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# NASA Contractor Report 178401

## COMPOSITE MATERIALS FOR RAIL TRANSIT SYSTEMS

(NASA-CR-178401) COMPOSITE MATERIALS FOR  
RAIL TRANSIT SYSTEMS Final Technical Report  
(Virginia Polytechnic Inst. and State Univ.)  
34 p CSCL 11D

N88-17738

Unclas  
G3/24 0124770

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**Grant NAG-1-673**

**December 1987**

**NASA**  
National Aeronautics and  
Space Administration  
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## **FOREWORD**

This study (NASA Grant NAG-1-673) was funded by the National Aeronautics and Space Administration, Langley Research Center and the Department of Transportation, Urban Mass Transportation Administration under DOT Agreement No. DTUM60-85-X-00007.

Mr. L. J. Rose of NASA, Langley Research Center, and Mr. Jeffrey Mora of DOT, Urban Mass Transportation Administration, were co-Project Managers, and Mr. Robert Baucom of NASA, Langley Research Center, served as Technical Monitor for the Grant. The investigators wish to express their appreciation for the assistance and support provided by them.

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## **SUMMARY**

This study explores the potential for using composite materials in urban mass transit systems. The emphasis was to identify specific advantages of composite materials in order to determine their actual and potential usage for carbody and guideway structure applications. The study consisted of a review of the literature, contacts with major domestic system operators, designers, and builders, and analysis of potential composites application to railcar construction.

Composites were found to be in use throughout the transit industry, usually in secondary or auxiliary applications such as car interior and nonstructural exterior panels. Some of the most common and promising areas were found to be sign structures and third rail cover applications where the nonconductive electrical properties of composite materials are desirable. Some consideration has been given to structural use of composites in carbodies, but little appears to have been done to date, possibly due to the perceived high cost of composites and/or the issues of flammability and toxicity. Both of these issues have been overcome, however, as a result of extensive research and development of composites for aircraft applications.

More recently, considerable activity has been initiated in the area of using composites in the load bearing elements of civil engineering structures such as highway bridges. It is believed that new and improved manufacturing refinements in pultrusion and filament winding will permit the production of beam sections which

can be used in guideway structures. These light-weight beams would reduce trucking and erection cost and time. The inherent corrosion resistance and low maintenance characteristics of composites should result in lowered maintenance costs over a prolonged life of the structure. Also identified during this study were fabrics, based on advanced fibers, which are cut-resistant. These could be the basis of vandal-resistant seat materials. Additionally, composites which resist painting can be achieved. Such blends, used as facing or in body panels, could alleviate the problem of graffiti and thus result in lowered maintenance costs.

## INTRODUCTION

Recent rapid advances in the utilization of advanced composite materials such as graphite/epoxy and Kevlar/epoxy have been primarily limited to the aerospace industry, with relatively minor usage in other industries (e.g. land and marine transportation). Basic reasons for the lag in composite application by other industries is the relatively high per pound cost of these materials and the lack of experience with them on the part of designers. It is obvious, however, that the benefits of composite materials (lower weight, higher specific stiffness and strength, longer life, lower maintenance cost, and superior thermal properties, among others) could be used to advantage in many other application areas.

This report summarizes a study conducted to determine the potential use of composite materials in urban mass rail transit systems. Usages in both vehicular and guideway structures were considered as well as in auxiliary equipment. Applications were found in all areas. It should be noted that certain large-scale applications of composites were found in railway freightcars (e.g. the Glasshopper car [1]) but are not reported herein since they are not part of mass transit systems.

A large portion of the information presented in the Current Practice section was obtained from the literature as well as from survey letters which were sent to a number of companies, both domestic and foreign. In general, the response from domestic companies was very good, whereas little was learned regarding foreign practice.

Most of the information on foreign practice was obtained from the domestic companies or from available literature [2]. The list of addressees for the survey letters is presented in Appendix A along with a copy of the survey letter.

## COMPOSITE MATERIALS

Composite materials, generally composed of a stiff, strong, fibrous phase (the fibers) in a more compliant, weaker phase (the matrix) have existed for centuries. Fiberglass, composed of glass fibers in a polymeric matrix, has been in widespread use for several decades. The so-called "advanced" composites, with fibers such as graphite or boron, are more recent developments. The fiber phase can either be "chopped" or "continuous", classified by the length of the fibers [3]. Composites generally exhibit higher specific stiffness and strength, as well as increased fatigue life, over their homogeneous counterparts. Some of the drawbacks to composites have been high per-pound cost, tendency to absorb water, degradation by ultraviolet rays, low impact resistance, compounded by the lack of understanding by the design community as to how to exploit the beneficial aspects of their anisotropy. As with all new, potentially advantageous materials, considerable research and development has been directed at overcoming the deficiencies of composites, and they are currently enjoying more use than ever before in a wider range of applications.

Although composite materials have generally been regarded as "high cost", new manufacturing techniques such as pultrusion and filament winding, which have been refined to produce high quality, low cost composite parts, have contributed to significant cost reductions in recent years. Entire tanks for railcars and trucks have been filament wound, as have hopper car containers [1]. A wide range of other manufacturing techniques, including hand lay-up, spray-up, vacuum and pressure bag mold-



ing, autoclave curing, press molding, vacuum injection, and impregnation of braided preforms are available at this time and are under continuing development by both government and industry. In addition, composites which may have higher per pound raw material costs may be formable to near net shape, resulting in lowered cost due to reduced scrap.

Currently, considerable research is directed towards improving the energy absorption capabilities of composite materials. Their extensive use in airplane, helicopter, and automotive structures, with the associated crashworthiness requirements, has forced the development of new materials, with high energy absorption capabilities, and the use of advanced structural concepts which force the composite structure to respond in such a way that large amounts of energy are absorbed. These efforts have been successful, and both materials and structural concepts designed for energy absorption and crashworthiness are currently available.

Flammability and toxicity of the combustion products of composites was a problem for some time and continues to be for some resins. Fire safety aspects of using polymeric materials for land transportation vehicles is discussed in Ref. [4]. A recent survey of the literature [5], however, indicates that there are a number of resins which are self extinguishing, have low flame spread rates, and give off no toxic products. There are also a number of chemicals which can be added to matrix materials to remove flammability and toxicity problems [6].

Designing with composite materials is considerably more complicated than designing with isotropic materials. The commonly used strength of materials approach is generally unsuccessful with composites. Design of composite components is by necessity computer-based, and requires additional training and experience. Design

software, in both simplified and sophisticated numerical methodologies, is now available to the public.

A number of excellent texts exist on composite materials technology and the reader is directed to those sources for additional information on material properties and design concepts [7-9].

## **CURRENT PRACTICE AND DISCUSSION**

Current applications of composite materials in rail transit systems are reviewed along with brief discussions of their problems, advantages and potential. Applications to vehicles, guideway structures, and auxiliary equipment are reported, along with the rationale for selection of composites.

### **Vehicle Applications**

Although not yet widespread, composite materials are used in various applications in railcars. Most were nonstructural, with only a few being major components of the railcar structure. The majority of structural members of railcars continue to be fabricated from aluminum or stainless steel, though low alloy, high tensile strength steel has also been used.

A study by the U.S. Department of Transportation [10] details some of the material selection criteria. Important ones are:

1. Effect on initial cost
2. Energy consumption
3. Material availability
4. Manufacturing considerations
5. Durability

6. Structural maintenance
7. Appearance maintenance
8. Safety.

It appears that composites offer advantages in all of these areas with the possible exception of initial material cost and manufacturing considerations. Fabrication of composites is currently under vigorous development, largely funded by the government and the aircraft industry and significant cost reduction is projected through the use of advanced manufacturing techniques such as filament winding and pultrusion. For the initial material cost, consider the effect of material cost on total railcar cost as shown by Table 1. Note that only 10% of the car cost is attributable to materials, so even if the initial cost of composites is higher (which may not be the case) the cost of the car will not be considerably different. If car weight can be reduced, however, then energy requirements for system operation are correspondingly reduced. Lower car weight also results in lowered center of gravity, thus resulting in safer cornering and enhanced ride comfort.

An indication of how initial cost and maintenance costs may be traded off is shown in Fig. 1, Ref. 10. The line on the figure is drawn at a 45° angle so that it represents equal totals of initial and maintenance costs. It can be concluded that higher initial cost is economically acceptable if life cycle maintenance cost is reduced so that the total life cycle cost remains the same. Similar arguments could be made for trading off initial cost against operating cost. Since composites appear to offer both reduced maintenance and operating cost, some initial cost increase appears justified.

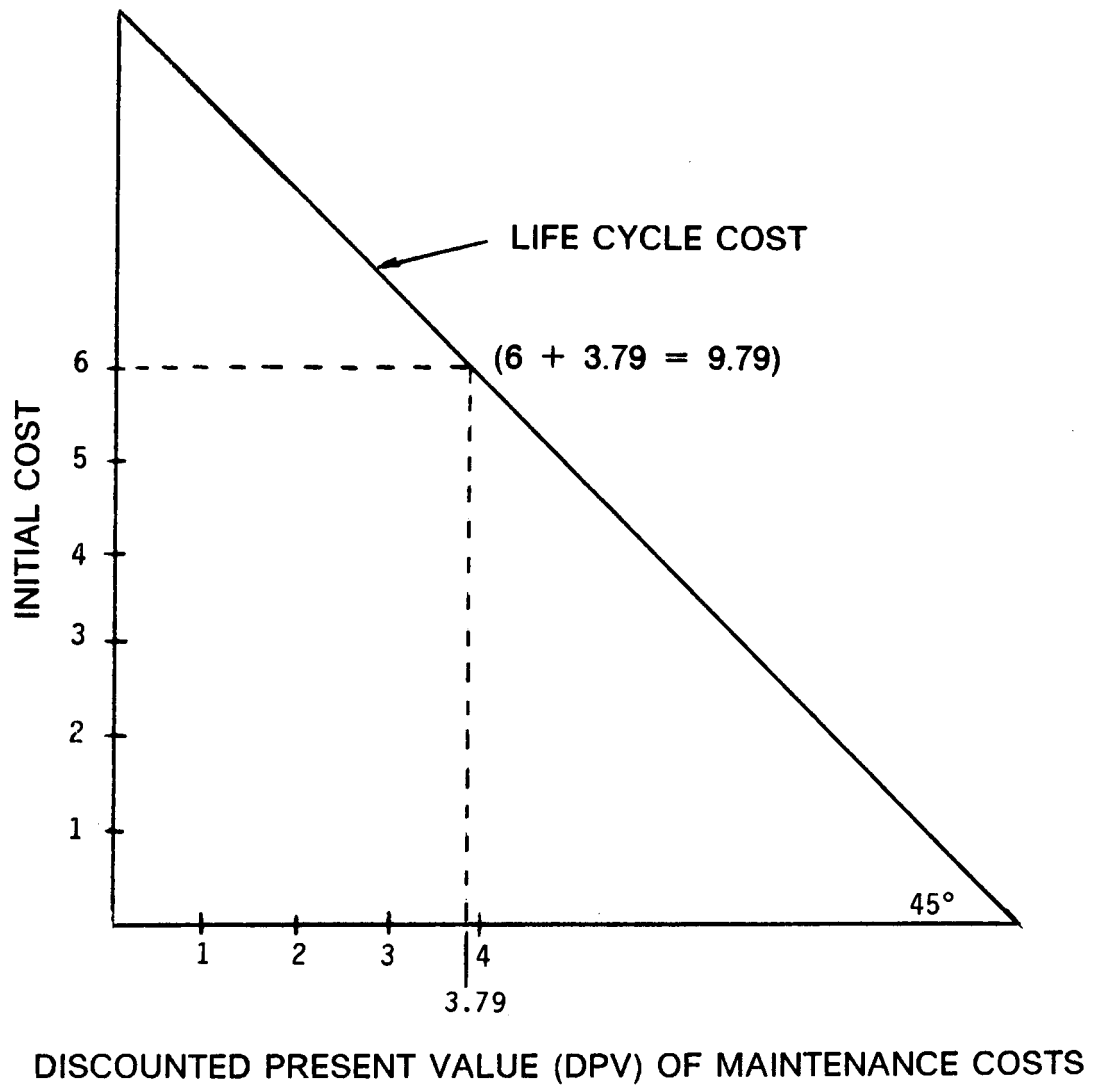
## Table 1

### Typical Railcar Cost Distribution

(200 Car Order)

(From Reference 10)

<b>DIRECT RECURRING COSTS</b>	
Direct Manufacture and Assembly	11.5%
Outside Procurement	
Car Body Materials	10.0%
Equipment and Subcontracts	50.0%
	<hr/>
Subtotal	71.5%
<b>NONRECURRING COSTS</b>	
Engineering	3.0%
Tooling	1.0%
Testing	1.0%
Human Factors, Reliability, etc.	.5%
Facilities Improvements (write off)	4.0%
	<hr/>
Subtotal	9.5%
<b>BUSINESS RISK AND PROFIT</b>	
Field Service and Warranty	2.5%
Interest, Cost of Money	2.5%
Penalties for Late Delivery, Weight Energy Consumption, etc.	1.0%
Profit (15% of Est. Cost Items)	13.0%
	<hr/>
Subtotal	19.0%
	<hr/>
<b>TOTAL</b>	<b>100.0%</b>



**Figure 1. Cost Trade-Off**

Work on a composite bogie (wheel truck) has been under continuing development in Germany for some time. It appears that this is the most significant current development program of a major heavy component of a railcar which is being redesigned in composites. The bogies represent a large portion of the weight of a car, hence, significant weight reductions in the bogie should result in considerably lighter overall car weight, along with reduced acceleration and braking energy consumption. Weight reduction in the propulsion and braking systems, in turn, should result in additional savings in car weight. Reductions in car weight would result in lighter loads on guideway structures.

Considerable use has been made of composites in railcars for both interior liners and exterior shells [2]. The bulk of these applications use fiberglass, a glass fiber in a polymeric matrix, which may be epoxy, vinyl ester, polyester, or any of a number of other materials. These composites have an overall good appearance and are very durable. Their weatherability and cleansability characteristics are good. The formability is such that shapes which are both aesthetically and aerodynamically attractive can be easily produced. The residual properties of composites after forming are sufficient to permit their use in exterior surfaces. In general, composites are resistant to vandalism, although it appears that the non-paintability property for graffiti resistance has not been fully exploited. The materials can be made almost any desired color through the use of pigments in the matrix material.

Composites have been used in both window and door frames, largely due to their light weight and low maintenance requirements. For application to sliding door systems, reduced weight reduces power requirements for opening and closing doors. The lighter weight allows the doors to be opened and closed more rapidly and reduces shock absorption during door deceleration. Composites have been used in seats in a number of systems, primarily due to their colorability, formability, and re-

sistance to vandalism. The seats are often unpadded to increase vandalism resistance, although passenger comfort is somewhat reduced. Composites have also been used for handrails, steps, and sheathing.

The Morgantown, WV, people mover system, designed by Boeing, utilizes fiberglass in the carbodies. These bodies are 10% lighter than the aluminum bodies used in a similar installation in Japan. In addition to the lighter weight, the fiberglass body offers passengers insulation in case of an electrical fault to the chassis.

Composites are routinely used for insulators and cable cleats due to their high dielectric properties and their good formability, which results in smooth, cleanable surfaces. They are also used in current collector arc shields, again due to their superior dielectric properties, formability, and cleanability.

### **Guideway Structure Applications**

Applications of composites in guideway structures appear to have been entirely nonstructural and primarily driven by the good dielectric properties of the materials. The ability of composites to withstand deterioration in highly ionized air is also an advantage. Composites can also withstand harsh environments, e.g. where highway deicing chemicals are used in proximity to railways. Composite third rail strain insulators are currently the industry standard, and are in widespread use. They have proved to be more economical than the materials previously used. Composite (glass/polyester) is currently replacing wood as the material of choice for third rail cover board. The composites require low maintenance, have good strength, and can be fabricated in a wide variety of shapes. One of the limitations of wood is the restriction imposed by a limited choice of acceptable shapes which can be fabricated. The composite third rail cover board is being widely used as replacement for wooden



originals in existing systems and are being installed as standard practice in new systems.

Some use of composites in bridge fascia panels was discovered. This application is again nonstructural. The good formability and weatherability of the materials makes them an excellent choice for such applications. They can be formed to a wide range of shapes and in various colors. The latter, which does not require painting, is achieved through pigmentation of the matrix. Maintenance requirements are substantially lowered, and the expected lifetime is much greater than other materials, even in harsh environments.

### **Auxiliary Equipment Applications**

The use of composites in auxiliary components is increasing. The applications reported here include materials that were originally classed as composites as well as some materials which are indeed composites but not in the original context. They are included for completeness.

There is widespread use of fiberglass board for mounting of electrical equipment. The electrical properties of the composite offer safety and durability in this application. Fiberglass is also being used in conduits and fittings in electrical systems. In addition to the "standard" composites, there is also use of concrete reinforced with plastic fiber as material for cable ducts.

Composite signboards are finding acceptance by a number of transit systems. These signs are light, thus permitting lighter supporting structures, are durable and require low maintenance.

Use of composites in tunnel structures appears to be increasing. Fiber reinforced shotcrete is being used in Scandinavia for construction of tunnels. Silica fume with steel fibers is being used for precast concrete tunnel liners.

A recently opened section of the Milan, Italy, transit system used composite catenary arms and reported a 70% cost reduction when maintenance costs were considered. The atmosphere around the highly charged catenary is ionized, and metal components deteriorate rapidly as a result. Composites have a much longer life in such environments. The nonconductive properties of the arms also make the system safer to repair, which allows catenary of one of a set of parallel railways to be shut down and repaired without having to shut down the parallel lines, as had been the case in the past.

Currently under investigation is the use of precast glass/concrete panels for station concession booths. One transit system has injected methyl methacrylate (MMA) resin into deteriorating concrete to bring its properties back up to standard. Fiberglass panels are being used as vibration attenuators on floating slabs.

In other related areas, complete pedestrian walkway and bridge structures have been fabricated from composites. These structures exhibit all of the previously mentioned advantages, such as light weight, reduced trucking and erection costs, inherent colorability, and low maintenance.

## **POTENTIAL APPLICATIONS**

A number of potential applications of composites to urban mass transit rail systems are obvious and would entail low risk development programs for implementation. Other application areas are higher risk, but also of potentially high benefit.

### **Vehicle Applications**

Since entire automobiles (Ford Motor Company), airplanes (Beech), and ships (Italian minehunters) have been fabricated from composites, there is little doubt that mass transit railcars could be designed and fabricated entirely from composite materials. The risk to the car builder of a development program to introduce composites in carbody structures would be low. The potential benefits are dependent on the number of cars which could be manufactured and sold. It is anticipated that nonstructural or secondary structural retrofit parts such as seats, trim panels, and equipment boxes for the existing fleet rail of cars will be composite. Such parts will likely be supplied by small manufacturers who have existing facilities in place and can fabricate these parts in concert with their production of other components. Small quantities can be made by hand lay-up or spray-up in order to provide replacements and spares.

The newly developed cut-resistant fabrics should be investigated for use as seat covering materials. Most of the current fabrics appear to be generally loose weaves or knits which should be adaptable as cover materials, either new or retrofit.

Non-paintable composite panels should be considered for use as replacement for facing parts on railcars. They are formable, easy to clean (normal grime), and should greatly reduce the expenditures of systems which currently have large budgets for graffiti removal. In addition to this saving, environmental problems associated with the strong chemicals used for unwanted paint removal should be greatly reduced.

A new brake band, employing fiber reinforced polymers, resulted in important performance advantages over traditional brakes [12], and may be applied to rail transportation vehicles. The new design resulted in a 40% weight reduction while providing higher fatigue strength (longer fatigue life).

### **Guideway Structure Applications**

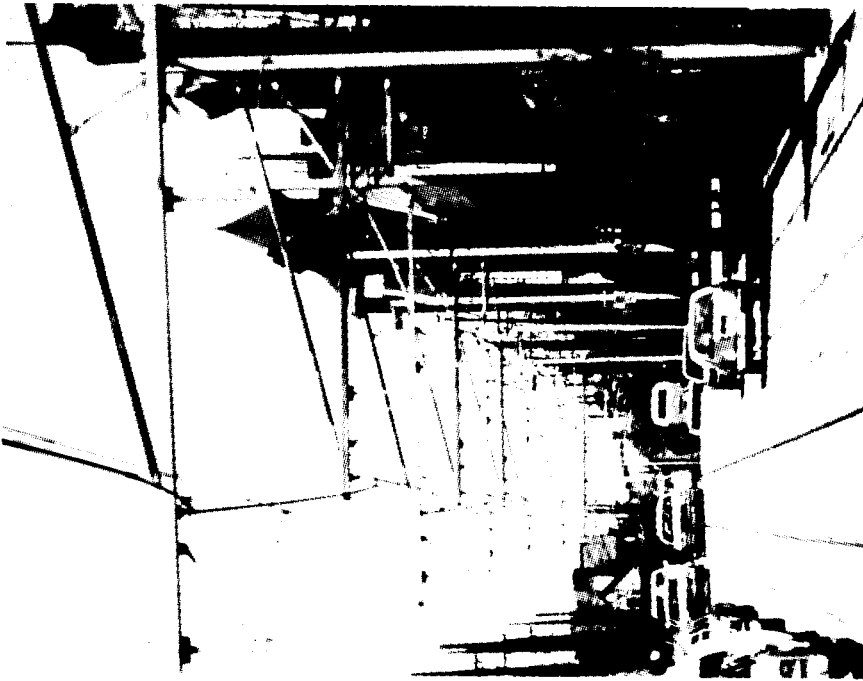
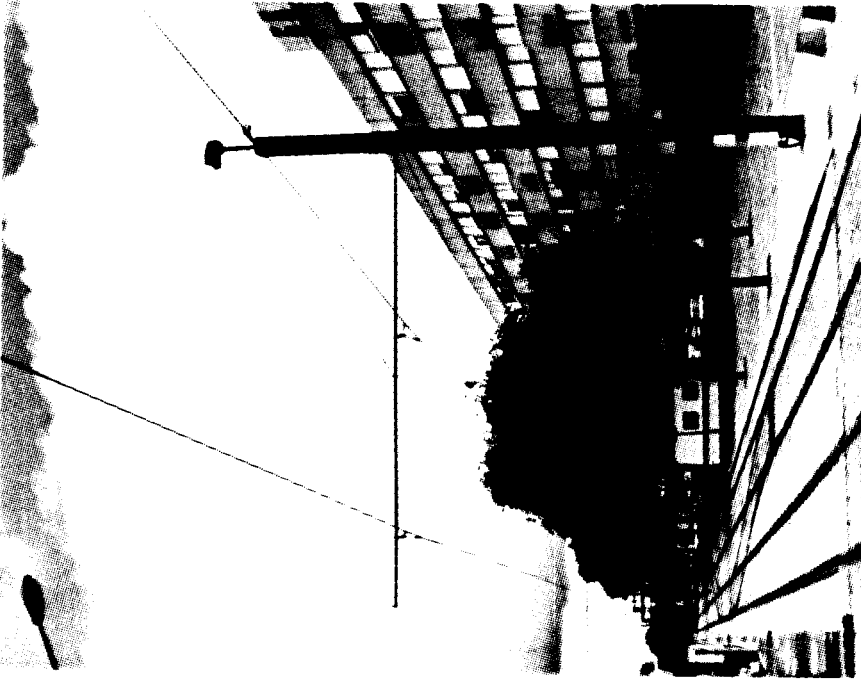
This area appears to be the most promising for application of composites to urban mass transit systems.

Catenary support structures are an obvious structural application of composites. Filament wound and pultruded tubes have been in use for a number of years as structural components of trusses, wind turbine blades, driveshafts, and other devices. Fabrication of complete catenary support structures from composites should present few problems and should entail a low risk development program. A bibliography of such applications and relevant design articles is presented in Appendix B. As noted earlier in the Milan, Italy, system, composites in catenary support structures offer a range of benefits. Their stiffness and strength allow them to withstand the loads, and their ability to survive in the ionized atmosphere surrounding the power lines gives them a much longer service life. Their insulation properties result in safety for workers. The lighter weight offers reduced costs in trucking structural members to the construction site and also in their assembly and erection. Catenary systems of

vertical poles can be made less obtrusive due to reduced member size, increased member spacing, and colorability of material for aesthetic purposes. An example of the wide variability in appearance of existing catenary support systems is shown in Figure 2. Both pictures are of double-track bracket suspensions, but there are large differences in the aesthetics and obtrusiveness of the designs.

Composites are eminently suitable for replacement components in the catenary support structures of existing U.S. rail transit systems. Even if the structural member cost is somewhat higher (which may not actually be the case) the longer life, reduced maintenance, and aesthetic benefits should far outweigh the increased investment. Engineering costs for design and certification of such components should be relatively small. Most manufacturers of such composite hardware have an in-house design staff to assist potential customers with design problems and with material selection.

The most promising application for composites in guideway structures is in the construction of overhead support and bridge components. This is also the highest risk application, but the potential savings are enormous as bolstered by current Federal Highway Administration (FHWA) plans to build modular composite replacement units for Interstate highway bridges. While there are no plans by FHWA to build other bridge members from composites, that presumably could be the next step after the bridge deck effort, which is underway. Some recent design effort at VPI & SU indicates that strength critical failure is not a problem even for "low-end" composite components such as glass/vinyl ester beams. However, deflection could be a problem for such materials unless nonconventional cross-sections are developed to allow minimum weight and acceptable deflection. Some manufacturers are currently producing complicated cross sections on a routine basis, and if a market for addition-



**Figure 2. Aesthetic Variations in Existing Catenary Support Systems**

Photographs copyright 1985 Traction Slides International, P.O. Box 123, Merrick, NY 11566; (516) 379-9797.

al structural sections particularly suitable to bridge construction were to present it-  
self, they would undoubtedly begin to produce the latter sections.

Bridge components could be partially assembled and trucked to the site as modules,  
with the shipment limited by size rather than weight. In some instances, it might be  
feasible to set up a pultrusion or winding installation near a construction site and  
essentially manufacture the components at the site, thus further lowering trucking  
costs, since only the raw materials (fiber and polymeric matrix) would need to be  
shipped to the site.

In a recent study funded by UMTA [13], it was concluded that composite beams used  
in fixed guideway systems would be half the weight and lower in cost than either  
steel or reinforced concrete beams, and were predicted to have "tolerable" de-  
flections. Reduced trucking and erection costs were predicted, as well as reduced  
requirements for piles and foundations.

Reduced maintenance costs are projected since properly selected composites should  
not have to be painted, and could be made highly resistant to deicing chemicals.  
Colors can be selected to provide a pleasant looking structure. It is also possible that  
longer spans could be used if composites were selected. It is therefore possible that  
bridges with longer spans could be designed such that disruption of automobile traffic  
by support columns is reduced, or that overhead structures could be placed in areas  
which might be impossible using conventional materials. Reduced numbers of col-  
umns could also result in less sunlight blockage and more aesthetically pleasing  
structures which are of particular importance in the urban environment.

## **Auxiliary Equipment Applications**

The array of applications for composites in auxiliary equipment and components is very large. The current applications listed above such as signs, equipment, mounting boards, and trim panels give some indication of the breadth of the field. It is likely that such applications in new systems will be made on a case by case basis by the system designer, whereas retrofits will be made on a case by case basis by the system operator and consultants.



## **CONCLUSIONS AND RECOMMENDATIONS**

1. Some composite materials are currently being used in railcars, guideway systems, and auxiliary equipment, primarily in nonstructural applications.
2. The desirable properties of composites, including high specific strength and stiffness, low maintenance, and superior fatigue properties make these materials good choices for both new construction and retrofit hardware.
3. The nonconductive properties of composites make their use in electric rail transit systems very attractive since they offer increased resistance to detrimental effects of ionized air, and also offer safety in case of electrical faults.
4. New materials and techniques for fabricating composite structures and structural elements, with good energy absorption characteristics, have resulted in the design of composite structures with improved crashworthiness.
5. Past problems with flammability and toxicity of composite material combustion products have been overcome.
6. Selected composites as used in cut-resistant fabrics or with surfaces to which paint will not adhere offer significant resistance to vandalism damage.

7. New materials and refined manufacturing techniques have resulted in composite components which are cost competitive with components of aluminum or steel.
8. Use of composite materials in railcars can be a relatively low risk venture and the benefits can be high because weight reduction translates directly into lower energy costs.
9. The most immediate and effective use of composites in railcars will likely be for retrofit components and other elements such as seat cushions and trim panels which can be designed to provide resistance to vandalism.
10. Due to the requirements for electrical insulation/isolation and resistance to harsh environments, use of composites in catenary support structures is considered to be very promising, both in new construction and as retrofit. The application should be a low risk one with potentially great benefit, especially if life cycle costs are considered, due to the projected longer life and greatly reduced maintenance.
11. Bridge and overhead support structures represent the most promising area for incorporation of composites in urban rail transit systems. Reduced weight, lowered transportation and erection costs, longer spans, aesthetically pleasing structures, and the potential for shipping modules or processing materials at the construction site are some of the advantages which can be realized. It is recommended that the transit industry pursue this aspect of utilizing of composites.

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## **APPENDIX A - Survey Letter and Addressees**

## Survey Letter

Dear \_\_\_\_\_ :

We are working on a joint NASA-DOT/UMTA project to assess the current and planned future utilization of composite materials ranging from fiberglass to graphite/cement in urban rail transit systems. We are very interested in learning about any use you are currently making of fiber reinforced materials as well as any potential application of such materials in the rail systems with which you have contact. UMTA's Office of Systems Engineering (Jeffrey Mora) told us that you might be able to provide such information. We are interested in application of all types of composites to all subsystems of rail transit systems including vehicular, guideway, and support items. Our interests in your achievements through use of advanced materials include weight and/or cost reduction, extended life, reduced maintenance, enhanced ride quality, and safety.

In the way of background on composite materials and their desirable properties in general, these materials exhibit higher stiffness and strength per unit weight, as well as longer fatigue life. Maintenance requirements are often reduced since painting may not be required. Internal damping is high in these materials, with the result that noise and vibration problems may be alleviated. Most of the previous shortcomings in terms of brittle failure mechanisms, low solvent resistance, and poor flammability and toxicity performance have been overcome by development of better polymer systems.

As a part of this study we will select items which we believe to be suitable for application of composites. If you have any thoughts on that subject, we would be very interested in your writing to us. In order to determine these areas we are in need of guidelines or techniques which you use to design vehicles, guideway structures (including support structures for elevated railways), auxiliary items such as electrification and/or signal systems, and any other items which you consider to be potentially successful if replaced by composites.

We would greatly appreciate any assistance you can give us in obtaining this information. Please write to:

Dr. O. Hayden Griffin, Jr.  
Department of Engineering Science & Mechanics  
Virginia Polytechnic Institute & State University  
Blacksburg, VA 24061

Thank you in advance for your assistance.

Yours truly,

O. Hayden Griffin, Jr.  
Associate Professor of Engineering Science & Mechanics

## Survey Letter Addressees

### Foreign:

- Japan  
Railway Technical Research Institute  
Tokyo
- Canada  
Railway Association of Canada  
Montreal, Quebec  
Canadian National Railway  
Montreal, Quebec  
Canadian Pacific Railway  
Montreal, Quebec
- Great Britain  
British Rail Engineering, Ltd.  
London
- West Germany  
German Railways DB  
Frankfurt
- Netherlands  
Netherlands Railways  
Division for Studies & Research  
Utrecht

### Domestic Manufacturers:

Boeing Aerospace Corporation  
Seattle, WA  
Westinghouse Electric Corporation  
Washington, DC

### Domestic System Consultants:

Bechtel Civil & Minerals, Inc.  
H & CF Division  
San Francisco, CA  
De Leuw, Cather & Company  
Washington, DC  
Daniel, Mann, Johnson, & Mendenhall  
Los Angeles, CA  
Parsons, Brinckerhoff, Quade & Douglas, Inc.  
Atlanta, GA

Raymond Kaiser Engineers, Inc.  
Oakland, CA

Tudor Engineering Company  
San Francisco, CA

Fluor Transportation and Infrastructure, Inc.  
Detroit, MI

**Domestic System Operators:**

Metropolitan Atlanta Rapid Transit Authority  
Atlanta, GA

Massachusetts Bay Transportation Authority  
Boston, MA

Chicago Transit Authority  
Chicago, IL

Greater Cleveland Regional Transit Authority  
Cleveland, OH

New York City Transit Authority  
Brooklyn, NY

Port Authority Trans-Hudson Corporation  
New York, NY

Southeastern Pennsylvania Transportation Authority  
Philadelphia, PA

Port Authority Transit Corporation  
Lindenwold, NJ

Bay Area Rapid Transit District  
Oakland, CA

Washington Metropolitan Area Transit Authority  
Washington, DC

Mass Transit Administration of Maryland  
Baltimore, MD

Metropolitan Dade County Transportation Administration  
Miami, FL

Southern California Rapid Transit District  
Los Angeles, CA



## **APPENDIX B - Abridged Bibliography on Catenary Support Structures**

## **Abridged Bibliography on Catenary Support Structures**

This bibliography, although abridged, indicates that there has been use of plastics in catenary systems for a number of years. It also represents a starting point for any future effort directed at design of such systems.

1. "Catenary Tension and High Speed Power Collection," *Rail Engineering- The Way Ahead*, Vol 1, 1975.
2. "Measurement of the Contact Force Between Pantograph and Overhead Contact System (BR, SNCF, and DB Methods)," International Union of Railways, DT 83 (A 129), May 1979.
3. "High Power Traction Current Collection at High Speeds on the Rome-Florence Direttissima Line- April 1978., International Union of Railways, DT 82 (A129), Nov 1978.
4. Borgwardt, H., "Electric Power Supply and Overhead Contact System of the Urban Rapid Transit Network in Stuttgart, West Germany," *Elektrische Bahnen*, Vol 33, No 5, May 1979.
5. Scholes, A., "Computer-Aided Design of Overhead Line Equipment," *Railway Gazette International*, Vol 136, No 3, Mar 1980.
6. "Power Supply for Light Rail and Rapid Transit Systems in Germany," Transportation Research Board Special Report No. 182.
7. "The Standard Catenary on the German Federal Railway," *Elektrische Bahnen*, Vol 77 No 6, June 1979. (see also Vol 77 No 7, July 1979, pp 207-208).
8. "Oscillatory Range of Fader Line and Protective Wire Under Strong Wind," *Rail Technology Record International*, Quarterly Reports, Vol 20, No 2, Jun 1979.
9. Wroblewska, M. and Kaminski, A., "Use of Plastics in Catenary Construction on the PKP (Poland)," *Zeitschrift der OSShD*, Vol 22, No 3, 1979.