volumes of SMA, but the method still required the discrete addition of films during lay-up, whilst also causing undesirable increases in laminate thickness (compared to baseline laminates with no SMA reinforcement).

Sigmatex UK Ltd., Runcorn, were approached to investigate the feasibility of developing fully integrated woven products containing carbon fibre and pre-determined volumes of SMA. This was a challenging request because the SMA wires were difficult to handle due to their 'springy' nature and tendency to twist during weaving. After a significant amount of development, including optimisation of weaving variables and the development of new fibre handling equipment specifically designed for SMA, Sigmatex were able to successfully produce very high quality SMA-reinforced carbon fibre woven fabrics. The volume of SMA introduced was controlled by changing the number of wires in the warp and weft directions of the fabrics.

Figure 1 shows one of the SMA reinforced fabrics produced for the study.

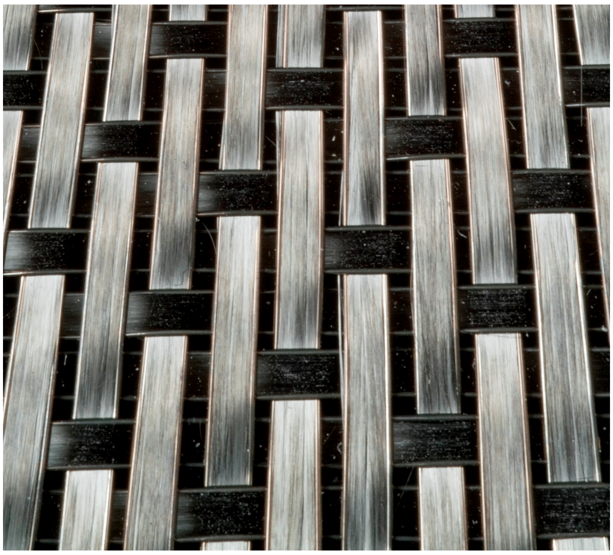

Fig. 1. Woven SMA – carbon fibre fabric produced by Sigmatex UK Ltd.

During the research, Sigmatex have delivered a wide range of fabric types, with many different SMA volume fractions, utilising different types of SMA. These have been introduced in varying quantities, and at various locations, within the PMC laminates manufactured for subsequent test and evaluation.

2.2 Laminate manufacture and alloy selection

The majority of research completed has utilised the resin film infusion (RFI) technique to produce PMC laminates for testing. In RFI the dry woven fabric and the matrix come together at the lay-up stage, providing flexibility in matrix/fibre combinations. Sheets of resin film are stacked and infused through the dry fabric, or, alternatively, they can be interleaved between individual fabric layers. For the purposes of this work, the resin and fibre stack was cured with pressure assistance in an autoclave to produce laminates of appropriate quality for subsequent testing. More recently, further manufacturing developments have taken place with Hexcel Composites, UK, leading to the production of a prepreg variant of the woven SMA / carbon fibre product. Further laminates were therefore manufactured for testing using this prepreg material and an equivalent autoclave cure.

Selection of SMA materials for study was based on the existence of two possible alloy phases; martensitic and austenitic. Either of these phases can predominate at room temperature, depending on the processing and heat treatment given to the alloy. Since the TiNi (Nitinol) alloys are the most widely available, two alloys of this type were selected. The first, denoted alloy A throughout this paper, had a predominantly shape memory state at room temperature, whilst the other, alloy B, had a superelastic state at room temperature. It was hoped that evaluating the behaviour of both types of alloy would provide an improved understanding of the optimum stress-strain characteristics required to improve the impact performance of the final SMA reinforced composite material.

3 Experimental

3.1 Impact testing

Impact testing was conducted using an instrumented falling weight impactor, using a range of impact ‘tups’. The data presented here has been generated from impacts tests completed at 50 Joules with a 16mm hemispherical impact tup, using laminates manufactured from four woven plies of AS4 fibre, combined with 8552 resin (from Hexcel Composites). All of the impact tests were completed using a clamped support ring, with inner diameter 100mm and outer diameter 140mm. Five impacts were completed for each material variant.

The relatively high impact energy was used to ensure that all of laminates tested were penetrated, thus allowing the full energy absorbing potential of the SMA-reinforced PMC to be assessed.

The instrumented impactor delivers force-time data, which, along with a measurement of velocity at the point of impact, allows the calculation of energy absorbed during the impact event (using an integration technique).

3.2 Lightning strike

Lightning strike testing was completed at the Direct Effects facility of Culham Lightning Limited, Culham, UK. Simulated Zone 1A lightning strike tests were requested, as these are the most severe; Zone 1A strikes are typically located at the aircraft nose, wing tips, or other extremity. For illustration of the severity of the test, the waveform corresponding to Zone 1A comprises three components, A+B+C, applied as a composite waveform, with details as follows:

- Component A:
  Peak Current: 200kA ±10%
  Action Integral: 2 x $10^6 A^2 s$ ±20%

- Component B:
  Average Current: 2kA ±20%
  Charge Transfer : 10 Coulombs ±10%

- Component C
  Current: 200-800A
  Charge Transfer: 20 Coulombs ±20%
  Time period: 45ms

The experimental test rig used for arc attachment tests to panels is shown in Figure 2. The test samples were secured to the rig by clamping the four edges between the test rig base plate and an aluminum alloy ‘picture frame’, and the arc attachment to the samples was initiated by a 100mm long, fine copper fuse wire, from an arc jet-diverting electrode to the sample under test.

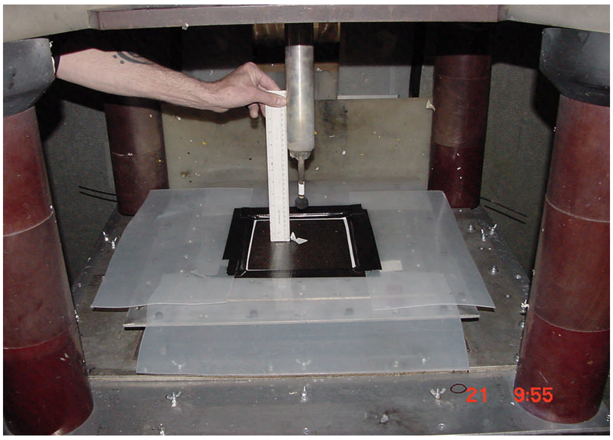

Fig. 2. Arc test rig with sample positioned showing the jet diverting electrode in position.

Lightning strike tests were performed using 4 ply laminates with nominal 5.9% and 11% SMA volume fraction, without any additional surface protection layers (as summarised in Table 1). A baseline sample with no SMA reinforcement, but with a commercially available Cu surfacing mesh (Astrostrike), was also tested for comparison purposes.

3.3 Other tests

A wide range of supporting tests have also been conducted to determine the suitability of the SMA-reinforced PMCs for use in load-bearing, safety critical applications. These tests included;

- Galvanic corrosion
- High temperature impact performance
- Low temperature impact performance
- Thermal cycling
- In-plane mechanical performance

This data is outside the scope of the current paper, but further information is available from the authors.

3.4 Material variables and test plan

Testing has been completed to evaluate the effect of several different material variables on impact and lightning strike performance;

- SMA type
- SMA volume fraction
- SMA / carbon fibre weave style
- Distribution of SMA through the laminate

Table 1 shows the resulting test plan, illustrating the different test modes and laminate variables for study.

4 Results and discussion

4.1 Impact testing

The detailed impact results are shown in Table 2. Figures 3 and 4 show the effect of SMA volume fraction on absolute impact energy absorption and energy absorption normalised per unit mass, respectively. The mass normalisation was performed by dividing the absolute energy absorbed by the mass of the clamped region of material during test (i.e. 100mm diameter ring).

The results showed a significant improvement in the impact energy absorbed by the SMA-reinforced variants, compared to the baseline unreinforced, laminates; performance improvements of 61-227% were demonstrated compared to baseline. When normalised for mass, this corresponded to an increase from 0.42 for the baseline laminate, to 0.97 Joules per gram for the 10.8% SMA Vf Variant 5 laminate.

Table 1. Laminate test plan

Laminate code	Test Type	Alloy type	Manufacturing route	Weave pattern
AO654	Impact Testing	N/A	RFI	4xCF baseline
AO910		N/A	PREPREG	4xCF baseline (p)
AO660	Impact Testing	Alloy A	RFI	3xCF + 1xVariant1
AO661		Alloy A	RFI	3xCF + 1xVariant2
AO653		Alloy A	RFI	3xCF + 1xVariant3
AO662		Alloy A	RFI	3xCF + 1xVariant4
AO663		Alloy A	RFI	2xCF + 2xVariant1
AO664		Alloy A	RFI	2xCF + 2xVariant2
AO665		Alloy A	RFI	2xCF + 2xVariant3
AO666		Alloy A	RFI	2xCF + 2xVariant4
AO667		Alloy A	RFI	4xVariant1
AO768	Impact Testing	Alloy B	RFI	3xCF + 1xVariant2
AO770		Alloy B	RFI	3xCF + 1xVariant3
CO471		Alloy B	RFI	3xCF + 1xVariant4
AO772		Alloy B	RFI	3xCF + 1xVariant4
AO769		Alloy B	RFI	2xCF + 2xVariant2
AO771		Alloy B	RFI	2xCF + 2xVariant3
CO472		Alloy B	RFI	2xCF + 2xVariant4
AO773		Alloy B	RFI	2xCF + 2xVariant4
AO911	Impact Testing	Alloy A	PREPREG	3xCF + 1xVariant5 (p)
AO912		Alloy A	PREPREG	2xCF + 2xVariant5 (p)
A0909	Lightning strike testing	Alloy A	RFI	4xCF baseline + Astrostrike
A0906		Alloy A	RFI	2xCF + 2xVariant3
A0907		Alloy A	RFI	3xCF + 1xVariant3

Key;

- All laminates consist of 4 woven plies, with lay-up 0/90/90/0.
- ‘n’ x CF denotes number of carbon fibre baseline plies
- ‘n’ x VariantX denotes number of SMA plies of Variant ’X’.

Table 2. Impact test results

Alloy type	Weave pattern	SMA Vf (%)	16mm tup Impact Energy			
			Joules	% increase	J/g	% increase
N/A	4xCF baseline	0.0	9.4	-	0.56	-
N/A	4xCF baseline (p)	0.0	8.3		0.42	
Alloy A	3xCF + 1xVariant1	3.1	15.1	61%	0.75	32%
Alloy A	3xCF + 1xVariant2	4.5	16.8	79%	0.76	34%
Alloy A	3xCF + 1xVariant3	5.7	17.2	83%	0.75	34%
Alloy A	3xCF + 1xVariant4	7.1	20.7	120%	0.85	50%
Alloy A	2xCF + 2xVariant1	5.8	18.4	96%	0.75	33%
Alloy A	2xCF + 2xVariant2	8.1	21.0	123%	0.75	33%
Alloy A	2xCF + 2xVariant3	10.0	26.1	178%	0.89	59%
Alloy A	2xCF + 2xVariant4	11.8	29.0	209%	0.94	67%
Alloy A	4xVariant1	10.3	26.5	182%	0.93	65%
Alloy B	3xCF + 1xVariant2	4.1	14.0	49%	0.60	7%
Alloy B	3xCF + 1xVariant3	5.3	15.8	68%	0.63	12%
Alloy B	3xCF + 1xVariant4	7.0	16.0	70%	0.64	13%
Alloy B	3xCF + 1xVariant4	6.6	16.7	78%	0.64	14%
Alloy B	2xCF + 2xVariant2	8.1	18.0	91%	0.65	15%
Alloy B	2xCF + 2xVariant3	10.0	19.2	104%	0.64	13%
Alloy B	2xCF + 2xVariant4	11.7	24.0	155%	0.75	33%
Alloy B	2xCF + 2xVariant4	11.7	24.7	163%	0.74	32%
Alloy A	3xCF + 1xVariant5 (p)	5.3	18.8	126%	0.76	81%
Alloy A	2xCF + 2xVariant5 (p)	10.8	27.2	227%	0.97	131%

4.1.1 Effect of SMA position and volume fraction

A number of conclusions related to the importance of different material variables can be drawn from the test data. Of these, perhaps the most important is the fact that impact performance did not appear to be dependant on the position of the SMA reinforcement through the thickness of the laminates. This is best illustrated by the comparison of two Alloy A data points corresponding to approximately 10% SMA Vf. One of these data points was produced using laminate AO667 which employed 4 Variant4 fabrics distributed throughout all four laminate plies; whereas, the other laminate AO665 was produced using Variant3 fabrics at plies 3 and 4 only. Despite this significant difference in SMA distribution, the impact performance produced was very similar.

This data suggested that SMA fabrics can be placed at optimum positions based on other needs; for example, to optimise in-plane performance characteristics or, alternatively, for other non-structural performance considerations. This is particularly useful from a lightning strike perspective because some of the SMA reinforcement must be placed at the outer surface.

More generally it can be concluded that a simple linear relationship between SMA Vf and energy absorption has been established. This has been seen in all of the tests completed, including tests with different resin types, SMA weave architectures and impact tup geometries (not reported here).

4.1.2 Effect of shape memory alloy type

A significant difference was established in the performance of composite laminates reinforced with SMA alloy A and alloy B materials. This was somewhat unexpected since the fracture energy (as indicated by the area under the stress-strain curve) was similar for both alloy types. The results therefore suggested that the increased energy absorption could not be attributed solely to the strain energy required to fracture the SMA wires. Further work revealed the importance of selecting alloy types which offer similar stress-strain characteristics to the bulk composite, up to the point of its failure in the impact event, in order to achieve the optimal ‘hybrid’ effect from the different materials employed.

4.1.3 Effect of manufacturing route

The results summarised in Table 2 reveal that there was some improvement in the SMA-reinforced laminates produced via a prepreg manufacturing route, compared to those produced by RFI. This slight improvement was increased considerably when the data was normalised for mass. For example, test data from prepreg laminate AO911 (5.3% SMA Vf) produced an increase in energy absorption of 81% compared to baseline; however, the increase was only 33% for RFI laminate AO663 which had an SMA Vf of 5.8%.

The main reason for this difference was due to the lower impact performance of the prepreg baseline, compared to that produced using RFI; the prepreg baseline absorbed 8.3J compared to 9.4J for the RFI equivalent. This difference was explained because RFI laminates tend to have higher impact performance due to slightly increased resin content and therefore increased ductility.

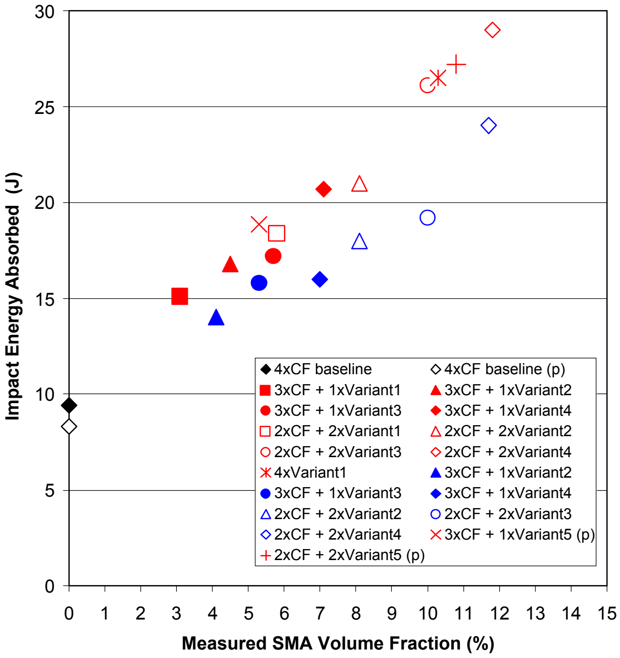

Fig. 3. Effect of SMA type and Vf on impact energy absorption

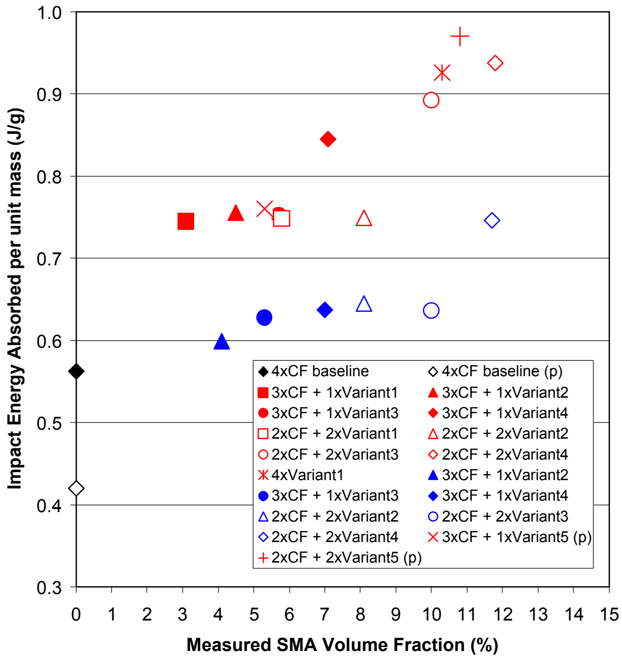

Fig. 4. Effect of SMA type and Vf on impact energy absorption per unit mass

4.2 Lightning strike

Laminates were tested using a Zone 1A simulated lightning strike, as described in Section 3.2. Following testing, none of the laminate variants showed any visible damage or punctures on the back face. The front face with the least amount of visible damage, and the smallest damage area, was the 11% SMA laminate (AO906), as shown in Figure 5.

Only a small amount of resin burn off was visible around the arc attachment point, exposing some carbon fibres. The laminate with 5% SMA had a slightly larger damage area, but similar damage characteristics. The front face of the baseline sample showed that the copper mesh was substantially eroded over a 100mm diameter (the size of the open arc) around the arc attachment point. Tufting of the composite substrate was observed in the eroded area (Figure 6).

Thus, in summary, the best lightning protection performance was provided by the laminate with 11% SMA volume fraction, and the worst by the baseline laminate with copper mesh protection.

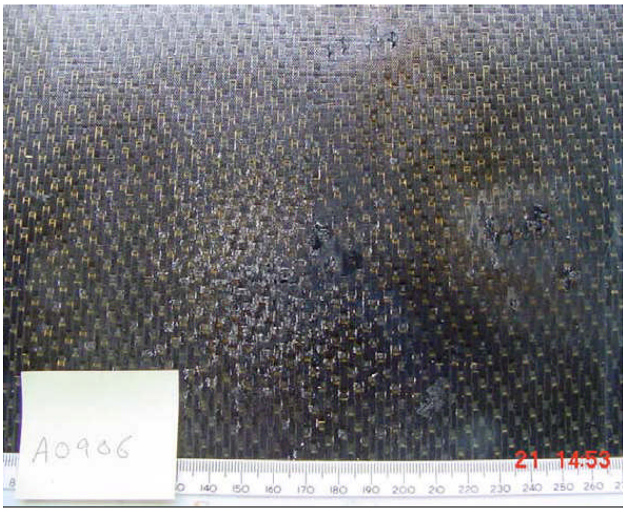

Fig. 5. 11% SMA laminate post Zone 1A lightning strike testing

Fig. 6. Baseline laminate with Astrostrike surface layer protection post Zone 1A lightning strike testing

4.3 Test results summary

The data presented here represents a dramatic, step change, improvement in the impact performance of traditional PMC materials. It demonstrates the potential of the technology in relieving some of the difficulties associated with impact performance in composite structures. Data showing an increase in the energy absorption of SMA-reinforced laminates which is more than double that of baseline, suggests that the mass of some structures could be considerably reduced where design is 'driven' by the need to absorb energy (e.g. aircraft leading edges). The data has also validated the novel weaving approach developed by Sigmatex.

The Zone 1A lightning strike test results indicated that the SMA reinforcement is able to provide an inherent lightning strike protection capability, thus negating the need for further protective surface layers, helping to further reduce mass (and cost).

5 Conclusions

The following specific conclusions can be drawn from the results presented here;

1. An increase of up to 227% in energy absorption has been demonstrated in SMA-reinforced prepreg laminates. This corresponded to an increase of 131% per unit mass.
2. Impact performance was independent of SMA position and variant, but appropriate selection of alloy type was found to be critical in delivering significant improvements in performance.
3. An improved understanding of important SMA stress-strain characteristics has been established, allowing the improved definition of optimum SMA reinforcements in the future.
4. SMA-reinforced laminates showed superior lightning strike protection capability compared to commercially available copper meshes.
5. The combination of data presented here confirms that the SMA-reinforced PMCs can be considered a truly integrated, multi-functional material system, which is capable of delivering both improved impact performance and lightning strike protection.

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