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Development of a pultruded FRP composite material ROPS for farm tractors

John R. Etherton, Mahmood Ronaghi, Richard S. Current*

Division of Safety Research, National Institute for Occupational Safety and Health, Morgantown, WV 26505, USA

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Abstract

The goal of this research was to explore the feasibility of fabricating a fixed-structure ROPS (rollover protective structure) for farm tractors from an FRP (fiberglass reinforced plastic) composite material. Evaluating the strength of proposed joint designs for the base and the upper corners of the FRP ROPS was the focus of this study. Three factors were investigated: base fixture strength for connecting the ROPS to the tractor, upper corner fastening strength, and FRP failure mechanisms under static loading. Results indicate the need for a well-bolted mounting connection. Also, the failure modes at bolted upper corners of an FRP ROPS were related to where bolt holes are located. Additionally, long cantilever beams similar to the vertical members of a ROPS absorbed energy well without significant lengthwise fiber failure. Failures observed were only at the base, rather than in the localized matrix failure that occurs at the loading point of shorter beams. When the full ROPS was loaded to failure, it exhibited three shear breakthroughs of matrix material at bolt holes before reaching its ultimate load strength at 53,370 N (12,000 lbf). An ultimate performance comparison to be evaluated is whether an FRP ROPS has equal or better impact energy absorption performance than a steel ROPS and whether it deflects no further than a steel ROPS element with an acceptable amount of deformation. Damage tolerance that takes into account changes in strength of an FRP ROPS due to tools and other objects striking it must be considered. With appropriate impact characteristics factored into a design, the value of FRP composites for ROPS is expected to reside in longevity and lower manufacturing costs.
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Keywords: Fiberglass reinforced plastic; Agriculture; ROPS; Testing

1. Introduction

Pultruded composites are being used increasingly in agricultural products to take advantage of their convenient shapes, resistance to corrosion, and high strength-to-weight ratios. Since cost is a major design criterion for agricultural products, the relatively good cost-weight ratios for pultruded structural shapes have been a plus. In current research, the substantial energy impact absorption capabilities of pultruded composites are being investigated toward their possible use in rollover protective structures (ROPS) for farm tractors (Fig. 1).

Agricultural tractor rollovers kill between 75 and 180 people each year in the United States (National Safety Council [1]). ROPS, with the operator wearing a seatbelt, are the most effective method for preventing these deaths. Many tractors still do not have ROPS. A composite ROPS with lower shipping weight and lower fabrication cost, and that is easier to use in manual deployment would help get more ROPS on these tractors. Another new method for increasing the use of ROPS is the NIOSH automatically deployable telescoping ROPS (AutoROPS) [2]. One concern with this new technology is reducing the weight of the upper structure; thereby permitting a less bulky deployment mechanism.

Pultrusion is a continuous process for manufacturing composites that have a constant cross-sectional shape. This process consists of pulling a fiber-reinforcing material through a resin impregnation bath and through a shaping die, where the resin is subsequently cured. Composite pultrusions have been increasingly used in automotive applica-

* Corresponding author. Fax: +1 304 285 6047.
E-mail address: rcurrent@cdc.gov (R.S. Current).

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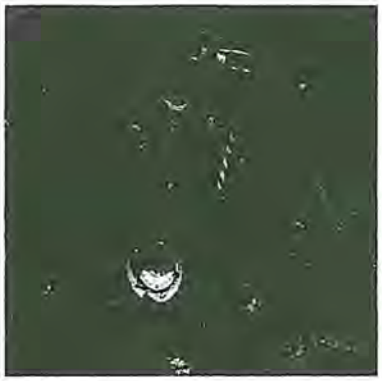

Fig. 1. The ROPS has prevented the tractor from crushing the driver (manikin).

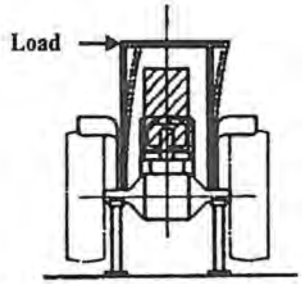

Fig. 2. Transverse loading for ROPS test SAE J2194.

tions over the last three decades. Civil engineering applications include causeways and pedestrian bridges [3]. The cost benefits of using pultruded composites include: (1) highly skilled labor is not required to cut and fasten lengths of pultruded material and (2) minimal material is removed (just drilled holes and sanded surfaces for adhering).

Applications of pultruded FRPs in agriculture are numerous. Fiberglass ladders were originally developed for electrical utilities but have increasingly gained acceptance for general industry and residential use. Fiberglass now holds a significant market share of industrial ladders and is steadily replacing aluminum and wood in residential ladders. Fiberglass ladders are stronger than wood or aluminum ladders and will not absorb water, rot or corrode. Fiberglass tool handles have increasingly gained acceptance for tools used by farmers. Fiberglass tool handles are designed for a variety of implements including shovels, rakes, hoes, pruners, and post hole diggers. Combining heavy gauge steel tool implements with pultruded fiberglass handles results in tools that are strong and durable.

The purpose of this paper is to describe initial tests on pultruded composite components of a ROPS made from composite materials. Design considerations for a ROPS made from pultruded material are presented first, followed by a description of tests on prototype ROPS made from pultruded material and results of these tests.

2. Background

ROPS must satisfy the energy absorption criteria of SAE J2194 [4]. The standard provides for either static or dynamic energy application tests, with similar results expected whether the test is performed in a static or a dynamic fashion. The purpose of SAE J2194 static testing is to simulate, with slowly applied loads, the variety of dynamic loads encountered in various types of overturns (90° rearward; 90° sideways; 180° all-wheels-up). The laboratory test is designed so that the energy that the structure absorbs during slow loading will be equivalent to the energy that would be absorbed if the structure impacted the ground in an overturn. The transverse loading application region of a two-post ROPS is at the uppermost side member and the energy requirement is 1.75 times the tractor's mass. For the transverse loading (Fig. 2) on a test tractor, greater than 1341 J (11,861 in lb) of energy transfer is common [5]. Steel has limited ability to absorb energy in the plastic range, because ultimate failure soon follows. The minimum Charpy impact strength for a 10×10 mm steel ROPS specimen is 110 kJ/m^2 (SAE J2194 [4]). Composites, on the other hand, exhibit considerable energy absorption capability as they undergo deformation in the damage zone. For composites, the term "plastic" deformation is not appropriate. The preferred term is "damage zone" Composites in general do not exhibit much nonlinear behavior before failure. Popular models treat composites as "linear progressively fracturing solids" [6].

Cheon et al. [7] investigated the use of FRP for side-door impact beams for passenger cars. For their dynamic tests (1100 J), the composite impact beam had better impact energy absorption capability than the high strength steel impact beams. Caliskan [8] provides the following guidelines for designing composite structural elements for crashworthiness:

Fiber architecture	lay fibers for axial strength to achieve progressive crushing and hoop strength so that microbuckling occurs rather than global buckling
Fiber and matrix	the matrix should have a higher strain to failure than the fiber
Geometry	circular tubes have better energy absorption than rectangular and square tubes

He points out that because of the various failure modes of composites there is no finite element analysis (FEA)-based code that can predict the energy absorption of composite structures.

In addition to the good stiffness and strength characteristics of composites, these materials possess very good energy impact absorption capability (see Table 1). When the structure begins to permanently deform, progressive crushing absorbs additional energy at a nearly uniform rate. To correctly characterize the impact properties of

Table 1
Properties of high strength steel and glass–fibre-epoxy composites

	High-strength steel (AISI 4340)	Glass–fibre-epoxy composites
Charpy impact (kJ/m^2)	214	622
Density (kg/m^3)	7870	1980

composites, the *specific energy absorption* rather than the *absolute energy absorption* should be quoted.

The specific energy absorption (SEA) of a longitudinally crushed tube is given by:

$$\mathrm{SEA} = \frac{\int_{L_c} P\,\mathrm{d}x}{m\frac{L_c}{L}}$$

where the integral is the area under the load–displacement curve of a crushed member, m is the mass of the tube, L is the total length, and L_c is the crushed length. For impact loading of cantilever beams, deflection per unit length due to crushing and mass are components of specific energy absorption on the crushing side of the neutral axis.

2.1. Progressive growth of damage

For composite strength analysis, it is necessary to account for microdamage and growth and accumulation. In bending, crushing failure occurs at one outer surface of the member. This can take the form of fiber microbuckling on the compression side. Fiber volume fraction is indicative of the failure mode in tensile loading [9]. This is similar to the situation in metals where accurate predictions of strength must account, in general, for plastic yielding [10]. Unlike metals, that are best evaluated by their fracture mechanics in tensile loading, laminated composites are best understood by examining their performance under compressive loading.

2.2. Damage tolerance and acoustic emission (AE) analysis

In normal use, it is likely that the ROPS would be struck by tools or other equipment. The size of flaws caused by damage varies by amount of loading force and type of composite material. Static indentation results of force versus damage size have been found to agree well with impact data [11]. The types of flaws or damage to be evaluated are penetrations, delaminations, and low-velocity impact damage. Damage tolerance needs to be factored into the design so that undetectable damage can be tolerated over the life of the ROPS. Structural efficiency must keep stresses low enough to allow for some detectable damage.

One avenue to be followed in the analysis of damage tolerance is acoustic emission (AE) measurement. The basic mode of operation for AE detection is simple. Small stress waves excite a piezoelectric transducer. The amplified signal is then conditioned, recorded, and analyzed. Prosser [12] has reported that modal acoustic emission measurement may be a means for pinpointing damage location and mechanism (flexural versus extension). His studies have focused on delamination of cross-ply composite coupons. Because his results are not yet generalizable to pultruded coupons, AE testing will be conducted to identify location and mechanism of damage in a pultruded structure.

Characteristic AE waveforms are associated with matrix cracks, fiber breaks, and 'macro-damage' respectively [13]. AE rate generally correlates with the rate of stiffness reduction due to damage. AE counts accumulate as a function of tensile stress.

3. Conceptual design

The ROPS under development is a planar frame that can be mechanically connected to the tractor axle housing. The frame creates an operator's clearance zone (OCZ) into which the ground plane cannot impede during the ground impact of a rollover. While within the OCZ, the seatbelted operator is protected from potentially fatal energy transfers during a rollover. In the concept developed at NIOSH, the base fixture design incorporates internal and external steel elements that grip the vertical pultruded post with bolts and adhesive (Fig. 3). This conforms to recommendations from the pultrusion manufacturer that a bolt and adhesive combination yields the strongest connection, with a high level of reliability. The properties of the FRP material analyzed and tested are shown in Table 2.

A building block approach toward full-scale testing of a prototype was followed, using manufacturer's material properties specifications to analyze the component and prototype design.

4. Finite element analysis procedure

Finite element (FE) modeling [14,15] was conducted to simulate a short and a long single-post FRP roll bar. In the analysis, these cantilever beams were subjected to 22,240 N (5000 lbf) loading at the free end. An FE model of a two-post ROPS made from 15.2 cm (6 in.) by 15.2 cm (6 in.) by 4.8 mm (0.187 in.) wall FRP was also developed. A 22,240 N (5000 lbf) load was applied to the model to predict deflection due to quasi-static loading

Fig. 3. Base fixture components.

Table 2
Properties of the FRP material used in this study

Modulus of elasticity, GPa (Mpsi)	$E_1 = 18$ (2.6)	$E_2 = 5.5$ (0.8)	$E_3 = 5.5$ (0.8)
Poisson's ratio, mm/mm (in./in.)	$\nu_{12} = 0.33$	$\nu_{13} = 0.33$	$\nu_{23} = 0.33$
Shear modulus, GPa (Mpsi)	$G_{12} = 2.9$ (0.43)	$G_{13} = 2.9$ (0.43)	$G_{23} = 2.9$ (0.43)
Axial strength, MPa (kpsi)	$x_T = 210$ (30)	$x_C = 210$ (30)	
Transverse strength, MPa (kpsi)	$y_T = 48$ (7)	$y_C = 103$ (15)	
Shear strength, MPa (kpsi)	$s_{xy} = 31$ (4.5)		

according to SAE J2194. ANSYS is the commercial FE package used for numerical stress analyses. Details of the ANSYS modeling are presented in Ronaghi [16].

5. Lab test procedures

Three design elements were selected for evaluation: strength of an FRP-to-steel base fixture for attaching the ROPS to a tractor; an FRP post's bending strength; and strength of a bolting pattern for connecting the vertical posts to the cross-bar of the ROPS. The three tests that were performed were: base fixture failure test, cantilever beam failure test, and upper corner joint failure test. Testing composite elements differs from testing isotropic material (metal) beam elements in that shear stresses (or strains) and deformations which depend on fiber orientation must be taken into consideration. Specimens, with all joints bonded and cured to manufacturer specifications, were tested to the ultimate load; a normal practice with composite structures. An adequately slow rate of loading (0.5 mm/s) was used for static tests. All static loading tests were run via a QuickBASIC program and PC link to an MTS MicroProfiler under displacement control. The program constantly computed the total energy applied, based on the area under the force–deflection plot. Loading was provided by a 88,960 N (20,000 lbf) capacity MTS hydraulic actuator. Fig. 4 shows the apparatus used to conduct the base fixture failure test and the cantilever beam failure test for the FRP ROPS.

5.1. Base fixture failure test procedure

The first round of tests focused on the base fixture (Fig. 4). A 91.4 cm (36 in.) long × 15.2 cm (6 in.) OD by 3.2 mm (0.125 in.) wall thickness FRP post was connected to an 8-bolt fixture. The post was bolted and bonded to the fixture that was then bolted to the testbed. An 88,960 N (20,000 lbf) hydraulic actuator was used to load the composite post. Load pads were used to prevent local crushing. The test was then repeated with a 16-bolt fixture.

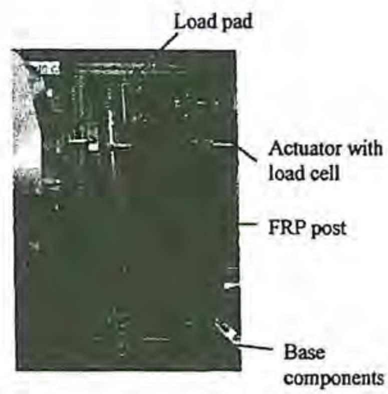

Fig. 4. FRP ROPS development apparatus.

5.2. Cantilever beam failure test procedure

A slowly increasing load was applied to the free end of a short (61 cm (24 in.) long by 15.2 cm (6 in.) OD FRP) tube (3.2 mm (0.125 wall)) mounted in a 16-bolt fixture. Then a long (106.7 cm (42 in.) long by 15.2 cm (6 in.) OD FRP) tube (3.2 mm (0.125 wall)) was mounted in a 16-bolt fixture test and the cantilever loading was repeated (Fig. 4).

5.3. Upper corner failure test procedure

A two-post ROPS was fabricated from 15.2 cm (6 in.) by 15.2 cm (6 in.) by 4.8 mm (0.187 in.) wall FRP (Fig. 5). The

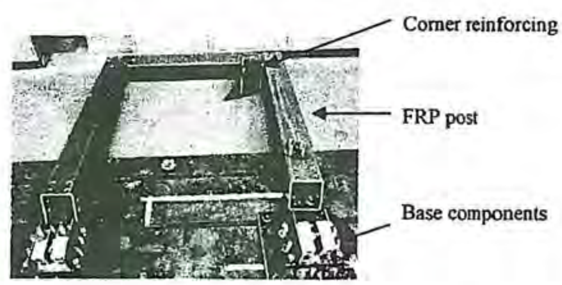

Fig. 5. The FRP ROPS before assembly.

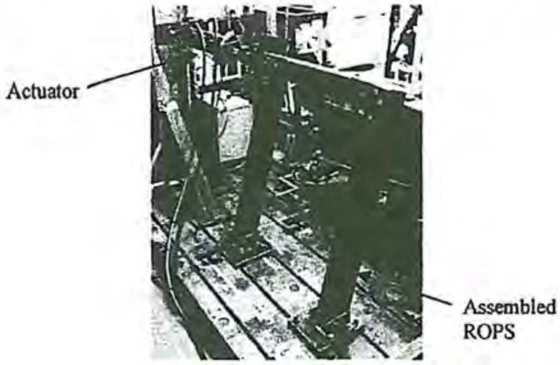

Fig. 6. The FRP ROPS assembled and the actuator ready to apply the load.

upper joint was formed by bolting (3/4 in.—12 bolts) and adhering triangular steel support plates to each face of the mitered joint. The base fixture consisted of an internal block welded to the base plate. The box beam was pressed snuggly into its upright position over the block. The FRP posts were then bolted (3/4 in—16 bolts) and adhered to the base fixture. A slowly increasing (0.5 mm/s) load was applied transversely to the upper corner of the FRP ROPS (Fig. 6).

6. Testing and modeling results

6.1. Base fixture failure test

The first round of tests focused on the mounting fixture. A 91.4 cm (36 in.) long × 15.2 cm (6 in.) OD tube (3.2 mm (0.125 wall)) was connected to an 8-bolt fixture. For a low level of cantilever loading (25,000 N), the steel outer plate of the base fixture failed (Fig. 7). In the second trial, with a 91.4 cm (36 in.) long × 15.2 cm (6 in.) OD tube (3.2 mm (0.125 wall)) connected to a 16-bolt base fixture, the base fixture did not fail (Fig. 8). Fiber tensile failure did occur in the attached FRP tube.

6.2. Cantilever beam failure test

For these tests, results are stated in terms of the failure modes of cylindrical FRP tubes of different lengths. For the 61 cm (24 in.) long by 15.2 cm (6 in.) OD FRP tube (3.2 mm (0.125 wall)) mounted in a 16-bolt fixture, the base survived. Vertical splitting of the matrix near the top of the tube was the primary failure mode, with a small amount of tensile fiber failure observed at the base (Fig. 9). The upper failure was due to exceeding the resin strength since the break was parallel to the fiber direction while just beginning to reach the tensile strength of fibers.

For the 106.7 cm (42 in.) long by 15.2 cm (6 in.) OD FRP tube (3.2 mm (0.125 wall)) mounted in a 16-bolt fixture test, the base also survived. The observed ultimate failure was a longitudinal fracture near the base at 45° from the tensile load direction. After the load was released, the top of the post remained deflected in a plastic set of 20.3 mm (0.8 in.) (this corresponds to an angle of 0.8 degrees). Fig. 10 shows the relatively close comparisons between FEA predictions and actual results for force–deflection response of the long tube when loaded to failure. The difference in the FEA results for the short tube resides in the shear failure mode not being fully accounted for in the model.

6.3. Upper corner joint failure test

When the full ROPS was loaded to failure (Fig. 11), it exhibited three shear breakthroughs of matrix material before reaching its ultimate load strength at 53,370 N (12,000 lbf) (Fig. 12). The failures that were occurring happened due to pull-out and hinging at the base fixture (Figs.

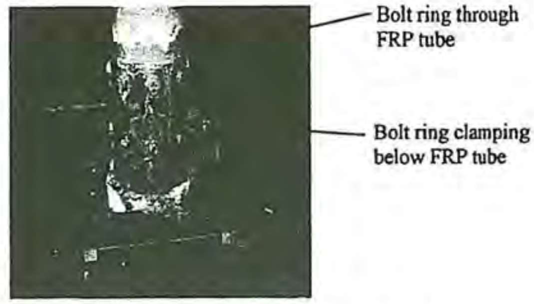

Fig. 8. The 16-bolt base fixture did not fail.

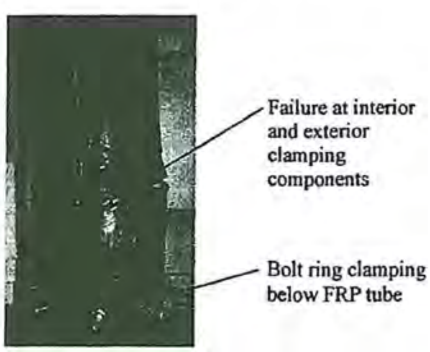

Fig. 7. Failure of the 8-bolt base fixture.

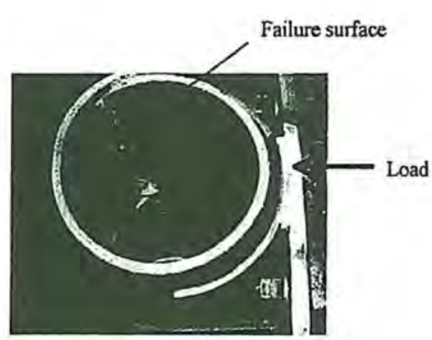

Fig. 9. Matrix failure on the short cantilever tube.

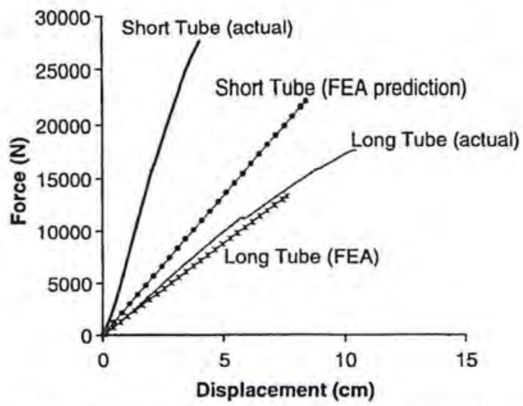

Fig. 10. Finite element analysis predicted force–displacement behavior of short and long single-post FRP ROPS.

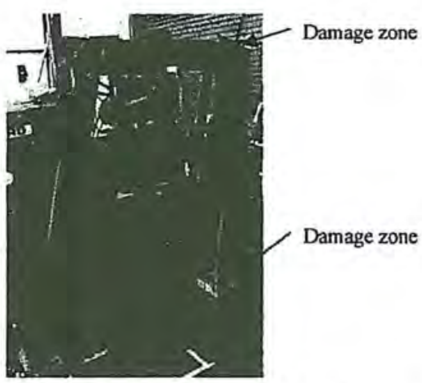

Fig. 11. The FRP ROPS after loading to failure.

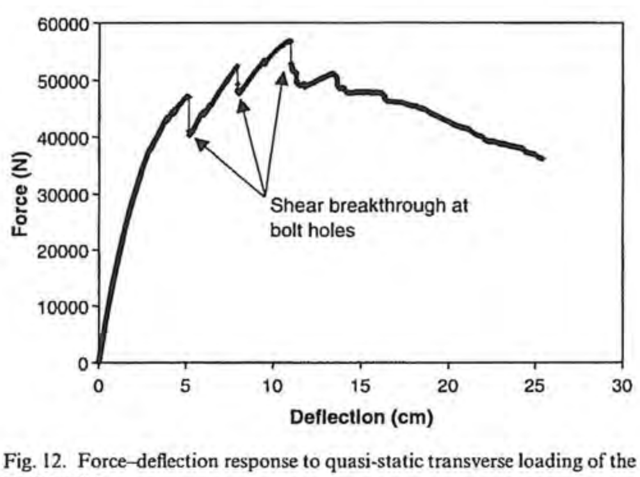

Fig. 12. Force–deflection response to quasi-static transverse loading of the FRP ROPS.

13 and 14) and due to split-out at bolt contact areas on bolt holes in the upper corner (Figs. 15 and 16).

The nature of ROPS testing is that "design load" is established by the permitted amount of structural deflection. This deflection is the limit beyond which the ground

Fig. 13. Base fixture before loading.

Fig. 14. Base fixture after loading.

Fig. 15. Upper joint before loading.

plane penetrates the occupant clearance zone that provides protection to a seatbelted operator of an overturned tractor (SAE J2194 [4]). In this test, the deflection of the full FRP ROPS at 50,260 N (11,300 lbf) was 12.7 cm (5 in.). In previous tests performed at NIOSH on a commercially available steel ROPS, the transverse loading needed to achieve a 12.7 cm (5 in.) deflection was 35,580 N (8000 lbf). Comparing the FRP ROPS to its steel counterpart, the FRP ROPS had a 1.41 Factor of Safety [11,300/8000] based

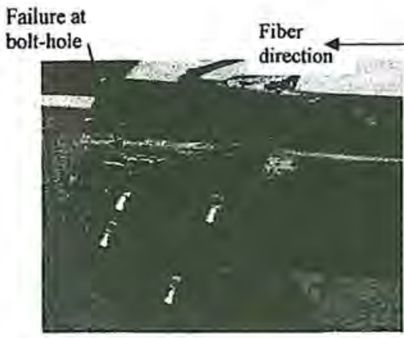

Fig. 16. Upper joint after loading.

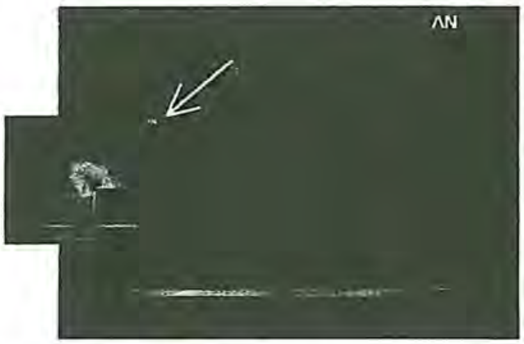

Fig. 17. FEA stress plot for a ROPS made from 6″ × 6″ × 3/16″ FRP. The high stress area is enlarged.

on the "design load" established in testing a steel ROPS for the same tractor model.

The results of the initial FEA modeling were that the upper corner would be the most highly stressed (60,000 psi) region with a 22,240 N (5000 lbf) load producing a predicted 4.78 cm (1.88 in.) deflection (Fig. 17). This predicted stress is probably a function of the reentrant corner geometry and a radius is being included in new models.

7. Discussion

The purpose of this paper was to describe initial tests on pultruded composite elements of a ROPS made from composite materials. The design considerations for a ROPS made from pultruded material were presented, followed by a description and results of tests on prototype ROPS made from pultruded material.

The tests of the bolted base fixture show that failure of the steel components of the base must and can be avoided. The predicted and actual stress–strain plots for the longer tube were a close match (Fig. 10). The shorter tube experienced matrix failure in the loading area at the top of the tube. The model did not include this failure mode, but only considered longitudinal fiber strength.

When the pultruded posts are tested to failure, there is an extended plastic region with increasing deflection as the matrix and fibers progressively separate. However, microfailures that are not easily detected are progressively weakening the structure. Steel structures normally go into the easily visible plastic range, allowing the greatest absorption of energy by the ROPS. With appropriate impact characteristics factored into a design, the value of FRP composites for ROPS is expected to reside in longevity and lower manufacturing costs. Further testing will focus on impact testing of FRP ROPS. The failures due to tearing through bolts in the direction of fiber will be addressed via the use of bonded reinforcing FRP overlay with fiber direction normal to the fiber direction of the FRP tube.

Disclaimer: NIOSH does not endorse any commercial products mentioned in this article. Such products were selected as a matter of convenience.

Acknowledgments

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John Etherton is a Senior Research Safety Engineer with the Protective Technologies Branch, Division of Safety Research, National Institute for Occupational Safety and Health (NIOSH) in Morgantown, WV. He

received his doctorate in Industrial Engineering from West Virginia University in 1995. His bachelors degree is in Mechanical Engineering and he also holds a graduate degree in Engineering Administration. He has been with NIOSH for over 25 years, conducting research to develop and evaluate the effectiveness of machine safeguards. He has numerous publications in the field of occupational safety engineering and ergonomics. He is a Certified Safety Professional and a Certified Professional Ergonomist. His professional memberships include the American Society of Agricultural Engineers, the American Society of Mechanical Engineers, and the American Society of Safety Engineers.

Mahmood Ronaghi is a Research Safety Engineer with the Protective Technology Branch of the Division of Safety Research at the National Institute for Occupational Safety and Health. His areas of interest are in finite element analysis, computational mechanics, composite materials, and modeling. He is involved in various projects such as Roll Over Protective Structures (ROPS), use of composite materials in ROPS, and modeling analysis of aerial and scissor lifts. Mahmood has received several awards, including the 2002 NIOSH Alice Hamilton, Honorable Mention Award and The Federal Laboratory Consortium Southeast Region, Honorable Mention Award. He received his MS degree in Mechanical/Aerospace Engineering from the University of Colorado at Boulder.

Richard S. Current is a Research General Engineer with the Protective Technologies Branch, Division of Safety Research, National Institute for Occupational Safety and Health (NIOSH) in Morgantown, WV. He received a BS in Aerospace Engineering in 1991 from West Virginia University, and has completed graduate level engineering and mathematics courses at WVU, including theoretical and experimental stress analysis, and fracture mechanics. He previously worked for the US Department of Energy in an engineering capacity for 7 years and has been working at NIOSH for the past 6 years. He is a member of the Society of Automotive Engineers and is a Registered Professional Engineer with the state of West Virginia.