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Static and Dynamic Strength of Scarf-Repaired Thick-Section Composite Plates

by Bazle A. Gama, Stephane Mahdi, Curt Cichanowski,
Shridhar Yarlagadda, and John W. Gillespie, Jr.

ARL-CR-549 **September 2004**

prepared by

Center for Composite Materials
University of Delaware
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under contract

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14. ABSTRACT

Composite structural armor is typically a sandwich construction consisting of thick-section composite, rubber, and ceramic layers, which are combined to provide an optimal balance of structural and ballistic performance at minimum weight. Our focus was on the scarf repair of the thick-section plain weave S-2 Glass/SC15 composite subjected to static and dynamic loading. Deliberate damage to backing plates was repaired at elevated temperatures using induction heating and at room temperature. The static response of control and repaired plates was compared via four-point bend testing. The effect of three scarf angles and four repair adhesives was quantified. Using these repair techniques, renewal of stiffness was achievable, except for the case of the highly ductile, low-stiffness adhesive. The renewal of moment capacity of the repair beams was highly dependent on the scarf angle for various adhesives, and a maximum renewal of strength was 60%. The dynamic strength of scarf patch-repaired composite specimens was investigated through axial compression strength testing using a split-Hopkinson bar. Under dynamic loading, the axial strength was found to be dependent on the scarf angle and rate of loading. Loci of failure are reported for the various materials, scarf angles, and loading conditions.

15. SUBJECT TERMS

repair, induction cure, thick-section composites, axial compression, Hopkinson bar, failure analysis, punch shear test, energy absorption, S-2 Glass/SC15, hybrid

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1. Introduction

Composite structural armor typically consists of different material layers stacked together to provide unique structural and ballistic properties, as well as satisfying other multifunctional requirements (e.g., fire, smoke, and toxicity [FST] resistance, electromagnetic shielding, etc.) (*1–4*). This program used a simplified four-layer configuration that consists of a composite cover layer for durability, a layer of ceramic tile for ballistic protection, a rubber layer, and a thick composite backing plate for structural and ballistic performance (figure 1). Fabrication of the composites used the vacuum assisted resin transfer molding (VARTM) process, which has been shown to provide superior mechanical properties in a single-step operation as compared to bonding individual layers in a multistep process (*5*). Additional details on structural behavior can be found in (*5–7*).

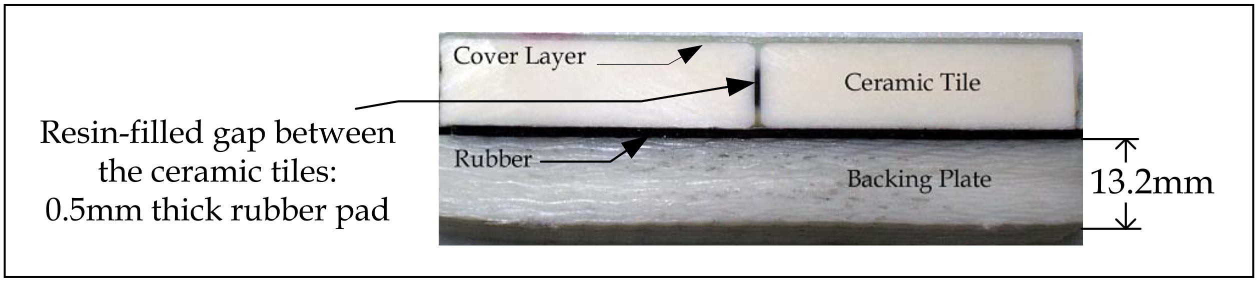


Figure 1. Cross section of a model four-layer structural armor (*5*).

Under ballistic impact, both the cover layer and the backing plates could be completely perforated, and the extent of damage in the ceramic tiles varied from a single tile to all of the tiles surrounding the impact site (see figure 2). Multiple interfaces in the backing plate also had delaminations that were larger than the extent of damage to the ceramic tiles (i.e., three tiles in length). Extensive fiber damage also occurred at the impact site. Experiments have shown that such damage degrades the ballistic performance of the structural armor (*8*). The compression strength after ballistic impact was also shown to drop to levels approaching 25% of the virgin strength (*9*). Repair that is capable of renewing the structural and ballistic performance after a ballistic impact is a key issue for the use of composites for Future Combat Systems (FCS).

The extent of damage in different layers determines the level of repair to be performed. Different repair strategies and repair methods that use conventional repair techniques or induction curing techniques have been documented in previous studies (*8*, *10*). Three levels of repair have been identified according to the level of damage through the thickness of the armor. Level I is concerned with the repair of the cover layer only, as in the case of damage due to a low-velocity impact. Level II represents the case of the repair of both the cover layer and the ceramic strike face. Finally, Level III addresses the repair of all the layers that compose the structure, including the repair of the composite backing plate, as in the case of the high-velocity ballistic impact damage shown in figure 2. A repair by resin infusion was attempted (*8*), but it was shown to provide only moderate improvement in the ballistic performance of the repaired panels. Because resin infusion does not effectively repair fiber damage, the present study evaluates a scarf repair that enables all damaged materials to be replaced for Level III repairs.

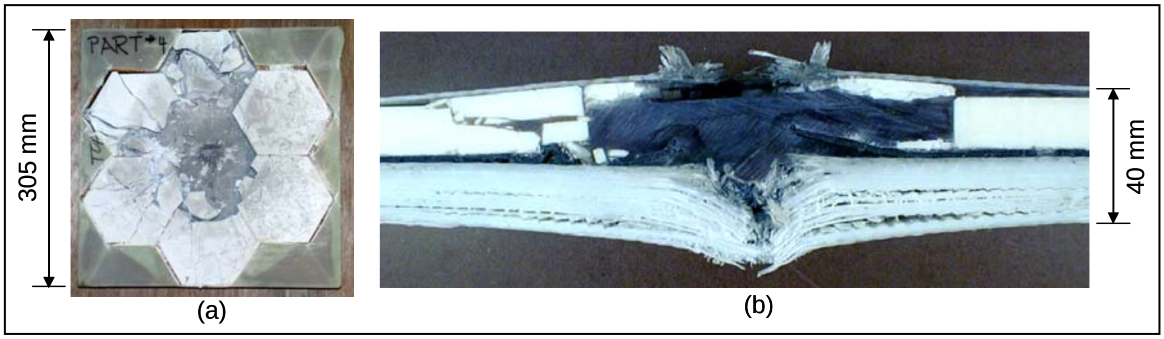


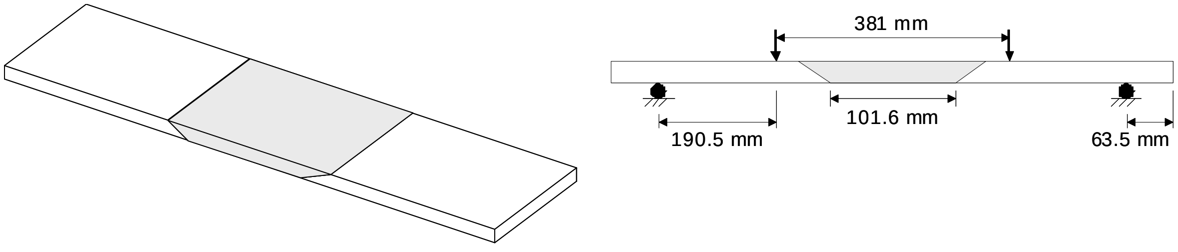
Figure 2. Ballistic damage of a composite structural armor: (a) the ceramic tiles after the cover layer have been removed and (b) cross section (*8*).

The repair should renew stiffness, strength, and ballistic performance to meet design requirements. The present effort on scarf repair builds on the procedures developed by Gama et al. (*10*) who demonstrated a Level III repair of structural armor. The repair involved the removal and replacement of all the layers shown in figure 1, including that of the composite backing plate. Following the removal of the damaged cover layer and the damaged ceramic tiles, the damaged region of the backing plate was removed using a wet grinding tool to form a circular hole. The edge of the hole was machined to produce a 45° scarf angle. The backing plate was then repaired with an adhesive-bonded flush scarf plug of the same material, and the ceramic and cover layer were replaced. The repair to the thin cover layer used a flush plug repair (i.e., butt joint). The repair of the entire cross-section was done in a single-step operation from one-side that used a vacuum bag for consolidation and induction heating for rapid heating and cure. Various susceptors were used at the various interfaces to locally heat the adhesive bond lines to cure temperatures without overheating any single interface. A repaired demonstrator panel was manufactured to prove process viability, but was not tested. These repair techniques were used in the present study to fabricate test specimens to characterize the structural performance of the backing plate with scarf repair subjected to static and dynamic loading.

Composite structural armor is subjected to bending moments and shear forces due to terrain-induced loads and lateral impacts. Some understanding of the complex interaction between layers of structural armor is needed to establish simple test methods that evaluate Level III repair approaches and maintain some relevance to the application loads. In previous work (*11*), the finite element method was used to model the deformation behavior of the armor in bending. The through-thickness strain distribution deviates greatly from that of the linear classical analysis due to the compliant rubber layer that decouples the ceramic from the composite backing plate. These results show that it is possible to idealize the behavior of the backing plate in the structural armor as a beam subjected to bending loads. In addition, in-plane axial compression loads can also be used to evaluate the strength of bonded joints. The present study focused on developing simple test methods to quantify the performance of scarf-repaired thick-section composite backing plates of composite structural armor.

2. Test Methods

The four-point bending test was selected to characterize the static behavior of the virgin and repaired beams. The nominal dimension of the test beam was 889 × 30 × 13.2 mm. The support span was 762 mm, which provided a span-to-thickness ratio of 57.7. The span of the loading noses was sufficiently large (381 mm) to include the scarf repair. The specimen and test configurations are shown in figure 3. An Instron 8562 (servo-hydraulic) machine equipped with a custom built four-point bend test fixture (support and loading nose diameter of 25.4 mm) was used to conduct the experiment at a constant crosshead displacement rate of 2.5 mm/min. Load and crosshead displacement data were collected using the Instron Series IX data acquisition software.



(a) 3-D view of the scarf-repaired beam

(b) Schematic of four-point bend test

Figure 3. Four-point bending testing of scarf-repaired composite backing plate.

Dynamic axial compression tests of scarf-repaired composite joints were performed using the compression split Hopkinson pressure bar (SHPB) technique (*12*) (figure 4). The results generated were representative of the response of the scarf repair joints loaded in axial compression. The striker bar, the incident bar, and the transmitter bar were all made from Inconel 718 alloy (Young's modulus–200 GPa, bar velocity–4920 m/s, Poisson's ratio–0.29, and diameter–19.05 mm). Specimens of a nominal cross section (13.5 × 13.5 mm) were machined from scarf-repaired composite plates. The lengths of the specimens were 37.5, 70, and 90 mm for 45, 18.4, and 11.3° scarf angles, respectively. In order to load such long specimens for sufficient duration, a long striker bar (711 mm) was used to produce a long incident pulse. A rubber disk was used between the striker bar and the incident bar to shape the pulse and to uniformly load the specimen. The impact velocity of the striker bar was varied between 5 and 10 m/s, which produced a displacement rate of 2.5–5 m/s. Maximum force at failure was calculated using a "3-wave" analysis from the incident, reflected, and transmitted stress pulses as obtained from each test. A minimum of two specimens was tested for each scarf ratio and adhesive used.

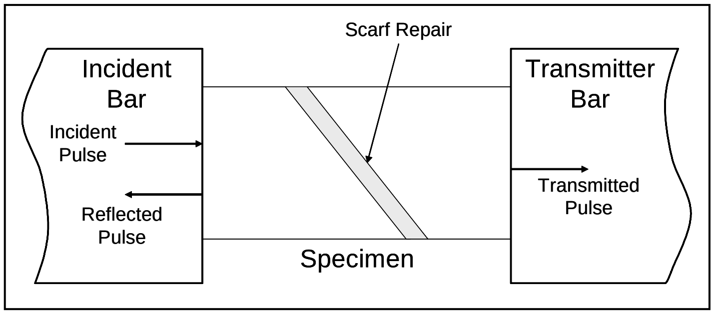


Figure 4. Hopkinson bar procedure for dynamic axial compression of scarf repair composite specimens.

3. Materials and Repair Procedure

3.1 Materials

The backing plate considered in the present work consisted of 22 layers of Knytex plain weave S-2 Glass* fabric of areal density 0.81 kg/m^2. The lay-up orientation used was (0°/90°) (i.e., the fabric warp direction is at 0°, and the weft direction is at 90°). The backing plates were fabricated by VARTM (*5*), using an Applied Poleramic SC15 epoxy resin system, specifically developed for the VARTM process. SC15 has a tensile modulus of 2.7 GPa and strain to failure of 6%. The SC15 system gels at room temperature (8–12 hr). Additionally, a 4-hr post-cure at 149 °C was used. The total thickness of the backing plate was nominally 13.2 mm with a volume fraction of ~50% and <1% void content.

The choice of a proper adhesive system for repair of structures is always crucial. The selected adhesive must offer good mechanical properties, high toughness, and meet service temperature requirements. It has to be polyvalent and adhere well to different materials. Also, a moderate viscosity is needed to fill the gaps in between the ceramic tiles and the adhesive should be easily spread. Finally, cure at a relatively low temperature in a short period of time is desirable.

Four adhesives were chosen for this study that offered a broad range of properties. The Dexter Hysol† EA9359.3NA adhesive is a two-part system that cures at 82 °C for 1 hr. According to the manufacturer's datasheet (*13*), it has a bulk tensile modulus of 2.2 GPa, a tensile strength of 31 MPa, and an elongation at failure of 10%. The Dexter Hysol EA9394 adhesive is also a two-part system that cures at 66 °C for 1 hr. According to the manufacturer's datasheet (*13*), it has a bulk tensile modulus of 4 GPa, a tensile strength of 46 MPa, and a much lower elongation at failure of 1.7%. Both systems have been successfully cured using induction heating of structural armor. The use of a room-temperature cure adhesive was also considered. Plexus‡

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[*] S-2 Glass is a registered trademark of Owens Corning.

[†] Hysol is a registered trademark of the Dexter Corporation.

[‡] Plexus is a registered trademark of ITW Plexus, a business unit of Illinois Tool Works.

MA425 is a two-part methacrylate adhesive that cures in 30 min at room temperature. This adhesive provides good gap filling capability as well as a much higher elongation to failure (120%). This adhesive has a lower tensile modulus (345 MPa) and strength (17 MPa) compared to the elevated temperature cure adhesives. The fourth adhesive was also a methacrylate (Plexus AO420), which has similar mechanical properties, but a much lower curing time of 6 min.

3.2 Repair Procedure

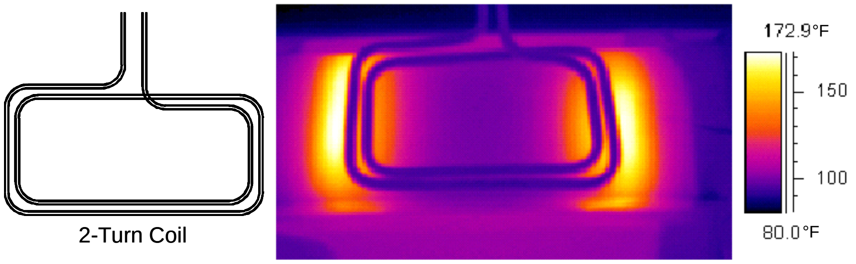
The scarf patch repair concept shown in figure 3 is a very efficient way of repairing highly loaded composite structures. Care must normally be taken to ensure that the scarf angle is low enough to allow for a smooth stress transfer between the two adherends. Scarf repairs of thin aerospace structures are commonly limited to angles ranging between 2 and 6°. This is not practical in thick-section laminates. In the present work on the repair of thick sections, the scarf patch was limited to a diameter of 350 mm (~3 tile diameters, where extensive fiber damage occurs). Therefore, the maximum allowable scarf angle was ~11° (i.e., 1/5 scarf ratio for a 13.2-mm-thick adherend). Three scarf angles were investigated using our test methods. The angles included 45 (1/1 scarf ratio), 18.4 (1/3 scarf ratio), and 11.3° (1/5 scarf ratio).

Twenty backing plates, 889 mm long and 30 mm large, were fabricated by the VARTM process (*5*) and used for the characterization of the static and ballistic performance of the repairs. Two backing plates were kept virgin and tested as control beams. Eighteen beams were machined to receive the scarf patch repairs, two beams for each repair adhesive and scarf angle combination. For the repair, a distance equal to 101.6 mm separates the lower tips of the scarf, as shown in figure 3b. The placement of the repair patch only required that the surfaces in contact be completely wetted with the repair adhesive. The repair stack was then placed in a vacuum bag for hardening of the repair adhesive.

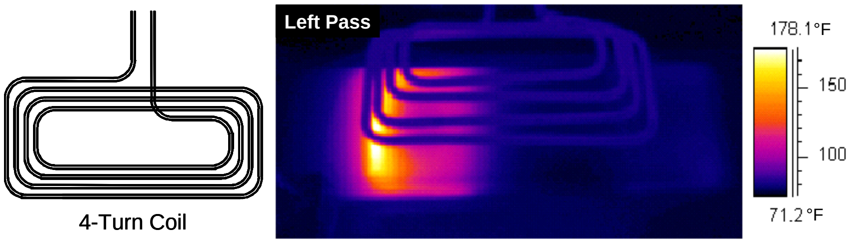
The backing plates repaired using the elevated-temperature cure Hysol adhesives were cured by induction-heating technique as described in the next section. The Plexus repaired beams were cured at room temperature. The quality of the control and repaired beams was visually observed to be very good.

4. Induction Repair

Induction heating is a noncontact method by which electrically conductive materials (susceptors) are heated in an electromagnetic field. This technique has successfully heated multiple interfaces as shown in figure 1 in a single-step operation, with the use of appropriately placed susceptors (*14*). A stainless steel mesh susceptor, with a wire density of $5 \times 5/\text{cm}^2$ and a wire diameter of 0.165 mm, was used in the present study. The stainless steel mesh was cut to the shape of the area to be bonded, cleaned with acetone, impregnated with adhesive, and then placed in the bond area between the parent and patch laminate (which was also covered with adhesive). The stack was then vacuum bagged and placed horizontally under the induction coil at an optimal stand-off distance. The power setting of the induction generator, the coil shape (see figure 5), and the coil stand-off distance were selected for uniform heating of the bond line to the adhesive cure temperature. This relationship was established experimentally by using an actual repair backing plate that incorporated the susceptor mesh wrapped in a Kapton[*] film to allow multiple heating cycles. A two-turn rectangular coil was used for the fabrication of the 45 and 18.4° scarf repair as shown in figure 5a. A four-turn spiral coil (shown in figure 5b) was used for the fabrication of the 11.3° scarf repairs. The 11.3° scarf repairs were bonded in two passes, in order to ensure a complete coverage of the bond area with the induction-heating field. The stack was placed underneath the induction coil at a selected distance, and the power was increased from 50% to 100%, in 10% increments. Process temperatures were recorded with a thermal camera and an embedded thermocouple.



(a) two-turn coil used for 18.4° scarf repair and temperature profile



(b) four-turn coil used for 11.3° scarf repair and temperature profile

Figure 5. Induction-heating of the elevated-temperature cure adhesives.

An AGEMA Thermo-vision[†] 900 thermal camera was positioned in front of the setup to capture the full-field surface temperature of the bond area in real time. An E-type thermocouple was placed at the susceptor/adherend interface to monitor the internal bond-line temperature. The bondline temperature was slightly higher than the surface temperature due to heat losses. Steady-state was reached in a few minutes for each increment in power. Once a susceptor steady-state temperature of ~82 (i.e., the cure temperature of Hysol EA9359.3) and 66 °C (i.e., the cure temperature of Hysol EA 9394) was achievable within the range of the power

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[*] Kapton is a registered trademark of DuPont.

[†] Thermo-vision is a registered trademark of AGEMA Company.

settings, the stand-off distance was recorded, and this combination was used for further bonding trials. The steady-state surface temperatures, recorded from the thermal camera, are presented in figure 5 for the 18.4° scarf and the 11.3° scarf repairs.

5. Static Performance of Scarf-Repaired Composite Beams

The load-deflection behavior of all the specimens tested was observed to be linear elastic until failure. Because the span-to-thickness ratio of the beams was large (i.e., 57.7), classic beam theory was used to experimentally determine the bending stiffness per unit width of the beams under four-point bending.

$$E_f I / b = (P / D_1) \cdot (L^3 / 96) / b \,, \tag{1}$$

where E_f is the flexural modulus, I is the moment of inertia of the cross section, P and D_1 is the instantaneous load and cross-head displacement in the linear-elastic region, L is the length of the support span, and b is the width of the beam. A comparison of the bending stiffness of the control beams with that of the repaired beams is presented in table 1. Results showed a 100% renewal of structural stiffness was attainable with the elevated-temperature cure repair adhesives. However, the room-temperature cure repaired backing plates were more compliant by ~15% due to the lower modulus of the Plexus adhesive (i.e., 0.345 vs. 2.2 GPa for EA9359.3NA). Because stiffness is typically the critical design parameter for composite armor structures, the lower stiffness of the Plexus repaired beams may prevent the use of the Plexus adhesive for repair of composite armor. However, it should be pointed out that the stiffness loss in a 3-D scarf repair is likely to be less than that measured in the 2-D beam specimen.

Table 1. Bending stiffness (per unit width) of the repaired backing plates.

Repair Type	**Bending Stiffness (kN-m)**
Undamaged	5.75
Elevated-temperature cure repaired	5.75
Room-temperature cure repaired	5.00

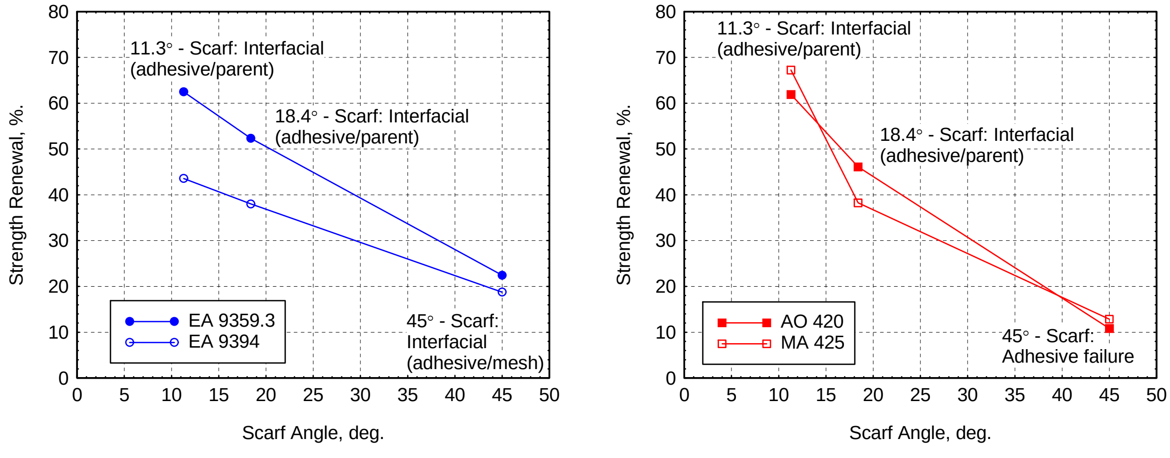
The strength renewal of repaired beams was evaluated using the ratio of moment capacity of a repaired beam to that of the control beam. The two baseline specimens (i.e., no repair) failed at an average bending moment of 8.79 kN-m/m (per unit width). The failure mode was observed to be a compressive failure of the fibers on the specimen surface layer. This failure mode did not cause catastrophic failure of the beam, and only a minor change in compliance resulted. However, the moment capacity at the onset of damage was used as the baseline for quantifying the effectiveness of the repairs. The bending moment at failure of all the repaired backing plates tested is summarized in table 2. The values given are an average value from two beams tested with minimal variation. In general, a major reduction in the moment capacity was observed and

Table 2. Bending moment at failure of the repaired baking plates.

Bending moment at failure / unit width (kN-m/m)[a]				
	Hysol EA9359.3NA	**Hysol EA9394**	**Plexus MA425**	**Plexus AO420**
45° scarf (1/1)	1.97	1.65	1.13	0.95
18.4° scarf (1/3)	4.60	3.34	3.36	4.05
11.3° scarf (1/5)	5.49	3.83	5.91	5.44

[a] To be compared with that of control beams, i.e., 8.79 kN-m/m.

was strongly dependent on scarf angle and adhesive type. Furthermore, the repaired beams failed suddenly at the adhesive bond line (in contrast to the progressive failure of the baseline). The extent of strength renewal (i.e., renewal of bending moment capacity), with respect to scarf angles and repair adhesives, is shown in figure 6a and 6b and ranges from 10% to 60%. The strength renewal of the induction-cured Hysol adhesives is shown in figure 6a. The repair efficiency of the 45° scarf angle was low (~20%) and was almost independent of the adhesive system used. The structural performance of the 18.4 and 11.3° scarf angles improved significantly as the scarf angle was reduced. It is observed in figure 6a that the Hysol EA9359.3 repaired beams restored as much as 62% of the control strength of the backing plates, compared with only 43% for the beams repaired with the EA9394 adhesive. The improved performance of the Hysol EA9359.3 may be attributed to the higher elongation and toughness of this adhesive system. In a recent study (*15*), induction-cured EA9359.3 single-lap shear joints tested in tension and four-point bending were also shown to be stronger and tougher than similar EA9394 joints.



(a) Elevated-temperature cure adhesive, Hysol. (b) Room-temperature cure adhesive, Plexus.

Figure 6. The renewal in static strength of the repaired backing plates.

The loci of failure of the repaired backing plates were, nevertheless, found to be similar for both elevated-temperature cure repair systems. The 45° scarf-repaired beams were seen to fail by an interfacial failure at the adhesive/metal mesh interface. Decreasing the scarf angle to 18.4°

resulted in a slight change in the failure mode, and the locus of failure was observed to be interfacial, but 50% between the metal mesh susceptor and the adhesive (top end of the scarf), and 50% between the adhesive and the parent (lower end of the scarf). The 11.3° scarf-repaired beams failed by an adhesive/parent interfacial failure. Some adherend failure was also observed to have occurred.

The strength renewal with respect to scarf angle for the Plexus adhesives is shown in figure 6b. The structural performance was mainly dependent on the scarf angle because the adhesive properties were similar. The repair efficiency was slightly lower (~10%) for the 45° scarf angle compared to the Hysol adhesives. However, the repair efficiency increased to 40% and 65% for the 18.4 and 11.3° scarf-repaired backing plates, respectively. This level was comparable to that of the induction-cured EA9359.3NA repaired backing plates. The locus of failure of the 45° scarf was in the adhesive. Decreasing the scarf angle to 18.4° promoted a mixed, adhesive/interfacial failure. The 11.3° scarf-repaired backing plates failed by interfacial failure. In summary, the 11.3° scarf angle enabled renewal of moment capacity approaching 65% of the static baseline. This range of scarf angles is considered practical for the repair of thick-section backing plates used in structural armor.

6. Dynamic Axial Compression of Scarf-Repaired Composite Plates

Dynamic axial compression of scarf-repaired composite specimens was performed using the Hopkinson bar technique. The Hopkinson bar responses for Hysol EA9359.3 adhesive repaired specimens are presented in figure 7. All of these specimens failed under dynamic loading. At lower impact velocity, a rubber pulse shaper generates an incident pulse that is almost triangular in shape. The incident pulse becomes trapezoidal in shape at higher impact velocities. The 11.3° scarf specimens did not fail when the pulse shaper was used, and thus these tests were performed without a pulse shaper.

The incident, reflected, and transmitted pulses were used to calculate the forces at the incident bar-specimen (IB-S) and specimen-transmitter bar (S-TB) interfaces, F_1 and F_2, respectively, following the procedure described in reference (*12*). The condition of stress equilibrium was checked using the nonequilibrium parameter, $R = 2(F_1 - F_2) / (F_1 + F_2)$ (*15*). Figure 8 shows the bar-specimen interface forces and the nonequilibrium parameter calculated for the 45 and 11.3° specimens (bar responses presented in figure 7). Stress equilibrium ($R = 0.09$) was achieved in the 45° specimen only at maximum/failure load. However, better stress equilibrium was achieved in the 11.3° specimen ($R = 0.06$ at failure). The average maximum force, $F_{\max}$, was used to calculate the average axial strength of the specimen. Because the thickness of the adhesive bond is small as compared to the length of the incident bar, it is assumed that a volume element in the adhesive layer is under stress equilibrium (see figure 9). The axial strength was then transformed into normal and shear stresses along the failure plane (figure 9b).

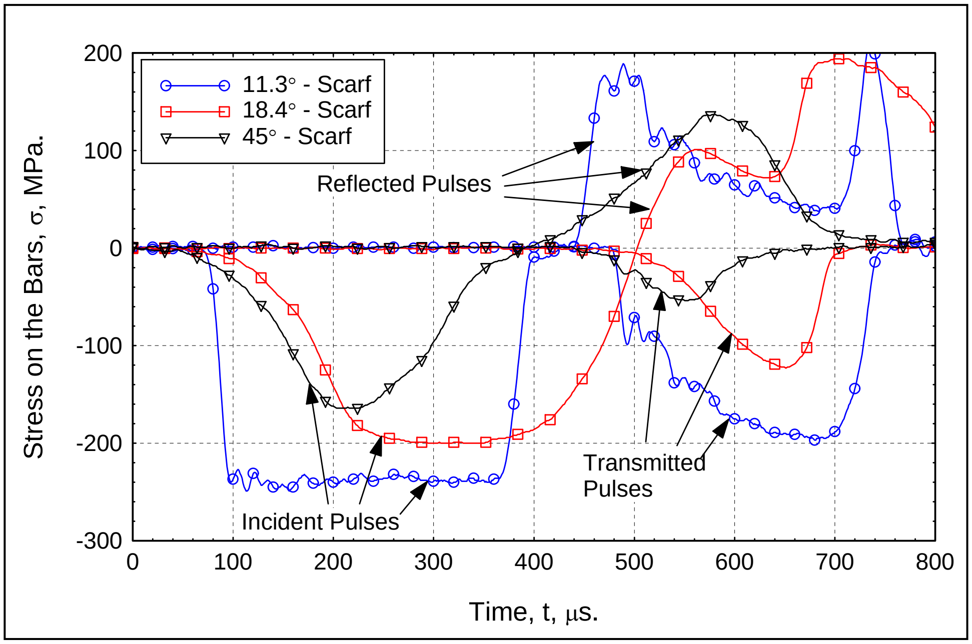
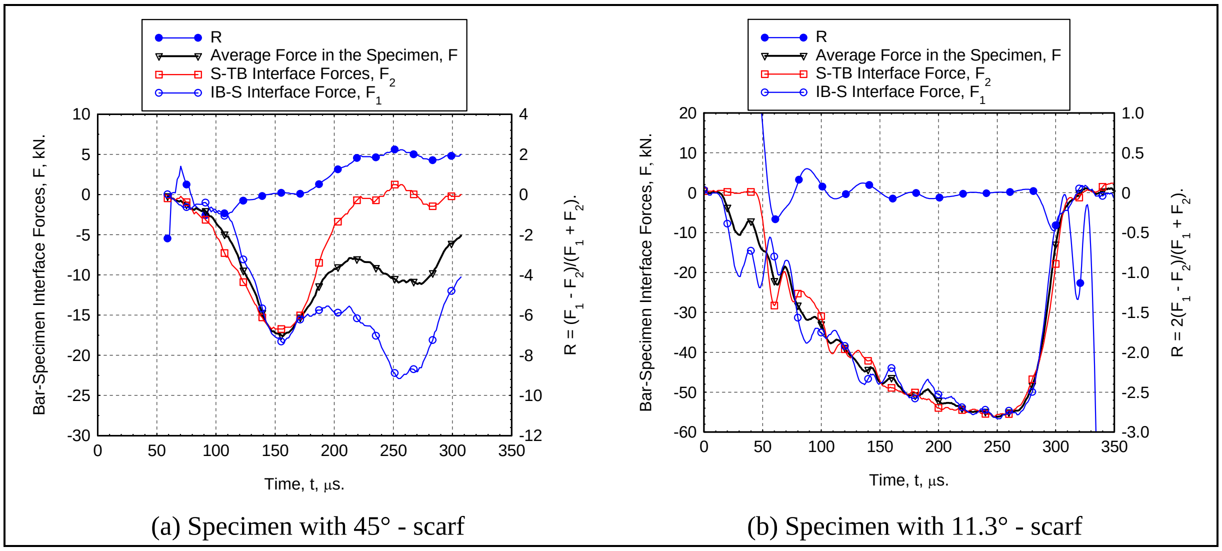


Figure 7. Hopkinson bar responses of Hysol EA9359.3 induction-cured scarf-repaired composite specimens under axial compression.

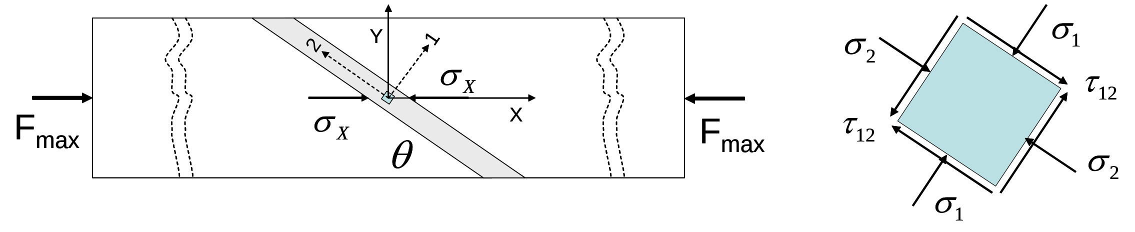


(a) Specimen with 45° - scarf

(b) Specimen with 11.3° - scarf

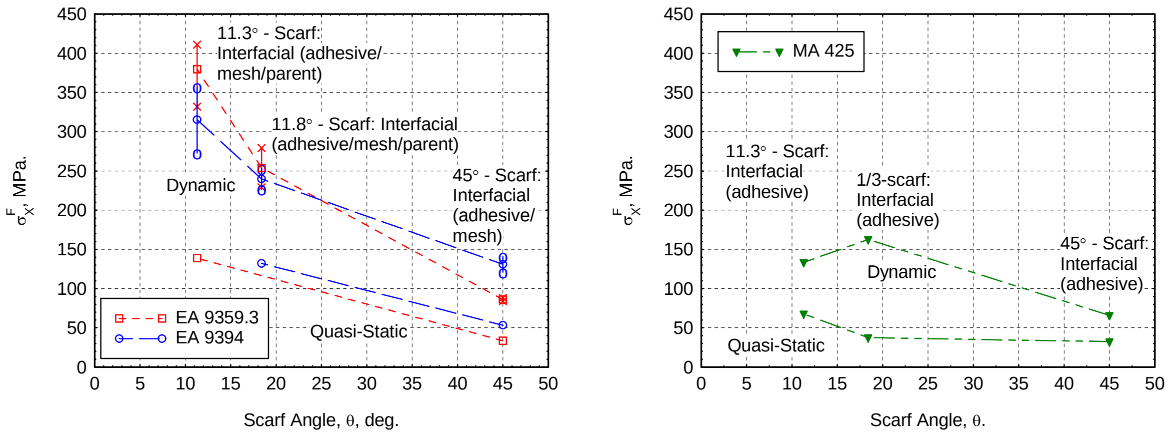
Figure 8. Stress equilibrium in Hysol EA9359.3 scarf-repaired composite specimens.

Figure 10 shows a plot of axial strength of the specimen as a function of scarf angle for quasi-static and dynamic loading cases for the various adhesives. One important observation from these tests is that the dynamic axial strengths of the scarf joints were higher than the quasi-static axial strength by a factor of 2-3 for each scarf angle. The influence of scarf angle was similar to the results shown in figure 5 for the four-point beam tests. The dynamic axial strength increased as the scarf angle decreased, for all adhesives under dynamic and quasi-static loading conditions (with the 11.3° scarf-repaired Plexus MA425 specimen being the exception).



(a) Notations (b) Volume Element

Figure 9. Stress analysis of scarf-repaired composite specimens under dynamic axial compressive load.



(a) Elevated-temperature cure adhesive, Hysol (b) Room-temperature cure adhesive, Plexus

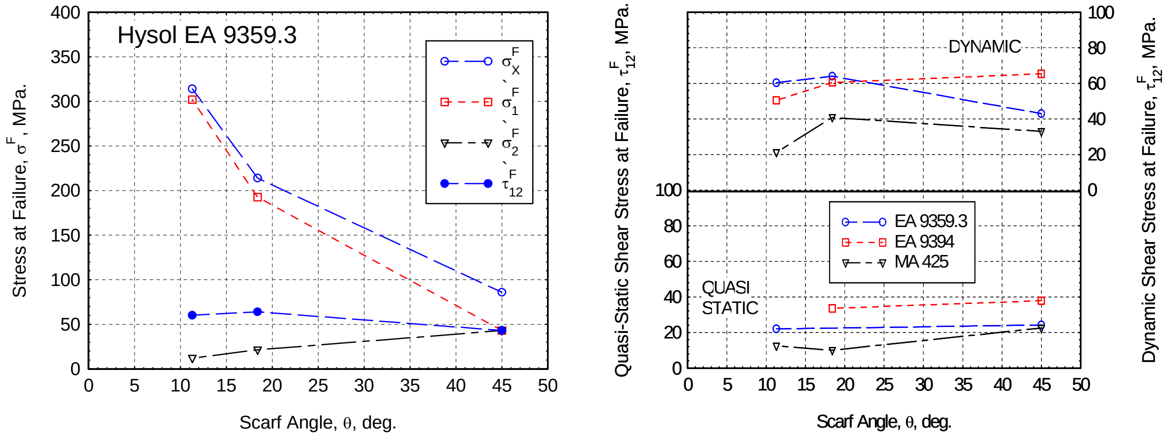
Figure 10. Axial compressive strength of scarf-repaired composite specimens under dynamic compressive load.

The loci of failure were found to be 50% in the adhesive/metal mesh interface and 50% between the adhesive and parent material in the case of Hysol adhesives (figure 11a), except for the 45° scarf for which the failure was 100% in the adhesive metal mesh interface. In the case of the Plexus adhesive joint, the loci of failure were found to be in the adhesive (figure 11b). These failure patterns were very similar to those obtained from quasi-static four-point bend tests.

(a) Hysol EA 9359.3 (b) Plexus MA 425

Figure 11. Fracture surfaces of scarf-repaired composite specimens under dynamic axial compression.

The axial compressive strength for the Hysol 9359.3 adhesive together with the transformed stresses in the scarf plane are presented in figure 12a. Results showed that the adhesive bond was subjected to normal compressive stress that varied significantly with the scarf angle. However, the shear stress was relatively constant in the range of 40–60 MPa. This suggested that the failure was governed by the shear stress component. In figure 12b, shear stresses of various adhesives are compared in case of static and dynamic loads. The results showed that the dynamic shear stresses at failure were significantly higher than those obtained under static loading. Furthermore, the Hysol adhesives offered higher dynamic shear strength compared to the Plexus adhesive.



(a) Stresses at failure

(b) Shear stresses at failure

Figure 12. Stresses at failure in the rotated coordinate system of the scarf-repaired composite specimens.

7. Conclusions

The scarf patch repair scheme used in the present study is viable for level III repair of composite structural armor. The scheme uses practical scarf geometries for thick-section applications, requires only one-sided access for repair and vacuum consolidation, and provides rapid heating via induction to cure adhesives at elevated temperatures. The repair procedure was demonstrated using four adhesive systems. Simple test methods were proposed to apply realistic static and dynamic loads to composite backing plates with scarf repairs.

The repair efficiency of scarf repairs, having scarf angles much greater than commonly used in aerospace applications, was assessed in a four-point bending test. The baseline behavior exhibited compression failure on the specimen surface followed by progressive failure. Scarf-repaired beams failed catastrophically in the adhesive bond, while the virgin specimens exhibited a progressive compressive failure of the fibers on the specimen surface layer. This difference in failure mode may indicate that the inherent energy-absorbing mechanisms of the composite were limited by the repair.

The results, however, have shown that complete renewal of stiffness is achievable for the elevated temperature cure adhesives (a slight reduction of 15% is measured for the low modulus adhesive). The degree of strength recovered (based on first damage in the baseline) from the repairs increased from ~10% to 20%, to 40%, and 60% for the 45, 18.4, and 11.3° scarf repairs, respectively.

In the dynamic experiments, scarf-repaired composite backing plates were subjected to compression loading using the SHPB. The dynamic axial strength for all adhesives was higher than the corresponding quasi-static data by a factor of 2-3 for each scarf angle. The dynamic axial strength increased as the scarf angle decreased, consistent with the four-point bend tests. The results showed that the dynamic shear strength in the scarf plane was also rate dependent and significantly greater than the static strengths. Higher rate impact testing is needed to fully characterize the strength and energy absorption capabilities of the scarf repair.

Based on the limited results generated for the adhesives considered in the present study, induction curing of Hysol EA9359.3 with a 11.3° scarf offered the best combination of structural and rate-dependent properties.

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