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**Federal Railroad
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State-of-the-Art Assessment of Guideway Systems for Maglev Applications

National Maglev Initiative
Washington, DC 20590

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16. Abstract

The engineering, environmental, diagnostic, and economic feasibility of Maglev guideway systems are assessed with an emphasis on composite materials as directed by Congress. This study further examines the performance and the cost of existing and innovative guideway systems that are applicable to Maglev and other mass transit guideways. Utilizing parameters such as strength, stiffness, and ease of construction and maintenance, sixteen conceptual systems are developed for preliminary studies and seven are finalized for an in-depth study. These seven systems are as follows: 1) trapezoidal concrete box with steel; 2) trapezoidal concrete box with fiber reinforced plastics (FRP); 3) rectangular concrete box; 4) all steel; 5) hybrid-system with concrete decking stiffened by steel truss; 6) hybrid-system with concrete decking stiffened by FRP truss; 7) all FRP box system. After establishing ten different load conditions and several serviceability criteria, the above systems have been evaluated for their applicability as Maglev guideway superstructures spanning 24.4 to 30.48 m (80 to 100 feet). Technical issues such as electromagnetic drag forces, sectional efficiency, feasibility of manufacturing, mass production, maintainability of system, and others have been studied along with feasibility to monitor these systems for degradation rates. In addition, economic data of mass transit system have been evaluated and extended to Maglev guideway systems. The maintenance cost data have been developed only to a limited degree. Finally, a set of options including a test plan in terms of laboratory, field experiment, and field demonstration phases is provided.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in.) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$[(x-32)(5/9)]$ °F = y°C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (kn^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

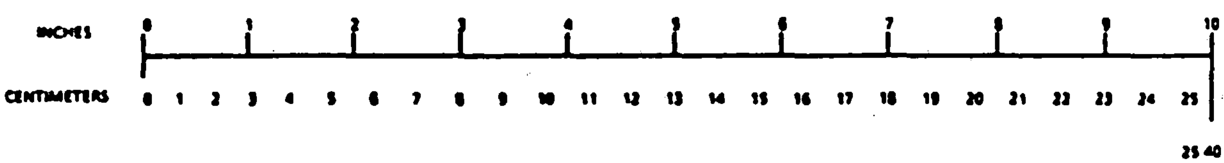
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

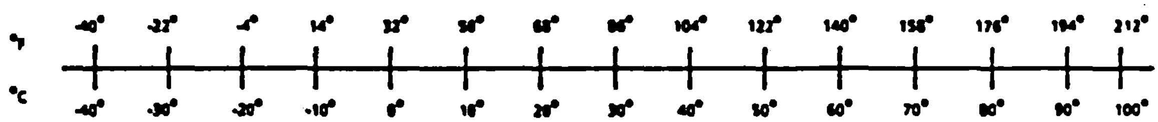
TEMPERATURE (EXACT)

$[(9/5)y + 32]$ °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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Foreword

"The State-of-the-Art Assessment of Guideway Systems for Maglev Applications" Project, begun August, 1991, by the Constructed Facilities Center (CFC), involved several engineering disciplines and eight principal investigators from the Departments of Civil, Electrical, and Mechanical and Aerospace Engineering, one research engineer, and five graduate research assistants from the College of Engineering, West Virginia University. This project is in response to Congressional direction to the Federal Railroad Administration to examine the feasibility of using nonmagnetic polymer matrix composites, embedment of sensors, nondestructive testing techniques and manufacturing issues in the development of Maglev guideways, identifying potential barriers, and proposing strategies to overcome those barriers. Several innovative guideway systems were developed and the performance and economic viability of each system were assessed. Furthermore, it should be noted that the guideway configurations contained herein have been developed to a conceptual level. Further analysis is required before any of these systems are used in the field.

The information contained in this report is based upon the available Maglev system data and practices. The CFC researchers have utilized the readily available technical material from existing literature, which is based upon highway, railway, and other mass transit guideway system design practices.

Design computations, details, or drawings referenced but not included in this report can be obtained from the theses prepared by Ralf Wendlik, Phillip Burnside, and Brad Hyre at West Virginia University in 1992.

EXECUTIVE SUMMARY

The research, conducted through the Constructed Facilities Center, West Virginia University, described in this report is a comprehensive study to assess the engineering and economic feasibility of several potential Maglev guideway systems with emphasis on the use of innovative materials and guideway systems.

This study draws upon the experience of Germany and Japan in order to develop conceptual guideway systems and to evaluate their technical feasibility. This study examines both existing guideway systems that were built for Maglev and other mass transit systems and conceptual innovative guideway systems. An assessment is made of the most promising systems in terms of performance and cost.

Utilizing parameters such as strength, stiffness, ease of construction and maintenance, sixteen guideway systems with several cross sections were developed and seven of these were selected for in-depth analyses. These seven systems are as follows:

1) Trapezoidal concrete box section with conventional steel reinforcement.
2) Trapezoidal concrete box section with Fiber Reinforced Plastic (FRP) reinforcement.
3) Rectangular concrete box section with conventional steel reinforcement.
4) Trapezoidal steel box section.
5) Hybrid-system with concrete decking stiffened by steel trusses.
6) Hybrid-system with concrete decking stiffened by concrete filled FRP trusses.
7) All FRP box system.

These systems have been evaluated for their applicability as guideway superstructures spanning 24.4 to 30.48 m (80 to 100 ft) on the basis of ten load conditions and three serviceability criteria. Such technical issues as electromagnetic drag forces, sectional efficiency, feasibility of manufacturing, mass production, and maintainability have been studied along with feasibility of several nondestructive evaluation techniques to monitor these systems for structural integrity. In addition, CFC researchers have conducted an economic evaluation of these guideway systems based upon economic data from various mass transit systems. Researchers have developed capital costs as well as the labor costs associated with new materials and construction procedures, a task which proved to be the most difficult step due to the lack of available data. Limited maintenance cost data have been developed for each guideway system.

Finally, a set of options, including a test plan in terms of laboratory, field experiment and field demonstration phases, is provided.

1.0 INTRODUCTION

Background

Magnetically levitated (Maglev) high speed ground transportation technologies offer the potential advantages of lower life-cycle costs, minimal environmental damages, higher energy efficiency, technology spin-offs through cooperative efforts of various fields of sciences and engineering, and increased productivity in our construction industry through implementation of innovative construction techniques, tools, and equipment (Moving America, 1989). In addition, a fully functional Maglev transportation system offers potential international trade benefits and relief of traffic congestion. Also, right-of-way acquisition problems may be reduced in terms of finding open lands near urban areas to expand existing highways, railways, and airports (Advisory Committee, Benefits of Maglev, 1989). However, several potential drawbacks of high speed ground transportation systems have to be carefully evaluated before embarking on a full-scale Maglev construction program. For example, impact of magnetic fields on the environment, excessive noise levels and human comfort levels due to vibrations at 480 kmph (300 mph) are just a few of the many potential issues requiring research beyond the levels of existing information.

Although the United States pioneered the early research and development work on Maglev high speed ground transportation technologies until the mid-1970s, it has not carried the research to the construction phase. Japan built a Maglev test facility based on a superconducting electrodynamic system wherein the magnetic repulsion principle has been adapted (Cortes-Comeres, 1988). The Germans also built a high speed Maglev test facility in the early 1980s by using an electromagnetic system wherein the principle of magnetic attraction was used.

U.S. federal agencies as well as state and local governments are working together to assess the engineering, economic, and environmental aspects of Maglev to determine its feasibility in the U.S. In order to build an appropriate partnership with U.S. industry, universities, and banking institutions, some preliminary engineering and economic issues related to Maglev would have to be identified and prioritized (National Maglev Initiative, 1990). Major decisions, including options for future United States Maglev development, can be made only after collecting and synthesizing appropriate engineering, environmental and economic data, and evaluating the data with reference to other high speed transportation system alternatives.

Problem Statement

In August 1991, the CFC received a research contract through the National Maglev Initiative (NMI) to conduct research into the development of innovative Maglev guideway systems. The primary purpose of the study is to examine innovative design, construction, and operation and maintenance approaches that can significantly improve the life-cycle costs of elevated guideway systems. Research relative to guideway systems is important because a large fraction of the initial capital costs (up to 80%) of an overall total Maglev system is spent on the guideway.

The successful implementation of Maglev systems in this country will depend to a great extent on the feasibility of constructing safe and economical guideways. Maglev vehicles have unique requirements which make them different from other mass transportation systems. Some of these requirements impose greater demands on cost and/or serviceability than the tracked guideways of lower-speed conventional rail systems. For example, the close surface tolerances required by Maglev mean higher construction and maintenance costs. Other features of Maglev systems may ease guideway maintenance requirements, e.g., fewer constraints on material durability due to lack of frictional contact surfaces. In any case, the unique features of Maglev systems call for unique approaches to the development of the guideways.

Areas investigated as part of this contract include:

1) use of non-conducting materials such as polymer matrix composites;
2) evaluations of nondestructive testing approaches to monitor guideway condition;
3) evaluation of contemporary construction techniques; and
4) analysis of life-cycle cost analysis to determine the economic impact of innovative materials on Maglev guideways.

Polymer matrix composites appear to offer a solution to potential problems arising from electromagnetic forces. Similarly, modern nondestructive evaluation (NDE) techniques and construction methods have to be carefully researched for their implementation during guideway construction in-service operations and for their economic benefits. We believe that the systematic evaluation of new materials, modern NDE and construction methods, and cost-benefit aspects for Maglev systems will lead to an economical guideway system.

This report summarizes the work on Maglev guideways that has been carried out at the CFC over the past year. Some of the information contained herein is summary-level material from theses written by graduate research assistants (Burnside, 1992, Hyre, 1992, and Wendlik, 1992). Additional technical information from these theses may be obtained from the CFC.

2.0 OBJECTIVES

The specific objectives of this project are to:

1) Examine the designs of existing or proposed Maglev guideways with emphasis on performance requirements.

2) Assess the state-of-the-art of nonconducting structural materials in relation to conventional materials, and assess the potential use of nonconducting materials for Maglev guideways.

3) Assess the feasibility of utilizing prototype composite systems.

4) Assess the modern construction methods for Maglev guideway construction and diagnostic and monitoring techniques to determine the guideway integrity, and determine possible impediments to their implementation.

5) Analyze costs and economic impact of objectives 2 through 4 on Maglev guideway systems.

6) Select several of the most promising materials and composite guideway systems for further testing and evaluation, and develop a test plan to determine their technical viability.

To meet these objectives, we have examined the designs of existing high speed transportation guideway systems as well as those proposed for Maglev guideways which use structural steel and conventional reinforced concrete as their major load-bearing members. Emphasis has been given to the design and performance criteria of guideway systems, life-cycle costs, use of new guideway materials, and efficient in-service data collection relating to distress and aging phenomena.

In addition, innovative, mass-produced, nonmagnetic materials have been examined for their potential use in the Maglev guideway systems. Limitations and costs involved with the development of these innovative materials have also been addressed. These nonmagnetic materials have been examined because of the generation of electromagnetic fields by a Maglev system. These fields may interact with structural steel guideways and control systems, resulting in impacts on ride comfort and energy consumption.

Nondestructive evaluation techniques, including data collection, are examined with a view towards accurate predictions of future maintainability of guideways and possible improvements in construction and rehabilitation techniques.

3.0 FEASIBILITY ASSESSMENT OF EXISTING GUIDEWAY SYSTEMS ADAPTABLE TO MAGLEV APPLICATIONS

3.1 Review of Existing Guideway Systems and Their Potential Applicability to Maglev Guideways

The guideways for Maglev as well as other mass transit systems are typically constructed of steel or concrete; representative systems are shown in Figures 3.1.1. through 3.1.4. For example, precast concrete double tee or box sections are used in concrete construction (Figure 3.1.1.). Similarly, two wide flange (plate girder) sections or steel box sections supporting a concrete deck are used in steel guideway construction (Figure 3.1.2). The trapezoidal cross sectional shapes with overhangs are used for existing Transrapid Maglev guideway (Figures 3.1.3 and 3.1.4) because they offer greater resistance and stability when subject to lateral as well as torsional loads, which are predominant in the design of a Maglev system.

Other systems:

In addition to the Japanese (Masada, et al., 1984) and the German systems (Transrapid, 1991), several other nations (Wendlik, 1992) have made an effort in advancing the Maglev technology.

The first magnetically levitated system opened for public transportation was constructed and developed by British Rail in Birmingham, England (Mustow, 1984). This "People Mover" runs on a 620 m (2034 ft.) long track connecting the town of Birmingham to its train station and

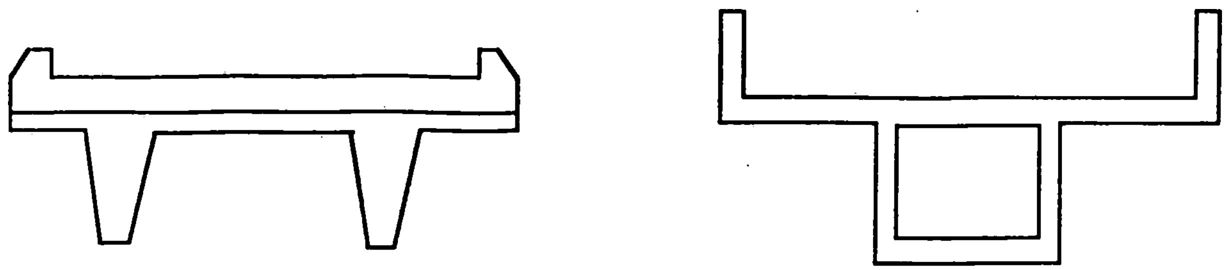


FIG. 3.1.1 CONCRETE GUIDEWAY CROSS SECTIONS (ACI-358 R-1980)

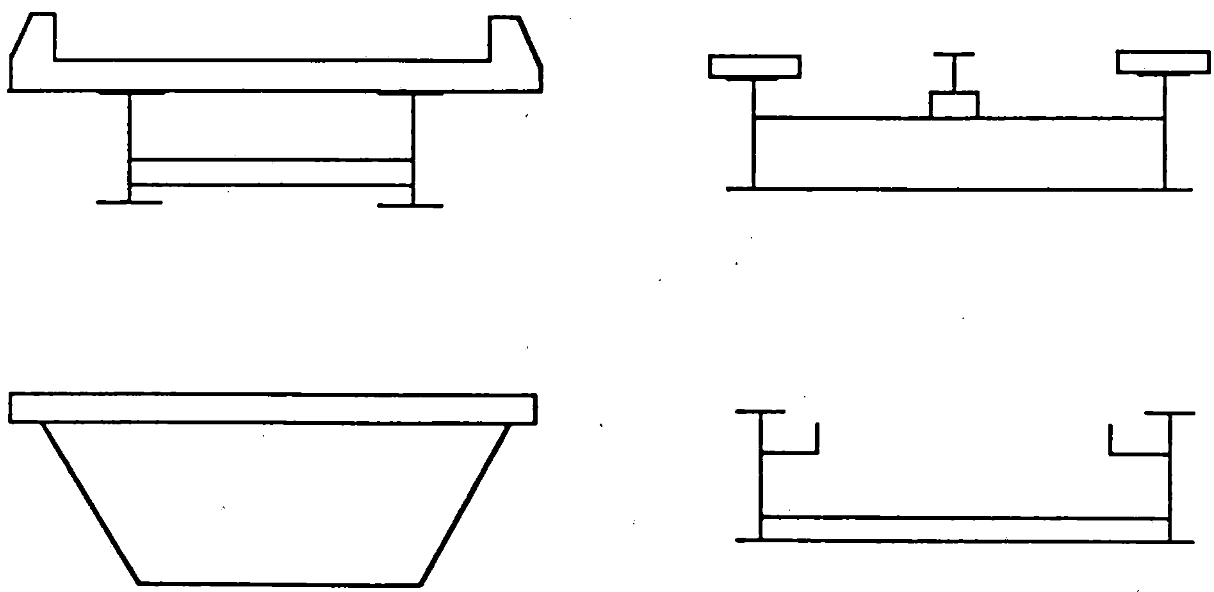


FIG. 3.1.2 STEEL GUIDEWAY CROSS SECTIONS (AISI - 1977)

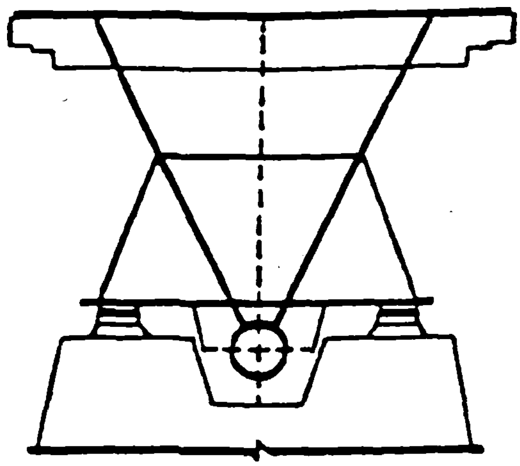


FIG. 3.1.3 STEEL GUIDEWAY SECTION FOR TRANSRAPID SYSTEM

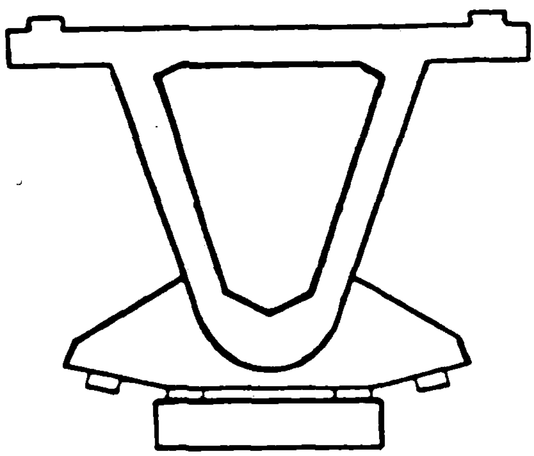


FIG. 3.1.4 CONCRETE GUIDEWAY SECTION FOR TRANSRAPID SYSTEM

airport. The 6 m (19.7 ft.) long vehicle cabin contains six seating and 26 standing accommodations. The Birmingham Maglev utilizes an electromagnetic levitation system and a linear induction motor (LIM) for propulsion. The vehicle cruises at a speed of 40 kmph (25 mph), separated from the guideway by an air gap of 15-20 mm (0.6-0.8 in).

In Canada, an electrodynamic system has been proposed using superconducting magnets (SCM) for levitation and a linear synchronous motor (LSM) for propulsion. This high speed Maglev proposal was developed for a maximum cruising speed of 483 kmph (300 mph).

France and Russia have been making efforts in developing their own Maglev technologies. Because they are at an early stage of their mass transit project, their progress is still limited. An overall summary of various Maglev systems is given in Table 3.1.1.

Outlook for Maglev in the USA:

The research on the basic principles on magnetic levitation and propulsion systems was initiated in the U.S. in the late sixties and early seventies, but by 1975 most government-sponsored activities in that field were suspended. Limited research efforts on single-sided linear induction motors (SLIM) were made beyond 1975; but even these efforts were terminated due to monetary constraints and lack of public support.

In the 1980s, feasibility studies were performed by the Budd Company in conjunction with Transrapid International on the Las Vegas-Los Angeles corridor, using the Transrapid 06 or alternative systems, the JNR-Maglev and the French TGV (Budd Company, 1983). The studies were based on traffic density, environmental aspects, financing, system evaluation, investment costs, and time scheduling. The results concluded that an EMS system is most viable for the Las Vegas-Los Angeles corridor. Other suitable routes for a high-speed system, such as the Boston-New York-Washington, D.C., connection or the Pennsylvania corridor between Pittsburgh and Philadelphia, are at a discussion stage.

As a minimum, Maglev guideways are to support, levitate, guide and propel vehicles at speeds up to 483 kmph (300 mph). Therefore, any Maglev guideway system to be built in the United States needs special provisions not found in the design and construction of typical American highway or railway bridges. Maglev guideway construction, so far, is predominantly a single beam construction because single beam construction with trapezoidal cross section is easier to build and easier to meet design tolerances (Hilliges, 1981) than other complex shapes. Even though multi-span guideway systems were developed by the authors in the conceptual stage (Appendix A) for American applications, herein the multi-span systems were not developed further because of possible difficulties in maintaining such systems for differential settlements (GangaRao, 1981).

Ride quality plays a crucial role in guideway design and construction of an American system. Higher levels of ride comfort can be achieved by properly accounting for the following in guideway design and construction: geometric design, camber and deflection limits for service loads, differential movements of piers, construction tolerances, surface roughness, and construction and maintenance joints.

Table 3.1.1. Summary of Various Guideway Systems

	German		Japanese		British	Canadian
System	Magnetbahn, GmBH	Transrapid International	High Speed Surface Transport (HSST)	Japanese National Railway (JNR)	British Rail	Atherton, D.L.
Existing Track	Berlin, in operation	Emsland, 31.4 km (19.5 mile) test track	Demonstrated at several expositions	Miyazaki, 7.1 km (4.4 mile) test track	Birmingham, 0.6 km (0.4 miles) in operation	Proposed
Year Built	May, 1987	1984	1985	1980	February, 1985	No full scale guideway was built
Levitation	Attraction, using permanent magnets	Attraction, electromagnetic	Attraction, electromagnetic	Repulsion, using passive coils & SCMs	Attraction, electromagnetic	Repulsion, using SCMs
Propulsion	Electromagnetic, using LSM, long-stator	Electromagnetic, using LSM, long-stator	Electromagnetic, using LIM, short-stator	Electrodynamic, using LSM & SCMs	Electromagnetic, using LIM	Electrodynamic, LSM
Lateral Guidance	Guide wheels	Electromagnetic	Electromagnetic	Electrodynamic	Electromagnetic	Electrodynamic
Air Gap	11-26 mm (0.43-1.02 in)	10 mm (0.39 in)	11 mm (0.43 in)	100 mm (3.94 in)	15-20 mm (0.59-0.79 in)	150 mm (5.91 in)
Gap Maintenance	Mechanical	Electronic	Electronic	Electronic	Electronic	Electronic
Magnetic Field	1175 mT (11750 gauss) @ track	< 0.5 mT (5 gauss) in compartment	Not available	10 - 20 mT (100-200 gauss) in compartment	.5 mT (5 gauss) in compartment	20 mT (200 gauss)-floor level 8 mT (80 gauss)-seat level
Cruising Speed	88.5kmph (55 mph)	498.8 kmph (310 mph)	96.5,193,289.6 kmph (60,120,180 mph)	418-498.7 kmph (260 - 310 mph) Runs on wheels until 100 kmph	40 kmph (25 mph)	482.7 kmph (300 mph)

Since the path of a Maglev vehicle is well defined on a guideway, guideway loading results in localized stress concentrations leading to wear and tear. The abrasion resistance of the top surface of the guideway in low speed sections is important to withstand surface wear over a reasonable period of time. In addition, fatigue stresses have to be adequately accounted for in the guideway design. The operational and maintenance success of a guideway system depends on the accuracy and reliability of its analyses and designs, incorporating all the loads and their combinations, and satisfying strength, stiffness, serviceability, and stability requirements. In addition, fabrication techniques; constructability (which includes geometric alignment); rehabilitation methods; and tolerance requirements should be considered carefully at the design stage.

The issues that govern the development of efficient Maglev guideway systems in terms of design, construction, and maintenance are described in the following sections.

Vehicle Geometry: Maglev vehicles have typical lengths of 24.4 m to 30.48 m (80 ft to 100 ft) (Transrapid, 1991) and the cross sectional geometry depends on the location of guidance magnets, cross sectional shape of a guideway, and type of magnetic levitation system. One of the considerations of vehicle geometry is guideway geometry which is a function of radius of curvature and a maximum cant for maximum speeds (Hilliges and Schambec, 1991). These guideway parameters have to be properly accounted for in the design of a vehicle.

Vehicle Loads: For the purpose of our guideway analysis and design, Maglev vehicle loading is idealized as uniform over a length of 243.8 to 304.8 m (800 to 1000 ft), i.e., a train of eight to ten vehicles. However, vehicle loading may not be uniform where bogies are used. The vehicle loading depends upon vehicle geometry, seating capacity, and any dead weight of magnets or other equipment in the vehicle. Vehicle induced dynamic loads, electromagnetic forces, and aerodynamic drag forces depend upon vehicle speeds, number of vehicles in a train, and vehicle shape.

Vehicle-guideway Interaction: Vehicle-guideway interaction analyses are required to establish the live load amplification factor (impact factor) and dynamic characteristics of the guideway. The vehicle-guideway dynamic characteristics relate to the human comfort criteria, vehicle stability, noise levels, and guideway maintainability.

Vehicle Braking: Vehicle braking is an important consideration. Normal braking is controlled by a linear motor by reversing the direction of the current in the motor. Emergency braking may be achieved by using skids to take advantage of friction between the vehicle and guideway. Substructure and support bearings may be most severely affected by the vehicle braking; therefore, special bearing materials and innovative joint detailing have been developed to minimize maintenance.

Lateral Guidance: A lateral guidance mechanism is very important for the maintenance of vehicle position on the guideway. A variety of guidance systems have been used depending upon the geometry of the guideway and the vehicle (Transrapid, 1991, Schwindt and Kindmann, 1990, M-Bahn, 1990). Accurate installation, strict tolerances, and maintenance of these guidance magnets are essential, especially for high vehicle velocities. In addition, lateral guidance should be designed to resist the loads caused by horizontal wind forces, centrifugal forces, and cornering effects. The guidance mechanisms should be adjustable to improve the ride quality. Switching is another important consideration in the design and construction of a guideway. Careful guidance mechanisms should be planned at locations where switching takes place so that the vehicle can transit from one guideway to another with a minimum effect on ride quality.

Environmental Loads: Environmental loads such as earthquakes, wind, ice, snow, and temperature are accounted for using normal design practice. The impact of some climatic effects such as ice or snow may be minimized by heating guideways through electrically heated cables or by supplying heated fluid through pipes embedded in a guideway. The heated fluid concept has been successfully adapted by the Morgantown People Mover guideway system (AISI, 1977).

Economic Considerations: The capital investment required for guideway systems is high; estimates are on the order of \$12 to \$15 thousand per track meter (3.3 ft) in 1990 dollars (National Maglev Initiative, 1990). Factors that influence the capital costs are soil conditions, site acquisition, site accessibility during construction, availability of manpower and equipment, materials and technical know-how. To optimize operational costs, a guideway system should be designed to minimize traffic interruptions (Hyre, 1992). A single-lane guideway system is narrow enough that it can be built using a span by span construction concept and prefabricated modular units (Hilliges, et.al., 1981). From the system response viewpoint, dual guideways may better serve their purpose by separating them into two halves. Modular design and construction concepts are ideal for building repetitive super- and sub-structural systems. The superiority of construction quality and time savings of modular construction were established through recent construction experience with modular timber bridges (GangaRao, 1990). The benefits of mass production and modularization are: (1) reduction of on site manual labor requirements and time savings (40-50% of the input in conventional construction); (2) faster construction process (reduction of 15-20 activities with conventional method to 10-12 activities with modularized system); and (3) higher quality modules through careful choice of materials and strict quality control (Warszawski, 1990).

3.2 DESIGN LOADS AND SERVICEABILITY LIMITS:

The ten different design loads and four serviceability limits shown in Tables 3.2.1 and 3.2.2, respectively are based on (1) information in the literature; (2) experience of CFC professionals, and (3) discussions with professionals having experience in guideway design and construction.

3.3 IDENTIFICATION AND DEVELOPMENT OF INNOVATIVE GUIDEWAY SYSTEMS FOR MAGLEV APPLICATIONS

Structural configurations were developed based upon the parameters: (1) strength; (2) stiffness; (3) manufacturing; (4) erection; (5) unit weight; (6) maintenance; (7) joint location; (8) sectional efficiency; (9) materials; (10) depth; (11) super-and sub-structure integrity; (12) single vs. continuous spans; (13) construction tolerances; and (14) substructure height. Sixteen guideway system concepts were developed. Schematic drawings for the sixteen systems are presented in Appendix A. The guideway systems consists of beam and truss type

Table 3.2.1 Design Loads

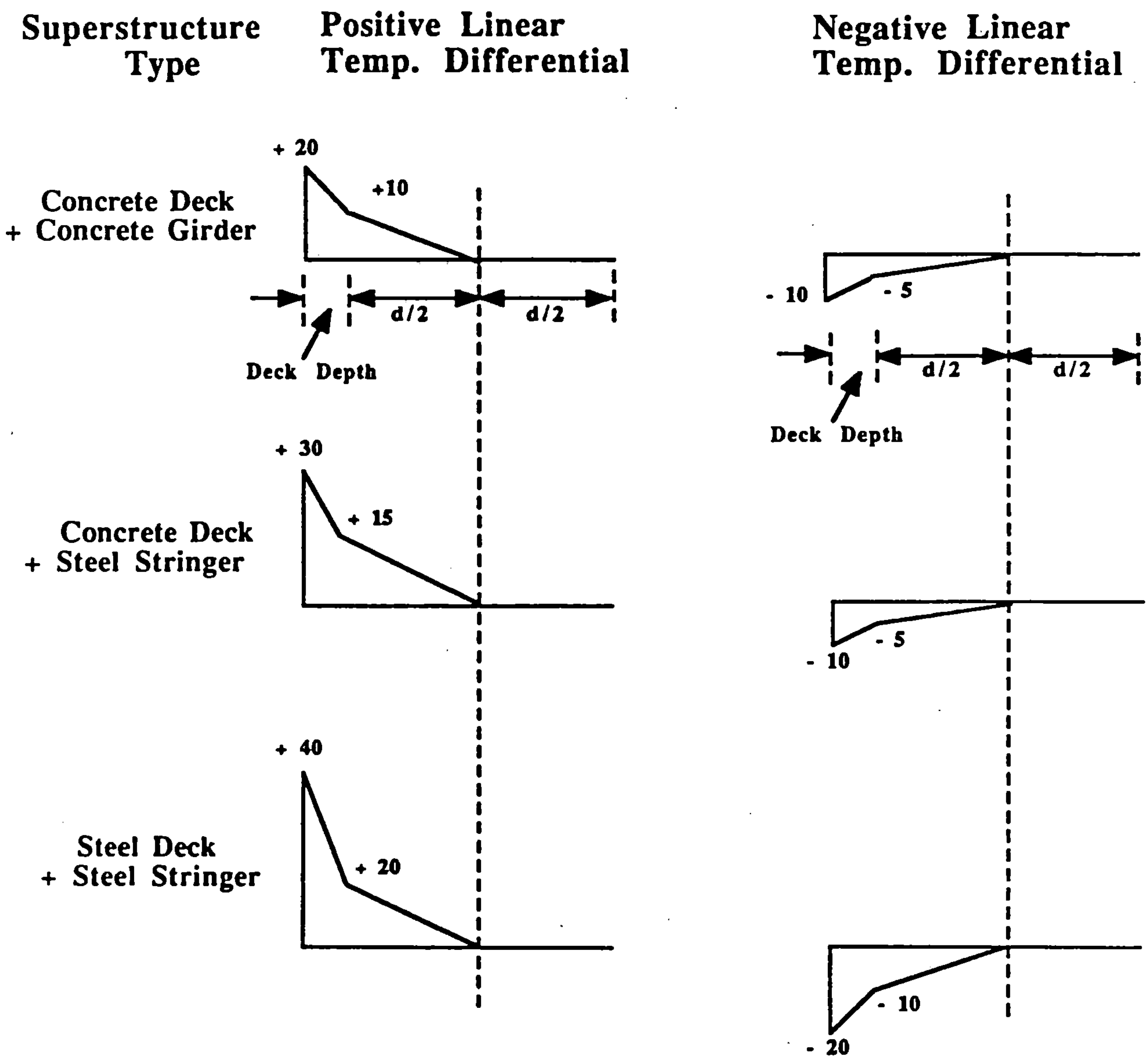
No.	Type of Load	Load	Reference
1	Dead Loads		
	Type 1. Trapezoidal Conc. Box with Steel Rebars (Fig. 3.3.1)	36.42 kN/m (2500 lb/ft)	Hilliges, et al., 1991
	Type 2. Trapezoidal Conc. Box with FRP Rebars (Fig. 3.3.2)	36.42 kN/m (2500 lb/ft)	Hilleges, et al., 1991
	Type 3. Rectangular Conc. Box with Steel Rebars (Fig 3.3.3)	41.59 kN/m (2855 lb/ft)	Wendlik, 1992
	Type 4. All Steel Trapezoidal Box (Fig. 3.3.4)	11.65 kN/m (800 lb/ft)	Schwindt & Kindman 1990
	Type 5. Hybrid-Conc. Deck with Steel Truss (Fig. 3.3.5)	32.05 kN/m (2200 lb/ft	Kim, et al., 1992
	Type 6. Hybrid-Conc. Deck with FRP Truss (Fig. 3.3.6)	40.79 kN/m (2800 lb/ft)	Kim, et al., 1992
	Type 7. All FRP Box	≈ 3.74 kN/m (260 lb/ft)	Burnside, 1992
2	Live Load	24.76 kN/m (1700 lb/ft)	Transrapid, 1991

3	a) Impact b) Dynamic Load - Continuous & Moving c) Unsprung mass, track irregularities, Coriolis and Centripetal forces	80% of Live Load (live load) {1-H(x-vt)} for arrival (live load) {H(x-vt} for departure where H(x-vt) = Heavyside step function Neglect	GangaRao, 1991 Fryba, 1970
4	Design Vehicle Braking Force Braking/Acceleration Forces	0.25g (Live Load + Impact) Note: German Standard	AISI, 1977 GangaRao, 1991
5	Wind Loads - Horizontal on guideway	$W_h = \frac{Z^{0.2} V_{30}^2 C_h}{600} \left(\frac{lb}{ft^2}\right)$ Z = Height in feet from ground to the top of the floor (not less than 30 feet) V_{30} = Fastest mile wind speed, in miles per hour at 30 feet height C_h = Shape factor for horizontal wind load = 1.5 or greater for plate and box girders = 2.3 or greater for truss bridges	American Society of Civil Engineers, 1981
6	Thermal Load	Figure 3.2.1	American Society of Civil Engineers, 1981
7	Centrifugal forces as % of live load	$0.00117\ S^2D$ S = Speed (mph) D = Degree of curve	American Railway Engineering Association, 1990
8	Induced Load from Soil Settlements	20% increase over live load stresses for a two span continuous system	GangaRao, 1981

9	Fatigue Steel	AASHTO Table 10.3.1	AASHTO, 1989
	Concrete Strength	$0.85 f'_c (1 - \frac{\sigma_{st}}{f'_c}) (1 - \log \frac{N}{17})$ N = Number of cycles per year = 26300 (Based on 72 trips/day) f'_c = conc. comp. strength σ_{st} = Sustained stress	Mikami, 1990
10	Aerodynamic and Electromagnetic Forces	Refer to Fig. 3.5.1	Rhodes and Marshall, 1991

Table 3.2.2 Serviceability Limits

No.	Serviceability Type	Limit	Reference
1	Vertical Deflection	(Span length)/2000	GangaRao, 1991
2	Longitudinal Angular Distortion (Differential Settlement/Span Length)	0.005 for Simple Supports 0.004 for Continuous Structures	GangaRao, 1981
3	Human tolerable levels for noise	40-50 dBA (inside the vehicle)	Merritt & Ambrose, 1990; Transrapid, 1991
4	Human response to vibration in amplitude	0.13mm (0.005 in) amplitude @ 3 Hz $a = \text{amplitude} = (DI)\delta_s(2\Pi f_b)^2$ Where DI = Impact Factor $DI = 0.15 + \bar{a}$ $\bar{a} = V/2f_bL$ V = Vehicle Speed $f_b = \frac{\Pi}{2L^2}\sqrt{\frac{E_bI_b}{m}}$ δ_s = static deflections computed with a transverse load distribution factor of 0.7 E_bI_b = Stringer flexural rigidity L = span m = mass/unit length of stringer plus a portion of the deck	Walker, 1971



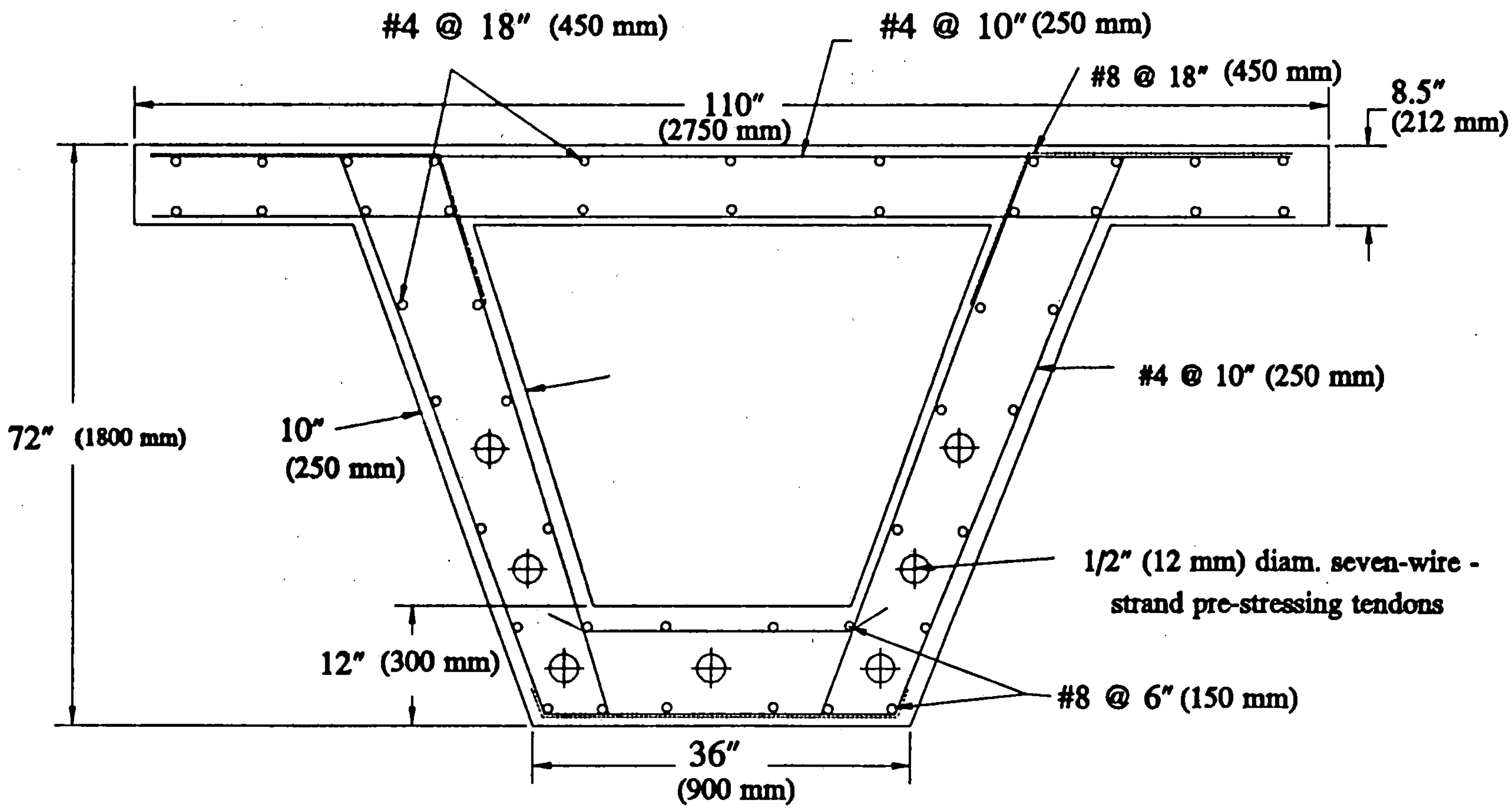
(Note : All Temperatures are Above or Below the Ambient Temperature in Degrees Fahrenheit)

Figure 3.2.1 Temperature Ranges and Distribution Along Deck/Girder Depths configurations, single span systems with and without overhangs, and continuous spans with and without moment transfer capability between the super- and sub-structural components. Guideway systems stiffened with post-tensioned cables were also considered in our analysis for longer spans, i.e., up to 92 m (300 ft.).

Of the sixteen conceptual systems, seven configurations were selected for a detailed assessment of design, construction, and maintenance efficiency and a basis of selection is described in Appendix A of this report. The seven guideway systems, shown in Figures 3.3.1 through 3.3.7 are as follows: (1) trapezoidal concrete box with conventional steel reinforcement, (2) trapezoidal concrete box with FRP reinforcement, (3) rectangular concrete box, (4) all steel trapezoid box, (5) hybrid system with concrete upper and lower decking stiffened by steel truss members, (6) hybrid system with concrete upper and lower decking stiffened by FRP truss members and (7) an all FRP box section.

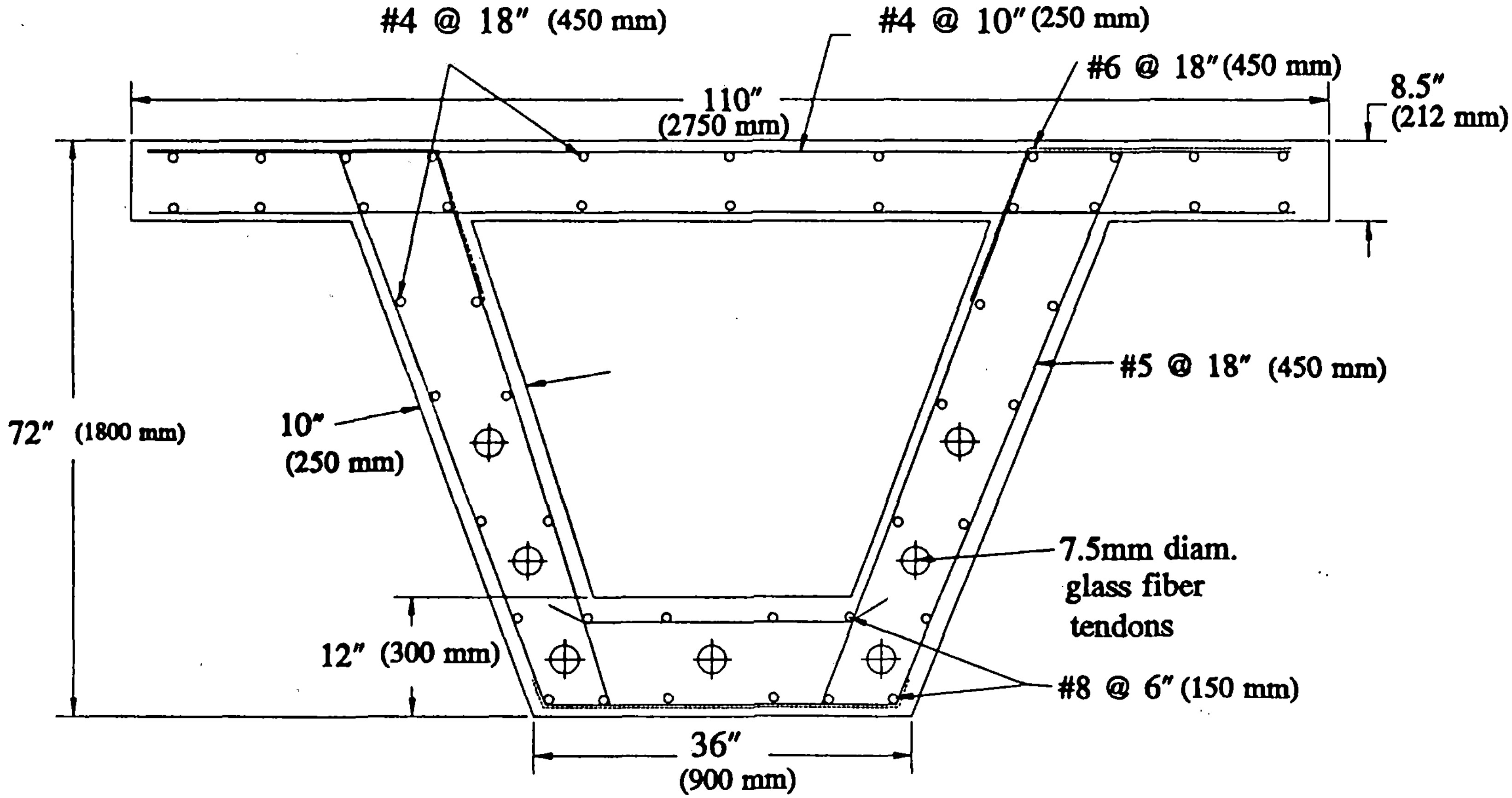
The guideway truss systems with steel and/or FRP members utilize less material and are easier to erect. Furthermore, erection of modular guideway systems with FRP members becomes quicker because FRP members are five to six times lighter than steel. However, the FRP truss joint design and detailing need special attention. To utilize the higher strength of FRPs in an efficient manner and to increase the stiffness of a structural system, the modular truss configuration using FRP members was selected for further studies and additional details are provided in Section 3.4. The conventional in-situ construction practices are possible at the expense of quality of workmanship and economics (Warszawski, 1990).

Special attention is focused on the trapezoidal and rectangular box sections because they have been typically used for steel, concrete, and hybrid materials. The trapezoidal and rectangular sections are efficient in resisting loads in lateral, transverse, and longitudinal directions under bending and torsion. Shallower depths can be achieved through these



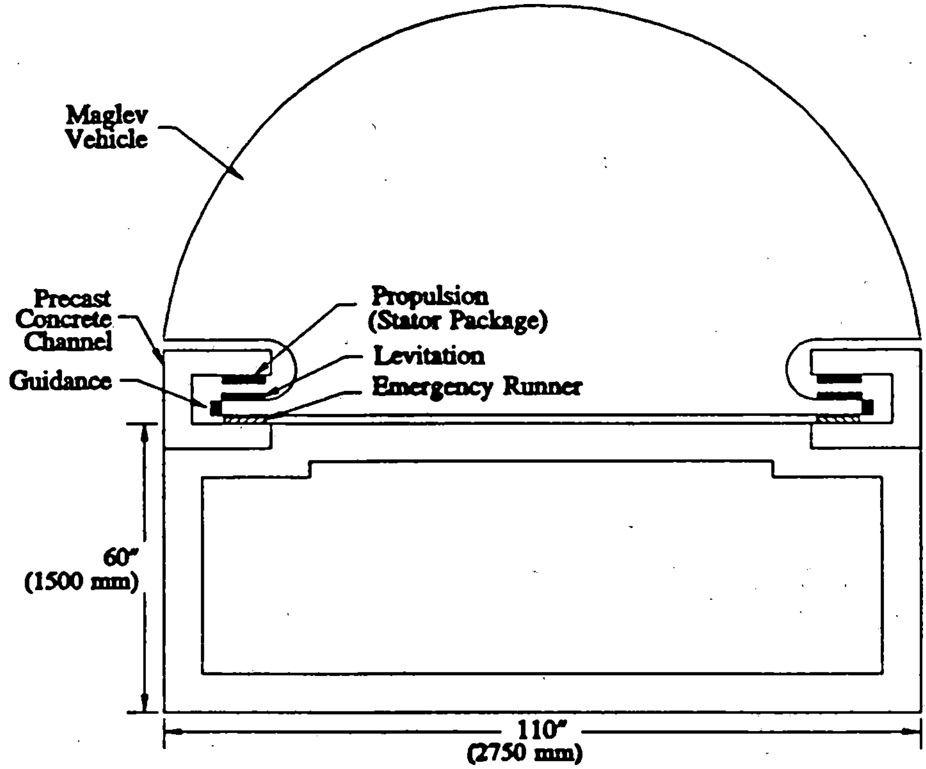
Note: Not shown is the anchorage zone reinforcement, #10 stirrups @ 4" (100 mm) within critical anchorage zone, which is h/2 = 36" (900 mm). For details, refer to Wendlik, 1992.

Fig. 3.3.1 Cross sectional Details - Concrete Maglev Guideway System with steel rebars

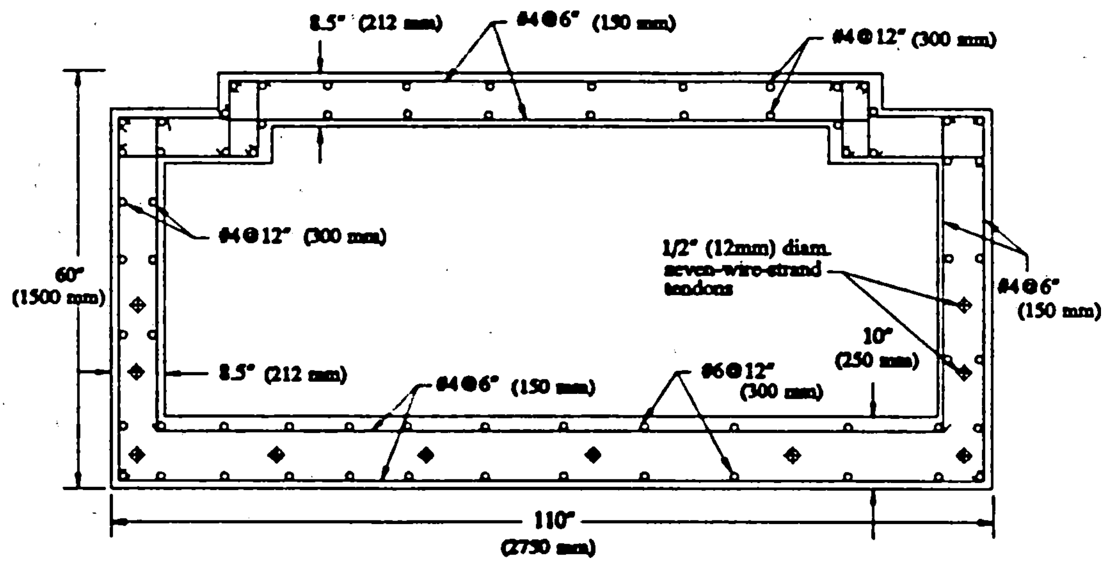


Note: Not shown is the spiral reinforcement cage for the tendon anchorage zone. For additional details, refer to Wendlik, 1992.

Fig. 3.3.2 Cross Sectional Details - Concrete Maglev Guideway System with FRP Rebars



Rectangular Concrete Box Section for Maglev Application



Note: Anchorage Zone Reinforcement not shown: 10 #11 Stirrups @ 3" (75 mm) within critical zone

Fig. 3.3.3 Cross Sectional Details - Rectangular Concrete Maglev Guideway System with Steel Rebars

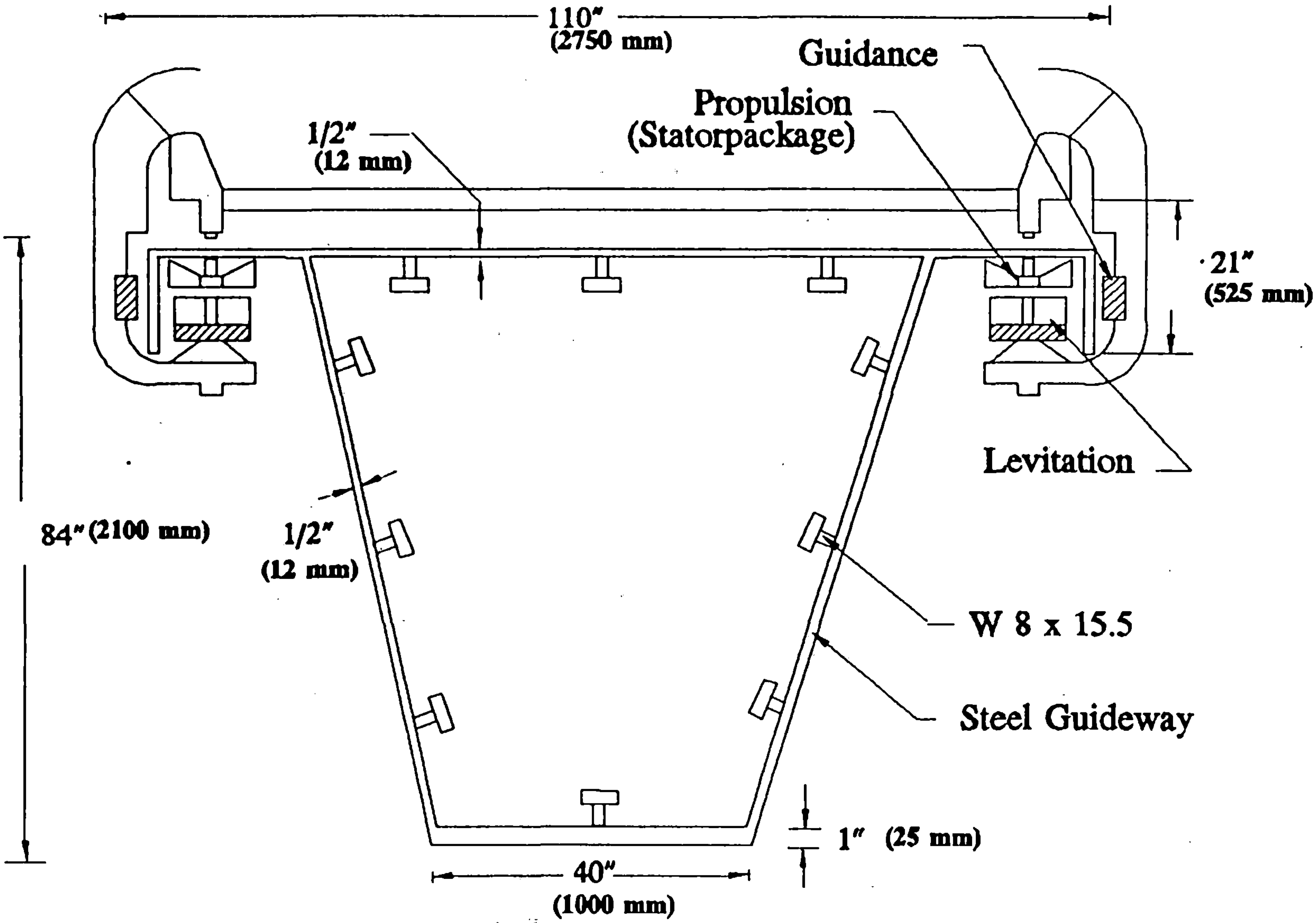
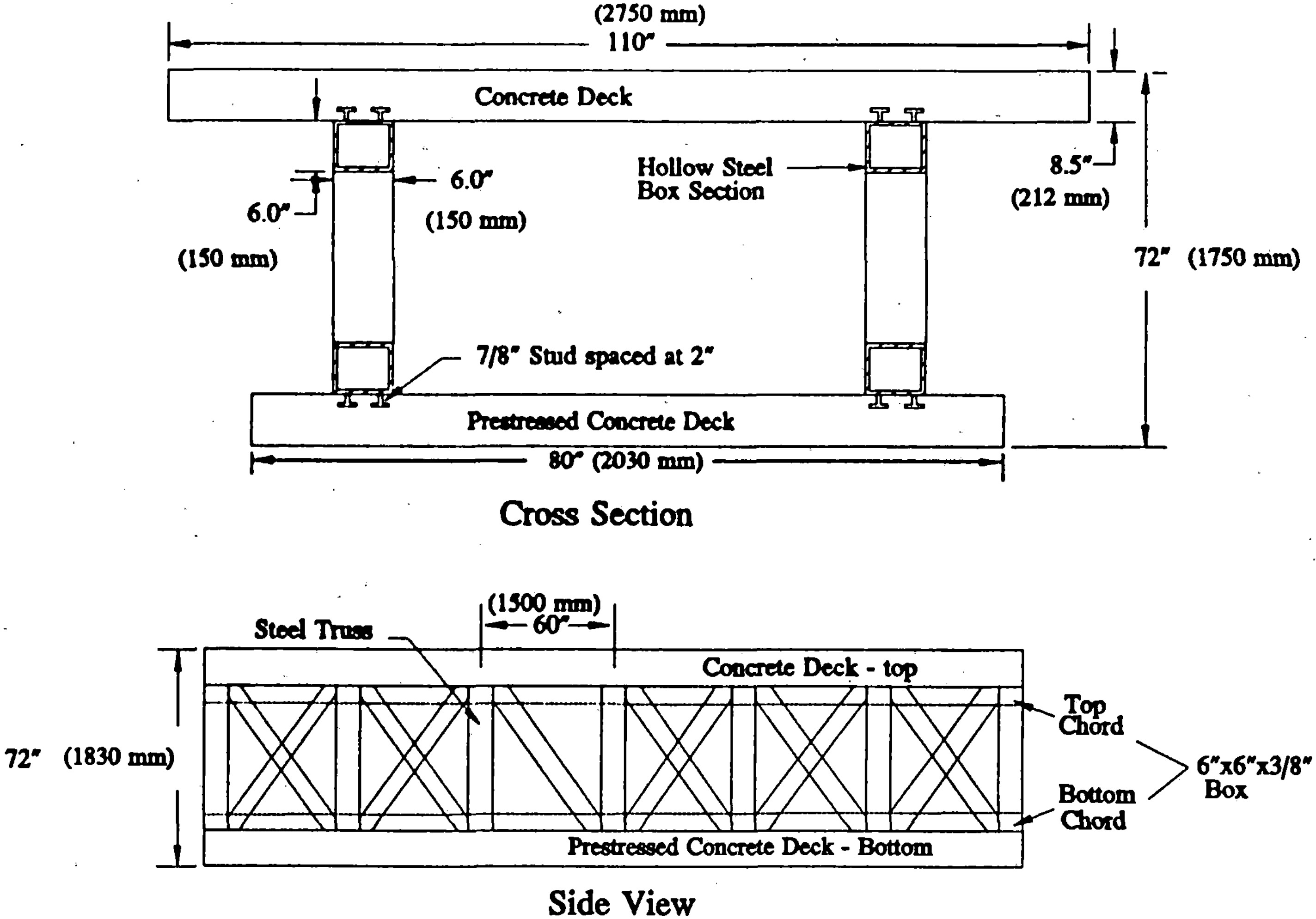
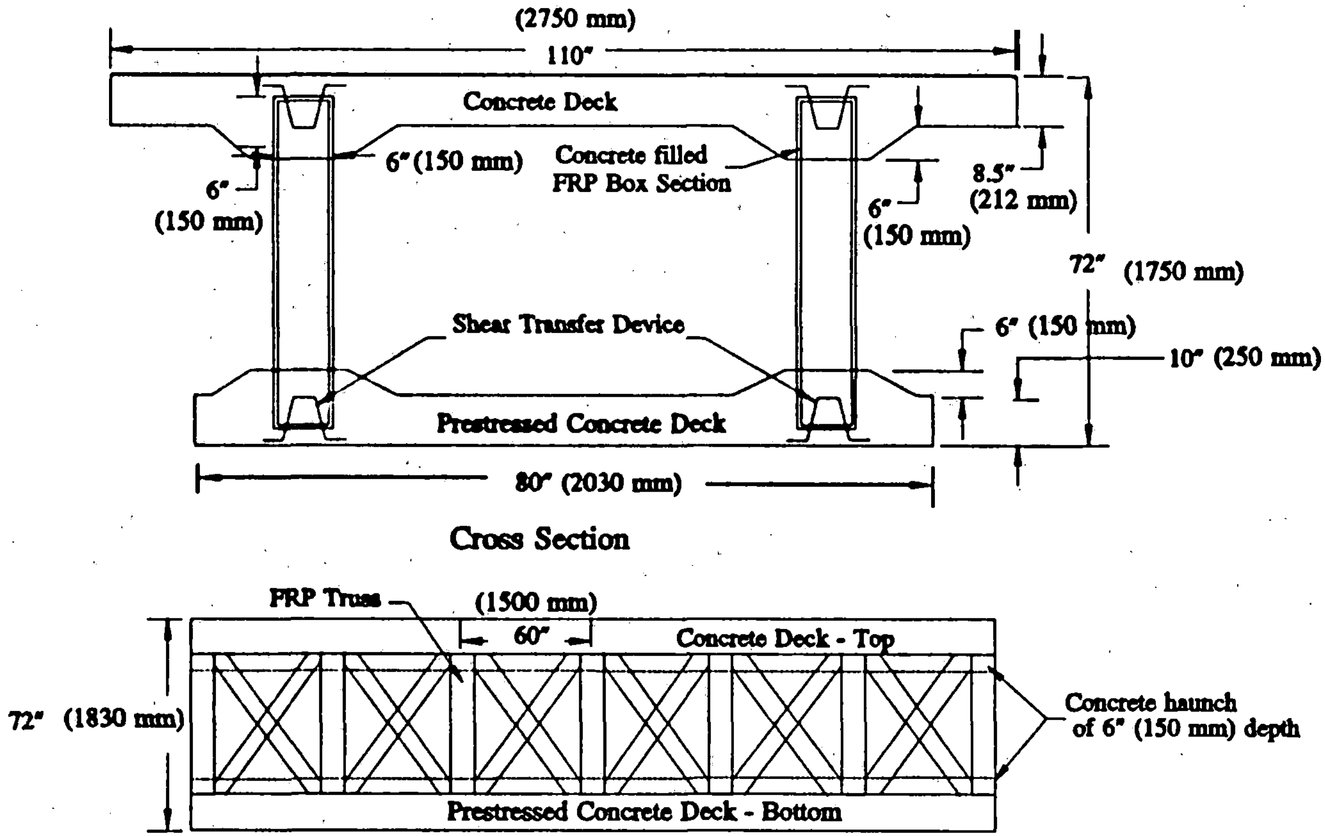


Fig. 3.3.4 Cross Sectional Details - Steel Maglev Guideway System



Note : For additional Details refer to Kim, 1992.

Fig. 3.3.5 Hybrid (Concrete - Steel) Guideway System (80′ Span)



Side View

Note : For additional Details refer to Kim , 1992.

Fig 3.3.6 Hybrid (Concrete - FRP) Guideway System (80' Span)

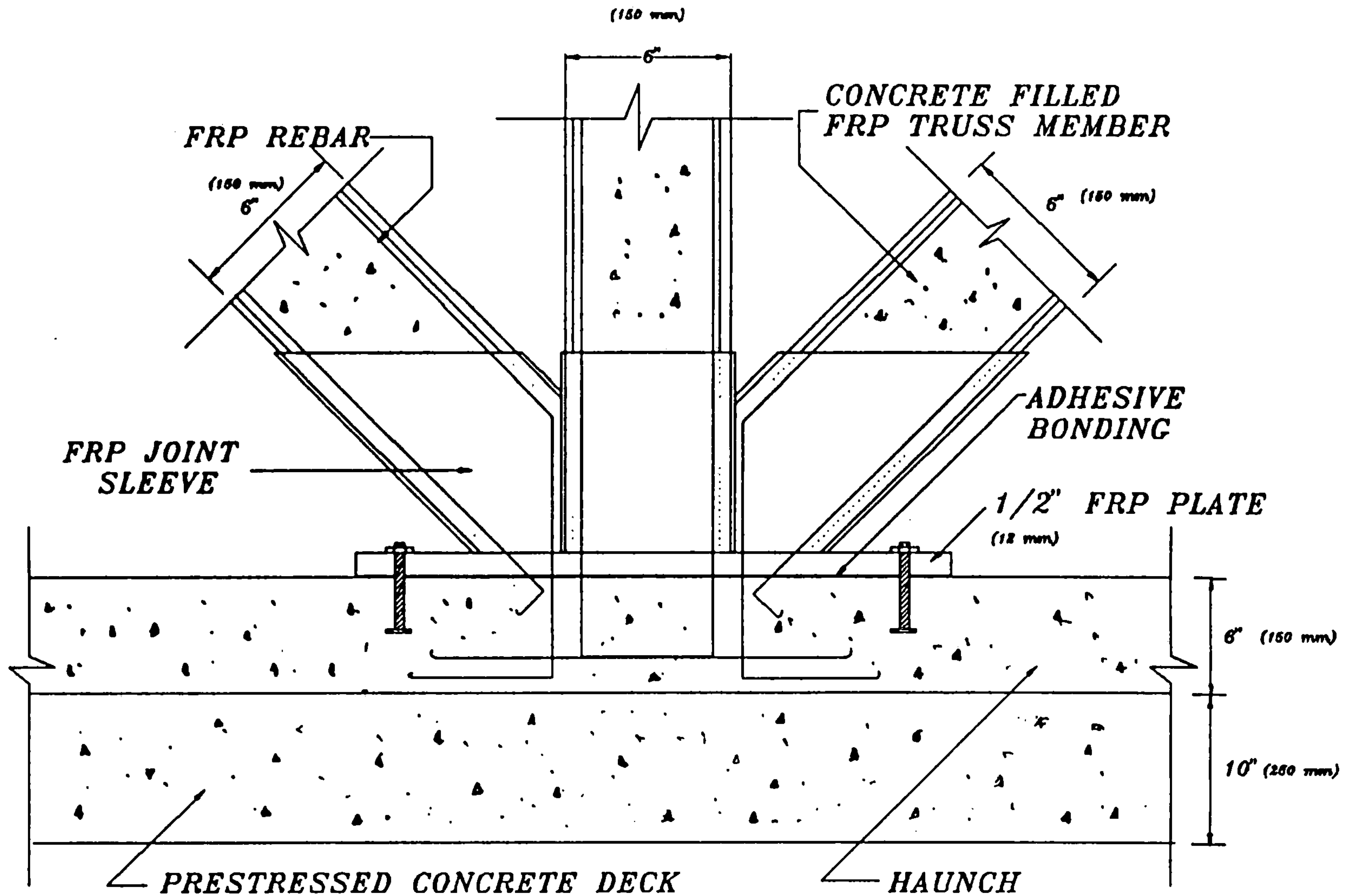


Fig. 3.3.6A TRUSS MEMBER CONNECTION DETAIL

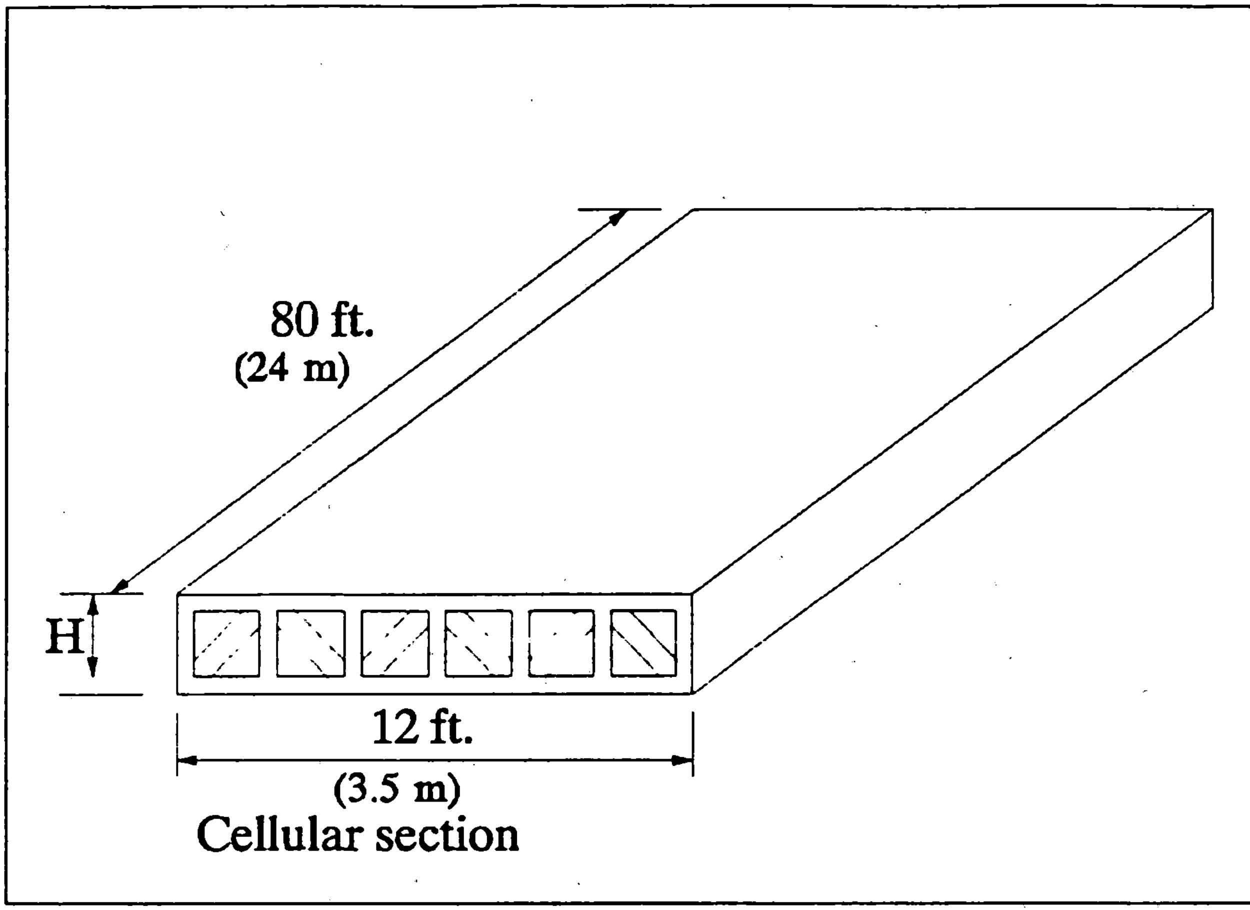


Fig. 3.3.7 All FRP cellular box system.

SUPPORT	FIBER	Depth H (in)
Simply Supported	Carbon	93.7
Clamped - Clamped	Carbon	42.2
Simply Supported	Glass	92.5
Clamped - Clamped	Glass	55.9

configurations, provided that local and global buckling are prevented by using web and flange stiffeners. Single span systems were studied from design, manufacturing and erection points of view. Additional details on design and erection can be obtained from Wendlik's report (Wendlik, 1992).

Single span systems can be converted to continuous span systems in the field through post tensioning or other joining techniques where nonprestressed rigid joints can be achieved in the field. Through continuity of multiple span systems, nearly uniform moment resisting capability can be attained in all spans. Multiple span systems have a smaller number of discontinuous joints than a single span system, leading to improved ride quality.

The in-plane stresses induced by acceleration, braking, and thermal forces should be properly accounted for in the design. Therefore, full moment transfer capacity has to be incorporated in the guideway design to effectively transfer acceleration and braking forces from the guideway to the supports. The moment transfer capability between super- and sub-structures has been researched in multiple guideway systems for their structural efficiency in transferring vertical and horizontal loads and found to be more efficient than single span guideways. In addition, joint locations (super- and sub- structure junction or sub-structure and footing junction) and joint types (roller, hinge, or rigid) have to be evaluated to optimize the guideway system efficiency.

The span length of 24.4 m (80 ft.) has been selected for this analysis. In continuous multiple span cases, because of redistribution of support and center span moments, the design span length can be increased to 30.5 m (100 ft.) or more without changing the cross sectional properties of a single span system designed for 24.4 m (80 ft.) spans. The span length may have to be increased in valleys to limit substructure height and to minimize the overall cost of a system. Even though cable stiffened superstructural guideway systems may turn out to be more economical than conventional guideways, additional details are not developed herein because of uncertainties in terms of long term performance of anchorage details, aerodynamic drag forces and torsional instability.

3.4 PERFORMANCE ASSESSMENT FOR MAGLEV GUIDEWAY SYSTEMS.

Two basic design approaches - working stress and load factor design - are used by the structural designers for bridges, buildings, and many other types of structures. For a Maglev elevated guideway system, the working stress design approach is recommended because the design is controlled by deflection limits rather than the strength limits.

The stresses and deflections were computed for the seven selected systems based on the conventional elastic design method. The finite element method was used to analyze some of the guideway systems. The stresses and deflections for all seven systems are shown in Tables 3.4.1 and 3.4.2. The live load (LL) deflection limit of 7.5 mm (0.25 in) for a 24.4 m (80 ft.) span and a 24.6 kN/m (1700 lb/ft) load is set for all three systems. The calculated stresses in all three systems are lower than the allowable stresses of the different materials. The dead loads (DL) of steel, concrete, and hybrid systems are about 11.65 (800), 36.42 (2500), and 32.05 (2200) to 40.8 (2800) kN/m (lb/ft.), respectively. The merits of each system are further investigated from the viewpoint of modular construction. In addition, detailed designs of superstructural systems with FRP truss members and FRP boxes were developed by Burnside, 1992, to compare their design efficiency, constructability, and cost competitiveness with conventional guideways.

3.5 POTENTIAL USE OF INNOVATIVE MATERIALS

Applications of fiber reinforced plastics (FRPs) in non-structural components of vehicles are well known (Green and Bisavnsin 1986, 1987, and Green, 1990). Also, additional information on the structural applications of FRP materials can be obtained through several references (Green and Bisavnsin, 1986, 1987, and Green, 1990; Ballinger, 1990, Smallowitz, 1985). The additional structural applications deal with FRP bridges, gable frames, industrial buildings and others. The technical literature on FRP bridges and frames can be utilized in fine-tuning the design computations of strength and stiffness for FRP Maglev guideway systems. Additional details on applications are given in Section 3.5.2. We concentrated our effort on the evaluation of FRPs for load carrying structural applications in Maglev guideway systems.

3.5.1 Evaluation of Magnetic Field Interference

While in motion, a magnetically levitated vehicle induces eddy currents in metal which is within the magnetic field of the lift magnets (Rhodes and Mulhall, 1981). These undesirable eddy currents cause electromagnetic forces that resist forward motion and lead to increased guideway component temperatures. Such temperature increases become a source of energy loss for a Maglev system. This particular type of energy loss has been termed the magnetic drag force on the vehicle.

The theoretical determination of the magnetic drag force is a very complex problem which varies greatly from system to system. Factors which affect the magnetic drag force are as follows: the type of system (i.e., electrodynamic versus electromagnetic suspension); configuration of magnets, number of windings, current through the lift magnets; the height of

Table 3.4.1 Bending Stresses in Different Guideway Systems

TYPE OF GUIDEWAY	Moment of Inertia mm^4 (in^4)	Prestress + DL Stress MPa (ksi)		Prestress + DL + LL Stress MPa (ksi)		Prestress + DL + LL + I Stress MPa (ksi)		REMARKS
		Top	Bottom	Top	Bottom	Top	Bottom	
Trapezoidal Concrete Box (with steel or FRP rebars) D.L. 36.42 kN/m (2500 lb/ft)	9.29×10^8 (1.44×10^6)	0.3654 (0.053)	7.6117 (1.104)	2.758 (0.400)	3.385 (0.491)	4.737 (0.678)	0.048 (0.007)	Whole section prestressed with a tension force of 5044 kN
Rectangular Concrete Box D.L. 41.59 kN/m (2855 lb/ft)	9.16×10^8 (1.42×10^6)	3.296 (0.478)	4.985 (0.723)	5.771 (0.837)	2.703 (0.392)	7.756 (1.125)	0.883 (0.128)	
Trapezoid Steel Box D.L. 11.65 kN/m (800 lb/ft)	1.42×10^8 (0.22×10^6)	8.412 (1.220)	11.514 (1.670)	26.269 (3.810)	35.921 (5.210)	40.541 (5.880)	55.433 (8.04)	Prestress force is zero
Hybrid (Conc. deck & steel Truss) D.L. 32.05 kN/m (2200 lb/ft)	1.10×10^9 (1.71×10^6)	2.827 (0.410)	4.723 (0.685)	5.033 (0.730)	2.379 (0.345)	6.826 (0.990)	0.517 (0.075)	Bottom deck is prestressed with force of 4003 kN
Hybrid (Conc. deck & FRP truss) D.L. 40.79 kN/m (2800 lb/ft)	1.10×10^9 (1.71×10^6)	3.309 (0.480)	3.896 (0.565)	5.171 (0.750)	1.758 (0.255	6.619 (0.960)	0.0345 (0.005)	Bottom deck is prestressed with force of 4003 kN
FRP Box	6.7×10^5 (1.04×10^6) for SS & Glass Fiber	No prestress	No prestress	18.616 (2.700)	18.616 (2.700)	No prestress	No prestress	For fixed end conditions. No prestress. Buckling results available in Burnside, 1992
	2.77×10^8 (2.3×10^5) for SS & Carbon Fiber	No prestress	No prestress	55.159 (8.000)	55.159 (8.000)	No prestress	No prestress	

Table 3.4.2 Deflections in Different Guideway Systems

TYPE OF GUIDEWAY	DL mm (Inches)	LL mm (Inches)	Impact mm (Inches)
Trapezoidal Concrete Box with Steel or FRP Rebars	10.083 (0.397)	6.756 (0.266)	5.410 (0.213)
Rectangular Concrete Box with Steel Rebars	9.550 (0.376)	6.528 (0.257)	5.207 (0.205)
Trapezoidal Steel Box	2.896 (0.114)	6.121 (0.241)	4.902 (0.193)
Hybrid (Concrete - Steel	7.442 (0.293)	6.198 (0.244)	4.953 (0.195)
Hybrid (Concrete - FRP)	10.973 (0.432)	6.223 (0.245)	4.978 (0.196)
FRP Box	0.000 0.000	13.513 (0.532)	10.810 (0.427)

the vehicle above the guideway; guideway design; and the presence and configuration of reinforcing material in the guideway.

A literature review dealing with the magnetic drag force of certain systems reveals one common result. At low speeds (below 100 kmph) the drag force increases monotonically with speed (Rhodes and Mulhall, 1981). At speeds above this value, the drag force is inversely proportional to the vehicle speed. Different systems yield different proportions; some vary with the inverse square, with the inverse 3/2 power, or the inverse square root of the speed. The basic shape of the curve remains the same for all systems as shown in Figure 3.5.1. When the type of Maglev system has been clearly defined (type of levitation and propulsion, vehicle magnet configuration, etc.), the magnetic drag force can be theoretically and experimentally determined.

Metal reinforcement within the guideway can greatly increase the drag force depending on the system design. The design of the reinforcement within the guideway also affects the drag force. If steel reinforcement is used, steel mesh increases the drag force much more than the use of individual steel rods because they provide a better conducting path for the eddy currents. One experimental study (Atherton, et al., 1970), gives a lift/drag ratio of 0.755 for welded mesh compared to a 1.75 lift/drag ratio for steel rods. These results indicate that welded steel mesh is unacceptable as reinforcement for that particular system. In electrodynamic systems which have aluminum levitation strips, reinforcing steel within the guideway may be less of a problem. Eddy currents only penetrate an aluminum sheet to a certain depth. This is known as the "skin effect." If the aluminum sheet on the guideway is thicker than the skin depth, the magnetic field does not penetrate into the steel reinforcement and no increase in magnetic drag force should occur.

An experimental analysis of the magnetic drag force is possible once the system parameters have been established. A system can be built which would model the Maglev system. A magnet configuration rotating inside a cylinder constructed of the same material as the guideway would simulate the Maglev system. Magnet strength and configuration, vehicle height, and guideway design could be accounted for. The system would be operated at varying speeds and the temperature change of the cylinder would be measured. The temperature change would correspond to energy loss due to magnetic drag force, and the drag force can be calculated from this measurement.

3.5.2 Applications of FRP Material

This subsection explains the strengths and limitations of fiber-reinforced plastic composite material application to Maglev guideway systems. The material applications can be highlighted in terms of primary and secondary structural member applications. The primary member is defined as the one providing structural integrity to a guideway whereas a guideway could perform temporarily without some of the secondary members.

Possible applications of composite material include the guideway superstructure, concrete reinforcement for piers or frame supporting the guideway, various parts of the vehicle, flexible switching for directional changes of the guideways, walkways, cable ducts, earth retaining panels for slope stability, tunnel panels, and attachments to position the magnets for levitation, guidance, and propulsion.

Composite materials perform better as tension and compression members than as bending or shear members. This can be attributed to larger uniaxial stiffness developed in composite

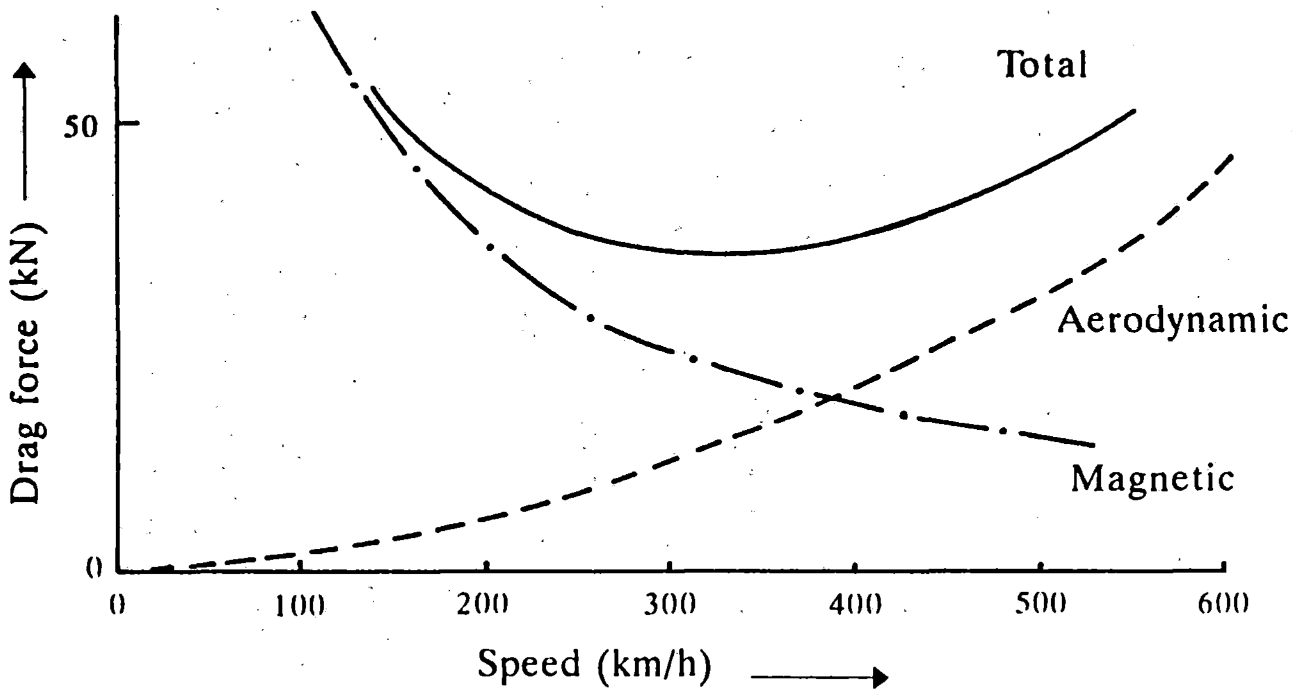


Fig. 3.5.1 Drag Force Versus Speed (Rhodes-Mulhall, 1981)

members which is achieved by aligning the fibers in the direction of the load. Furthermore, the high strength of the fibers is fully utilized in members that are fully in tension or compression. Tension or compression members can be produced at a very low cost by pultrusion. Therefore, truss members, reinforcing bars in concrete, and particularly post-tensioning cables, are believed to be the best candidates for Maglev applications.

Energy losses are expected when steel reinforcement is used in conventional guideways for electrodynamic systems due to magnetic drag. Composite materials are magnetically inert. Therefore, composites may yield significant energy savings if they can be used in lieu of steel reinforcement.

Several alternatives for using FRP composites in the guideway structure have been considered: first, the steel reinforcement of a concrete guideway could be replaced by composite rebars leading to elimination of magnetic drag forces. Second, the use of composite post-tensioning tendons have an advantage over high-strength steel tendons; because the prestress losses of composite cables are lower than those of steel cables because of the lower Young's modulus of the composite cables. Third, noncorrosive hybrid systems could be built with concrete slabs reinforced and post-tensioned with composite rebars and tendons. The slabs could be connected with a light-weight composite truss system. All these techniques would reduce the use of ferrous materials to a minimum. Typical properties of FRP composites are included in Table 3.5.1.

3.5.3 Evaluation of FRP Materials

3.5.3.1 Fibers

Glass, carbon, and aramid (commercial name: Kevlar) are commonly utilized fibers for reinforcement of composite structures. Other fibers such as boron have excellent properties, but they are very expensive for mass production purposes. Only continuous fibers are considered herein. Chopped fibers are not considered for primary structural load applications because they are not continuous, and it is not possible to develop the full fiber strength in either tension or compression.

Glass

Glass fibers come in four types: A-, C-, E-, and S-glass. Typical properties of glass fibers are given in Table 3.5.1, indicating their high strength and low modulus. Only E-- borosilicate) and S- (magnesium aluminosilicate) glass fibers are used for structural applications due to their excellent resistance to water degradation. E-glass is preferred due to its lower cost, i.e., about $1.76 per kilogram. E-glass reacts with alkalis in concrete and, thus, cannot be put in direct contact with concrete. On the other hand, S-glass has an excellent resistance to alkaline reaction and better physical and structural properties than E-glass, but is more expensive, currently costing about $6.6 per kilogram but possibly no more than $2.2 per kilogram in the future if it is mass produced. The FRP rods from E-glass and polyester resin are used as reinforcing bars (rebars) for concrete in the same manner as steel rebars, (Faza, 1992), however, S-glass rods have not been used as reinforcing bars for concrete because of the high initial cost.

Pultruded structural shapes use E-glass in polyester or vinylester resins with special fiber coatings, since there is danger of alkaline reaction between E-glass FRPs and concrete. Structural shapes with E-glass and vinylester have resisted the most aggressive environments in the chemical industry. Their corrosion resistance to the chemical environment developed through halo effects in Maglev guideways is being investigated by the Constructed Facilities

Table 3.5.1 Typical Material Properties of Various FRP Composites with 60% Fiber Volume Fraction.

Volume percent		Young's Modulus		Shear Modulus	Poisson's Ratio	Thermal Coeff.		Mass Density	Cost* in 1992
		E1 (Long)	E2 (Transverse)	G12	$\nu 12$	$\alpha 1$ (Long)	$\alpha 2$ (Transv.)	ρ	
60	40	[GPa]	[GPa]	[GPa]		[1/°C. 10^{-6}]	[1/°C. 10^{-6}]	[kg/m^3]	$/kg
E-Glass	Polyester	13.378	11.255	0.682	0.273	-0.019	-0.018	2.015	2.50 to 3.00
S-Glass	Polyester	14.638	11.746	0.684	0.279	-0.019	-0.018	1.949	10.00
Carbon	Polyester	40.078	15.615	0.706	0.276	-0.017	-0.017	1.484	10 to 60
Kevlar	Polyester	18.478	12.899	0.690	0.294	-0.017	-0.017	1.334	25 to 50
E-Glass	Epoxy	13.382	11.264	0.682	0.258	-0.019	-0.018	2.070	4 to 5
S-Glass	Epoxy	14.642	11.757	0.684	0.258	-0.019	-0.018	2.004	12 to 15
Carbon	Epoxy	40.082	15.633	0.707	0.258	-0.017	-0.017	1.539	20 to 80
Kevlar	Epoxy	18.482	12.912	0.690	0.282	-0.017	-0.017	1.390	30 to 60
E-Glass	Vinylester	13.386	11.274	0.682	0.270	-0.019	-0.018	2.015	2.50 to 3.00
S-Glass	Vinylester	14.646	11.767	0.684	0.270	-0.019	-0.018	1.949	10.00
Carbon	Vinylester	40.086	15.651	0.707	0.270	-0.017	-0.017	1.484	10 to 60
Kevlar	Vinylester	18.486	12.924	0.690	0.294	-0.017	-0.017	1.334	25 to 50

*prices vary somewhat with place, volume, inflation, demand and improvements in technology (aluminaCenter (Faza, et. al., 1992); but it is expected to be excellent (Fried, 1967). This is in contrast to the rapid degradation experienced by mild steel reinforcement in concrete (Stratfull, 1984) under a corrosive environment.

Aramid (Kevlar)

Aramid fibers (e.g., DuPont's Kevlar) have lower strength but higher stiffness than glass fibers. Aramid fibers have excellent impact properties and negative coefficients of thermal expansion. Aramid fiber costs range from $13 to $22 per kilogram. Low modulus Kevlar 29 is the least expensive fiber whereas high modulus Kevlar 149 is the most expensive fiber.

Aramid fibers are being used to develop high-strength rebars and cables by U.S. and Japanese manufacturers (Vega Technologies, 1988; Kodiak, 1989; Kakihara, et al., 1991). Aramid fibers have good chemical resistance to solvents, dilute acids and bases, as well as excellent fatigue strength and low relaxation (Kakihara, et. al., 1991; Pleimann, 1991). Typical properties are given in Lubin (1981) and are summarized in Table 3.5.1. The use of aramid fibers in construction is limited due to their water induced degradation. According to the present research trends, aramid fiber reinforced plastics do not seem to have high potential for application in construction because of their high initial cost and less than satisfactory performance.

Carbon (Graphite)

A broad variety of carbon fibers is commercially available. Typical properties of various carbon fibers are provided in Lubin (1981). Properties of carbon fiber composites are summarized in Table 3.5.1. According to their performance, carbon fibers are classified as low modulus - high strength (LM-HS), medium modulus - medium strength (MM-MS), and high modulus - high strength (HM-HS) materials. The latter are very expensive ($220 per kilogram), with limited possibilities of cost reduction in the future; therefore, guideway applications are most likely to use LM-HS materials because of their cost advantage over other fibers. The cost of LM-HS carbon fibers is becoming competitive (currently at about $20 per kilogram) and carbon fibers have the advantage of resisting virtually any chemical attack. MM-MS have a higher modulus of elasticity than glass fibers (LM-HS). The cost of MM-MS carbon fiber has been coming down over the last few years (less than $110 per kilogram) with cost expected to decrease to about $22 per kilogram over the next five years because of excessive plant production capacity and the decrease in demand from the U.S. defense industry.

Carbon fiber reinforced plastic rebars and seven-wire cables (Fig. 3.5.2) with higher stiffness than glass or aramid rebars are manufactured as reinforcing or prestressing elements for structural application (Kakihara, et. al., 1991). However, carbon fiber rebars and cables are more expensive than aramid or glass rebars.

3.5.3.2 Matrices

The matrix in a composite material serves as a binder and keeps the fibers together while transferring stresses from one fiber to another. Any material can be used as a matrix, but processing problems limit the number of practical matrices. Metals are being used for medium temperature applications (e.g., internal combustion engines), but their market is being eroded by advanced ceramic composites. Metal matrix composites (MMC) are expensive and the available production processes are limited to small parts.

The most successful composites for low temperature applications (e.g., guideways and highways) are polymer matrix composites (PMCs). PMCs are based on thermoset or thermoplastic polymers. Thermoset polymers undergo an irreversible chemical reaction from their original liquid state into their final solid state. The chemical reaction is called cure. Cured thermoset matrices cannot be reshaped or welded. Thermoplastics are usually solid in their original state. They can be brought to a viscous state repeatedly by an increase in temperature in order to process them along with the fibers into a composite; therefore, thermoplastic composites can be reshaped, welded, and repaired similar to metals. Thermoset polymers are less expensive and more developed than thermoplastics resins. Thermoset polymers also have excellent mechanical properties and resistance to chemical attack. Some of the more popular thermoset polymers are polyesters, vinylesters, epoxies, polybutadienes, and phenolics.

Thermoplastics are more expensive and difficult to process due to their high viscosity in their melted state but they can be reshaped and welded. They have excellent resistance to chemicals and impact loads. The more popular thermoplastics are Nylon, PEEK, and ABS.

Polyester resins

Unsaturated polyester resins are very common, with a U.S. production of more than a billion pounds a year. Polyester resins are mainly used in fiber reinforced plastics in the production of boats, building panels and parts of automobiles, aircraft, and appliances. Therefore, a good history of degradation with time and exposure to chemicals is available. Resistance of polyester resins to deicing chemicals is being investigated, and it is expected to

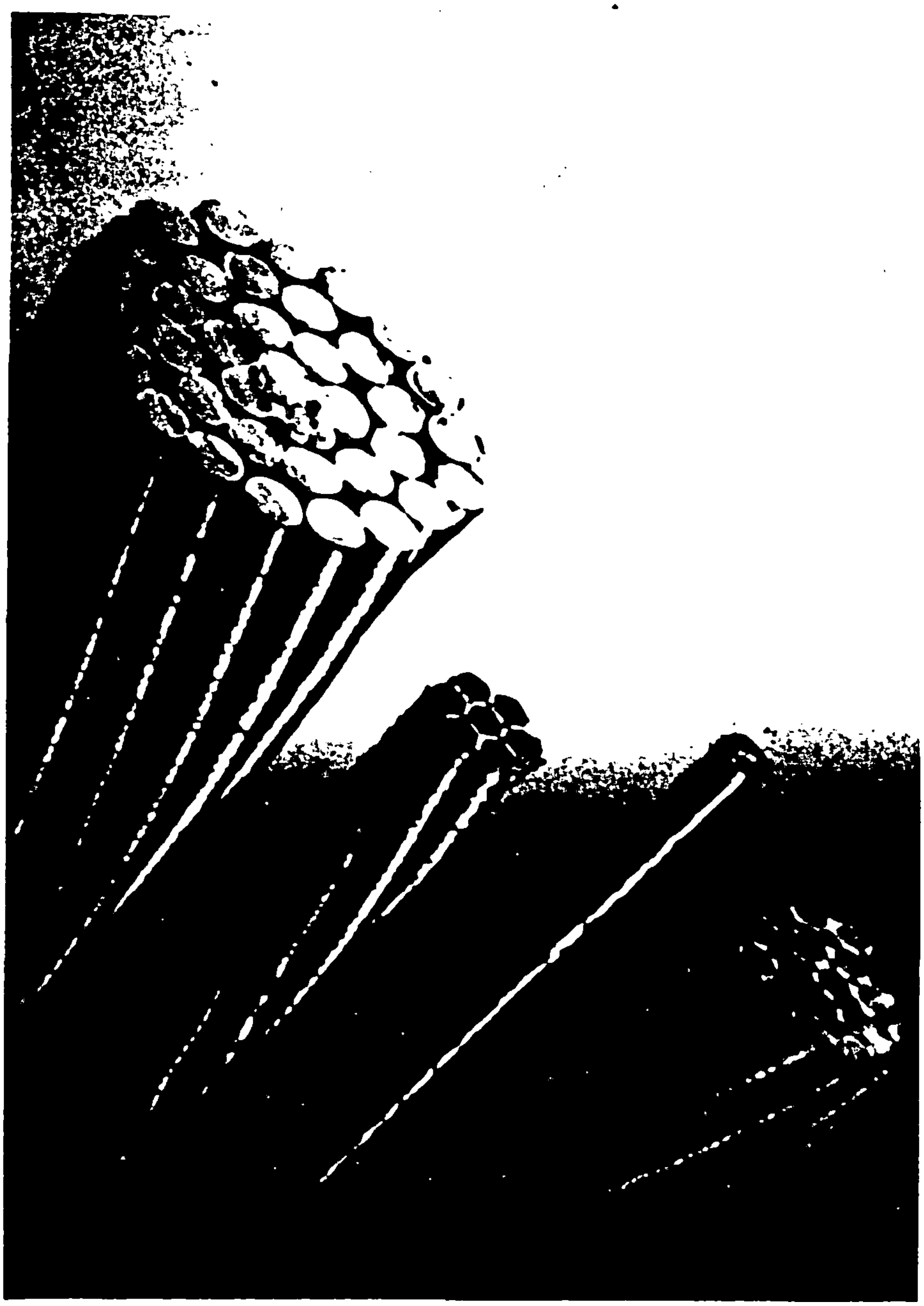


Figure 3.5.2 Cables with One, Seven, Nineteen and Thirty Five Strands.

be excellent. Polyester resins come in a broad variety of formulations, all of which emphasize various features such as flexibility, resilience, low-shrinkage, weather-resistance, chemical-resistance, fire-resistance, etc. Properties of cast polyester resins (without reinforcement) are given in Table 3.5.1. Regular polyester resins shrink 4% to 8%. The cured polymer is relatively brittle, being able to sustain elongations of about 5%.

Poor resistance to alkali, typical of polyester resins, is improved in chemically-resistant resins used for vessels, tanks, pipes, and fume hoods. Ordinary polyester resin reinforced with glass fibers is combustible but at a low burning rate. Once the surface of the FRP burns out, the glass fibers form a barrier to further combustion. Special formulations and additives are used to retard the ignition and burning of polyester resin composites.

Polyester resins are ideally suited for pultrusion because they expand before gelation, thus producing a highly consolidated part with little voids. After gelation, the exothermic reaction completes the curing process and the polyester resin shrinks, thus releasing the composite part from the wall of the pultrusion die. Pultruded composite products are perhaps the least expensive (Lubin, 1981), making pultrusion one of the most economical production techniques.

Vinylester resins

Vinylesters are very popular resins for pultruded products due to their excellent resistance to acids, bases, and solvents. Therefore, vinylester resins are used for pipes, ducts, scrubbers, flue stacks, and storage tanks. Mechanical properties of cast vinylester resins (not reinforced) are given in Lubin (1981). The mechanical proprieties of fiber reinforced polymer composites made of vinylester resins are given in Table 3.5.1.

Epoxies

Epoxy resins have superior mechanical properties. They shrink less than polyesters, vinylesters, and phenolics during cure, which makes epoxy resins very good adhesives. Typically, epoxies shrink 0% to 2% during cure. The cured polymer can sustain elongations of about 5%, although flexible epoxies can sustain up to 10% elongation. Epoxies are resistant to chemicals and are good electrical insulators. Typical properties of cast epoxy resins (not reinforced) are given in Table 3.5.1. The main reason for using epoxies is their superior properties. The strength of epoxies is about 50% to 100% better than polyesters and vinylesters. The cost of these materials ($6 to $22 per kg) has not been detrimental to the aerospace industry because they contribute greatly toward composite performance. New epoxy resins that can be pultruded have been recently introduced into the market (e.g. Shell introduced the EPON line of resins).

Polybutadiene resins

Polybutadiene resins have been used in compression, transfer, and injection molding processes as well as in pre-pregs and wet lay-out but not in pultrusion. However, the cure characteristics are similar to those of polyester resins. Polybutadiene resins have excellent resistance to acids and bases. The main feature of these resins is their low dielectric constant (dissipation factor), making them attractive in the presence of high-frequency electromagnetic radiation. This property may be useful for specialized applications in Maglev.

Phenolics

Phenolic resins are also attractive because they are based on renewable materials such as wood. Furthermore, phenolic resins have fire retardant properties superior to any other resin discussed thus far. One of the problems of phenolic resins is that they are difficult to pultrude. This problem, however, is being addressed successfully by the industry. Cost of phenolic resins is not very sensitive to oil prices and is currently comparable to that of polyesters.

Thermoplastics

Thermoplastic polymers do undergo physical, not chemical, transformation during processing. Thermoplastics are a combination of amorphous (like glass) and crystalline (like graphite) polymers. At ambient temperature, thermoplastics behave as viscoelastic materials, i.e., they are solids with properties depending on time and temperature. Significant increases in temperature lead to decreases in viscosity which allows thermoplastics to be processed along with fibers into a composite. The main advantages of thermoplastics are that they can be easily shaped, reshaped, repaired, welded, stitched, and recycled. Furthermore, some thermoplastics have higher toughness and impact resistance than thermosets. However, processing thermoplastics is more difficult because of their higher viscosity. Some well known thermoplastics include polypropylene, polyethylene, nylon, polycarbonates, polyvinyl chloride, polysulphones, thermoplastic polyesters, Acrylonitrile-butadiene-styrene, polyetheretherketone (PEEK), etc. Typical properties of thermoplastics are given by Ahmad and Plecnik (1989).

3.5.3.3 Core Materials

Core materials can be used in Maglev structural components to reduce the volume of high grade composites and reduce material costs, without sacrificing the quality. Innovations in terms of foam-core panel systems are being researched in order to reduce construction costs and improve earthquake resistance (GangaRao and Dlugos, 1986). The pultruded GFRP materials and shapes marketed by Creative Pultrusions have cores and are used as floor panels. The extruded core marketed by Siteco (Plastbau, 1990) of Italy has hollow sections spaced as forms in such a way as to accomodate reinforced columns. A sandwich panel with glass fiber reinforced concrete facings and polystyrene extruded foam core is being successfully used for walls, partitions, and floor panels. An acrylic emulsion additive in the concrete may inhibit the alkaline reaction between concrete and glass fibers and to improve bond between concrete and the core (McConnell, 1990). The connection between the reinforced concrete columns and the reinforced concrete beams and floor slabs are made using conventional construction methods. The Plastbau system was ranked first in all nineteen classifications in a study by the French government to compare different types of construction using various materials. The salient advantages of this fiber reinforced, sandwich composite material are its modular construction, sound insulation, and thermal insulation.

Although many types of foams have been used in pultruded products, wood is easier to process as a core material during the pultrusion process. The use of thin-walled composite sections coupled with the necessary wood core material may have to be restricted to light structural components, not the major load transfer elements, in any application.

3.5.4. Evaluation of FRP Processing Methods

Several processing methods are discussed herein to address the feasibility of producing guideway components with FRP materials. Most composite production processes have been developed to produce highly complex shapes of relatively small size. The most relevant automated production methods for large-sized structural components are filament winding, pultrusion, and resin transfer molding. These processes are apt to produce structural members with a high content of fiber (above 50% by volume), which is necessary to carry loads for long periods of time as in the case of guideways. It should be noted that hand lay-up techniques are too expensive to mass produce large size components. Similarly, bag or match die molding can not be used economically for large size structural components.

Fiber reinforced polymer composites are a combination of fibers and polymer resin. The processing of composites involves four main operations: fiber placement, impregnation, consolidation, and cure. Different processing techniques are used to accomplish these operations in sequence or simultaneously. Fibers are placed by hand or numerically controlled machines. Both impregnation and consolidation involve the flow of resin through an elastic net of fibers. For some processes, like Resin Transfer Molding (RTM), impregnation and consolidation are performed separately. Once the composite part is properly consolidated, the polymer is cured. Curing involves the cross linking of the polymer. The curing reaction of most polymers is usually initiated by heat and/or pressure. The reaction is usually exothermic with significant changes in the physical constants during cure.

3.5.4.1 Hand Lay-up

The oldest and simplest of all manufacturing techniques for FRP is the hand lay-up process. Sometimes the mold shape of the final product is built by hand lay-up over an original shape. The molder applies a gel coat to the mold which will constitute the surface of the final product. On top, several lamina are stacked and impregnated with resin. Each layer is usually reinforced with a mat or cloth before the next layer is placed. Consolidation of fibers (i.e., extracting air, gas, and increasing the fiber volume fraction) is done by pressing with rollers. Alternatives in achieving higher production rates are either to spray chopped fibers simultaneously with the resin onto the mold or to use prepreg sheets of resin and continuous fibers and cure the material in an autoclave. Since consolidation is difficult in hand lay-up, the fiber volume fraction is usually low, which translates to poor material properties.

Some of the advantages of hand lay-up are: a) large and complex items can be produced, b) tooling cost is low, c) design changes are easy to implement, d) molded-in inserts and reinforcements can be easily accommodated, e) sandwich construction is possible, f) prototyping for other processes is inexpensive, and g) semi-skilled labor is used. Some of the drawbacks of hand lay-up are: a) it is labor-intensive, b) only one surface is obtained, c) quality is related to the skill of the operator, d) it is low-volume process, e) cure time is long, f) product uniformity is difficult to maintain, and g) waste is high. However, it should be noted that such methods of production will be expensive for components of Maglev guideway systems and the hand lay-up method of production is not recommended for Maglev components.

3.5.4.2 Bag Molding

Bag molding is an efficient method of processing FRP while obtaining the desired shape of the cured product. Variants of bag-molding include: vacuum bag molding, pressure bag molding, autoclave bag molding, and press-pressure bag molding.

In vacuum bag molding, layers of fiber mat, cloth, woven roving or pre-pregs are laid-up on a mold, usually metallic. The fiber mat or woven roving or pre-pregs are covered by layers of bleeder plies to allow the escape of air, gas and excess resin. The part is covered by a flexible bag sealed on its contour and an edge bleeder is placed on the boundary of the part and tied to holes in the mold where a vacuum is applied. When vacuum is applied, the atmospheric pressure drives gas, air and resin out of the laminate. Curing is done in air circulating ovens or by other methods, including microwave, radio frequency technique, etc.

Pressure bag molding is similar to vacuum bag molding but the vents are vented to the atmosphere while pressure is applied to the bag. Curing is done by injecting hot pressurized gas to the mold.

Press-pressure bag molding is used for thin parts that can be bag-molded in a heated press which provides the heat source and an efficient method for sealing the bag. A pressurized, heated gas line is connected to the upper press plates. The vents in the lower plateau are vented to the atmosphere as in pressure bag molding. In this case the heat press provides structural rigidity to the pressurized mold.

3.5.4.3 Matched Die Molding

In the matched die molding process, the part is contained between a male and a female mold. This provides excellent dimension reproduction, uniform product quality, and production rates larger than bag molding. Tooling is expensive since two tools are required for each part. Matched die molding is commonly used to mold bulk or sheet molding compounds. Both molding compounds contain the fiber system, the resin and the catalyst. Complex parts can be molded, such as automobile bumpers, and shower floors.

3.5.4.4 Filament Winding

In filament winding, continuous fibers are wound over a mandrel. The rovings are placed on the mandrel by a shuttle that collects the rovings after they are impregnated in a bath of resin. The speed of the shuttle and the spinning of the mandrel determine the winding angle at which the fibers are placed. In order to improve fiber placement for mandrels other than cylinders (ex. the spherical heads of a pressure vessel) more axes are necessary. Computer controlled machines of up to five axes are available. There are basically two types of machines; a helical winding machine and a polar winding machine. Polar machines have a very high production rate, but they are more specialized and less flexible. A wide variety of products of circular or elliptic shapes are made by filament winding including pipes up to 3.65 m in diameter.

3.5.4.5 Resin Transfer Molding

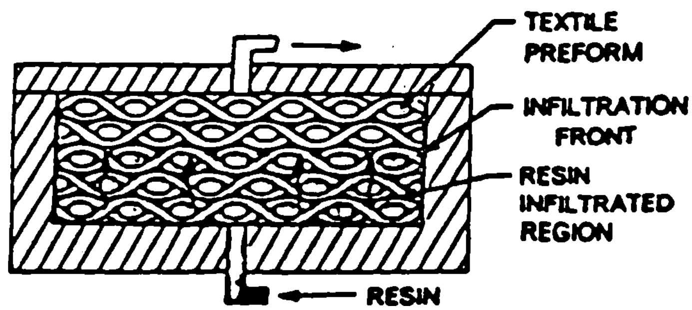
A closed, complete mold, with two or more faces of the final part is used in the Resin Transfer Molding (RTM) process (Fig. 3.5.3). Therefore, virtually unlimited flexibility of part shapes can be accomplished with RTM. The fibers are placed in the mold, then the mold is closed, and the resin is injected. As a result, very good fiber placement and high fiber volume fraction can be obtained with RTM, which results in excellent material properties. The cost of tooling is high but should not be a concern for high production volumes. The production rate is low but the process can be highly automated assuring uniformity of the parts which is essential for structural components. Because of all its advantages, RTM is the process of choice for the production of complex shapes, like connection details, that are needed for guideway applications.

3.5.4.6 Pultrusion

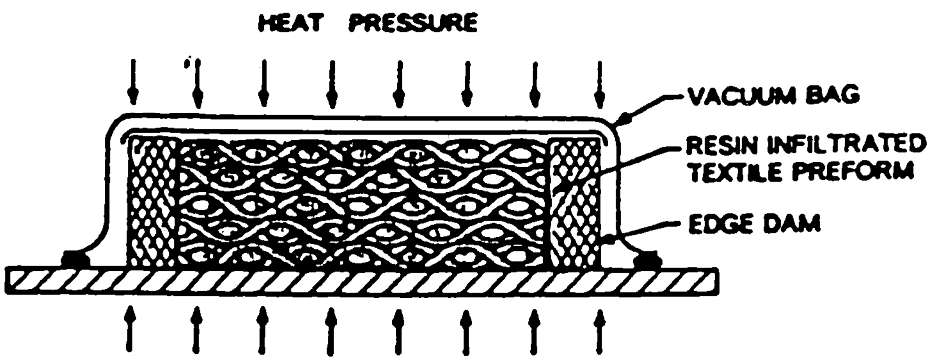
The pultrusion process has one of the highest production rates and the lowest production cost of all the processing techniques discussed herein. Pultrusion is a continuous manufacturing process of FRP prismatic sections. In pultrusion, the fibers are pulled continuously through a resin bath where they are impregnated with the resin (Fig. 3.5.4). The impregnated resins then go through a steel die with the shape of the final product. The steel die serves to consolidate the fiber-resin composite and cure the thermoset resin. Cure of the resin is initiated inside thesteel die by heating the steel die. Cooling may be necessary near the end of the die to dissipate the heat generated by the resin reaction. A caterpillar pulls the finished composite continuously at the exit of the die, and a saw cuts the composites to the required length.

A major modification to the pultrusion process described in this document consists of replacing the wet bath by injection of resin directly at the die. This modality has many advantages. Resins with a short pot-life (the time the resin remains without curing spontaneously) can be used since only the resin that is needed can be prepared directly at the injection port. Virtually no volatiles are released to the atmosphere, resulting in improved environmental conditions at the factory. However, the process can be very expensive and has not been tried extensively.

The pultrusion process can lead to the production of a variety of structural shapes, with unidirectional as well as bi-directional fiber orientations. Additional advances (e.g., fiber connection between back and flange) in mass producing pultruded structural shapes are being actively considered by the pultrusion industry to improve the strength, stiffness and stability of these shapes. Epoxies, phenolics and thermoplastics are being used to pultrude structural shapes in limited quantities.



INFILTRATION



CURE

Fig. 3.5.3 Resin Transfer Molding Process

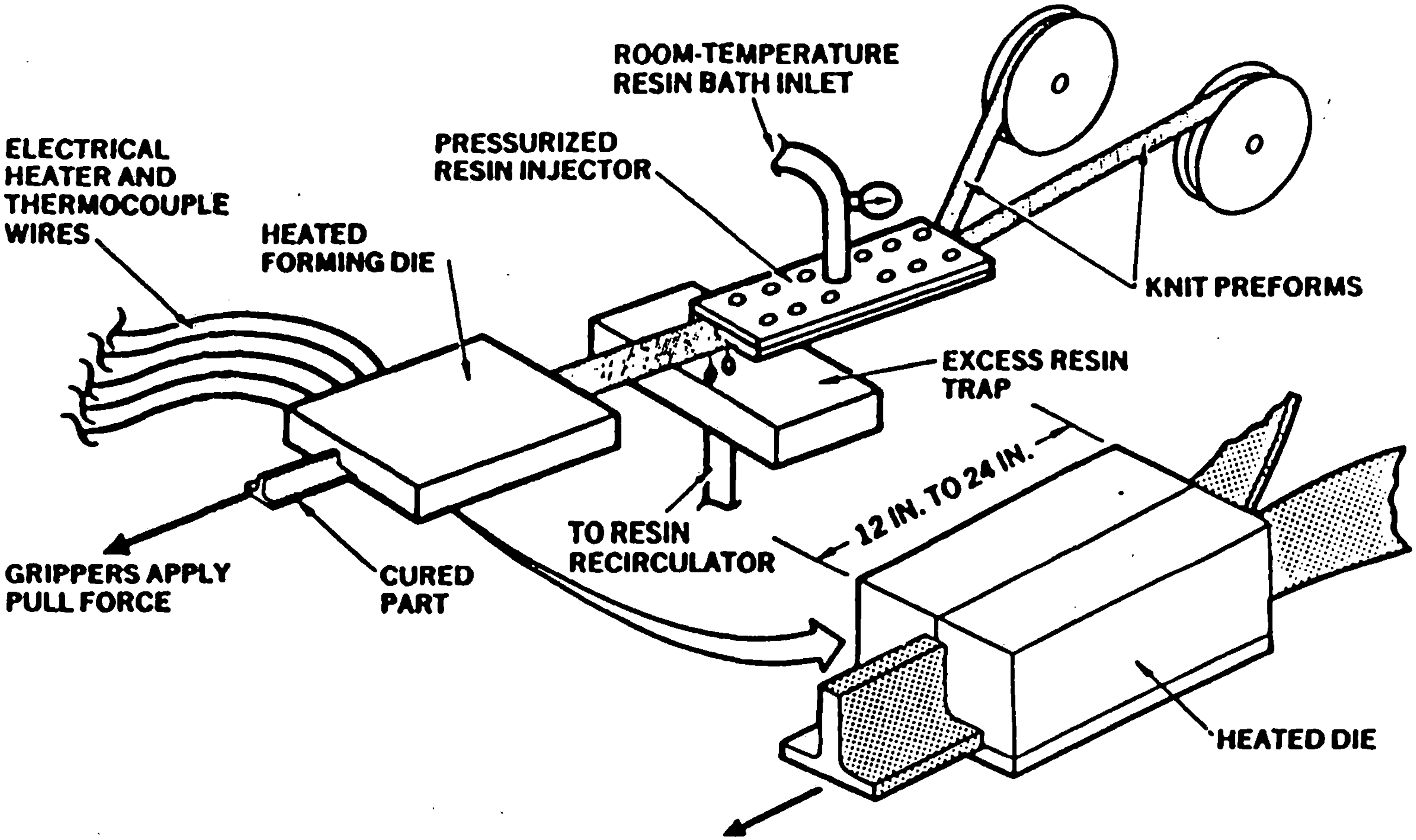


Fig. 3.5.4 Pultrusion Manufacturing Process

Pultrusion of phenolic resins is difficult because phenolics do not expand before gelation; therefore, phenolic pultruded materials tend to have a high void content. In addition, phenolics release water during cure, which tends to be trapped thus forming voids. These shortcomings are being overcome by new pultrusion arrangements such as the injection at the die and by new additives formulated specifically for pultrusion of phenolics.

Thermoplastics are difficult to pultrude due to high viscosity. Thermoplastic resin impregnation is being improved by various methods such as co-mingled fibers, ultrasound and mechanical impregnators, and ultrasound excited dies that reduce the pulling force significantly.

Currently pultruded sections with a cross sectional area of about 9700 mm^2 are commonly produced. The production rate varies from 300 mm/min to 7500 mm/min, depending on the size and complexity of the part. The production rate can be increased by running multiple pultrusion lines simultaneously. The capital investment requirements are low in relation to other manufacturing processes (e.g., filament winding). A cost comparison among various production methods used in aerospace applications is shown in Fig. 3.5.5. A cost comparison among various production methods used for large composite parts is shown in Fig. 3.5.6. From Figure 3.5.6, it can be seen that pultrusion has the lowest cost per part.

In hand lay-up, the operator reads the stacking sequence from the specifications and lays-up the laminate from tape pre-preg. Pre-plied broadgoods are stacks of pre-preg laminae (uncured) that already have the stacking sequence desired. Therefore, the production is faster and cheaper. Pre-plied broadgoods come in rectangular sheets that must be trimmed by hand. Custom broadgoods come already trimmed, making the production faster and cheaper.

The cost and production time of a typical aerospace part that can be produced by all the processes listed in Figure 3.5.6 are shown. The cost of the pultruded part was used to nondimensionalize all the costs in the figure. Four times the production time of the pultruded part was used as a reference time on the figure. It is concluded that pultrusion clearly out performs all other production techniques in cost and production time.

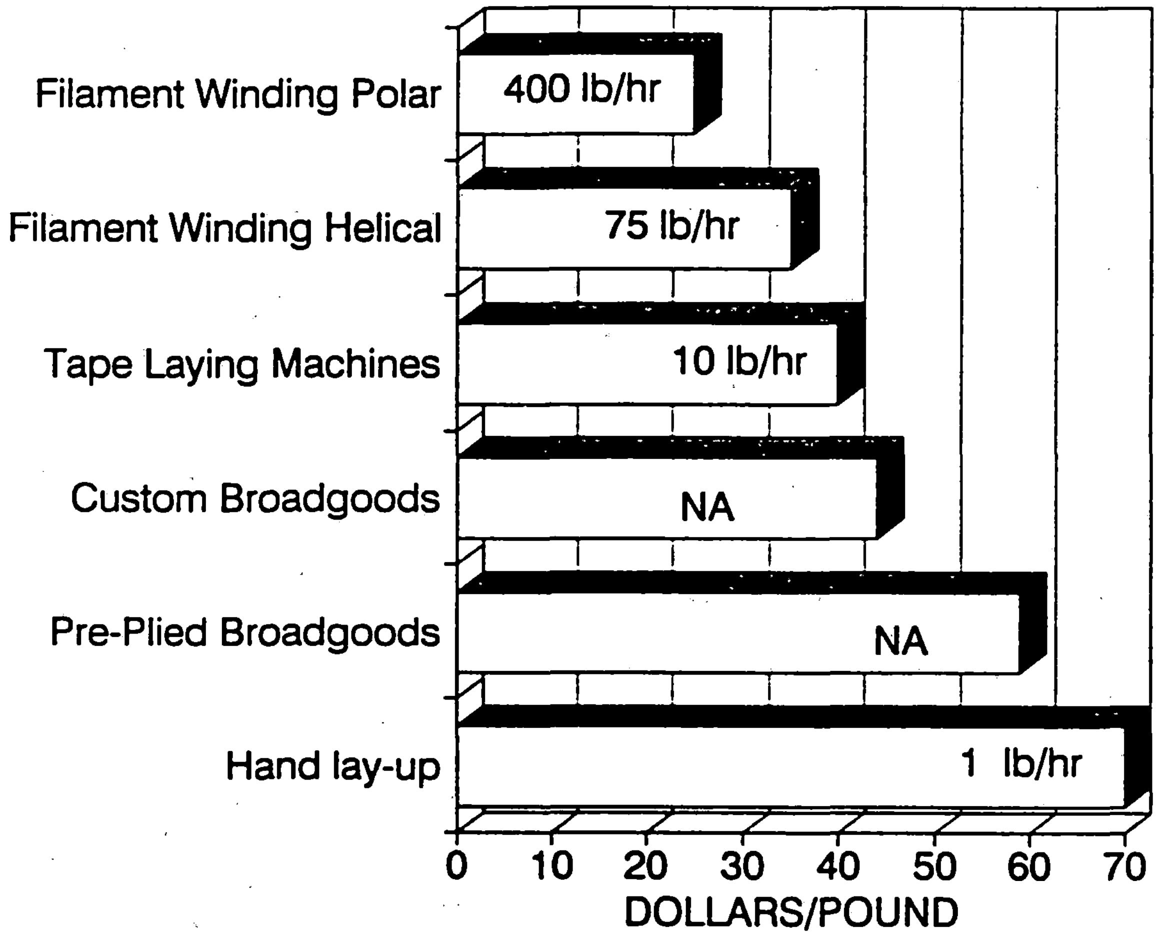
3.5.5. Evaluations of FRP Candidate Systems.

Based on the discussions of Section 3.5.3, two systems, a box and a truss, were selected for design optimization using the commercial finite element computer program, entitled ANSYS (Burnside, 1992).

3.5.5.1 Box Section

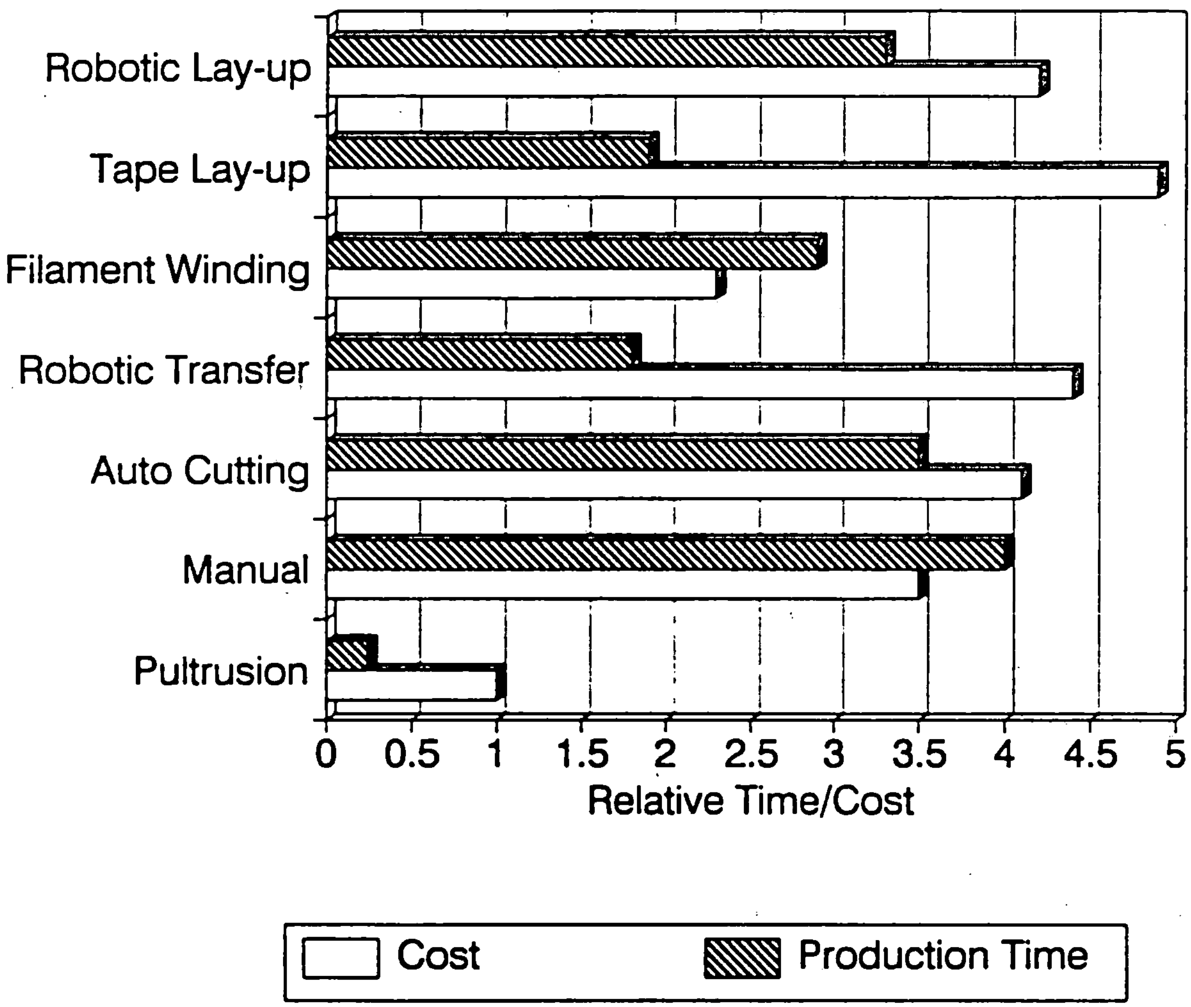
In this section, the geometry and boundary conditions of the optimized box sections are defined. The box section is to be completely constructed of composite materials. The Maglev loading, as stated in Section 3.2, has been used for optimizing the guideway. The strength and stiffness analyses of a box section with cross members have been carried out with different boundary conditions. A buckling analysis was performed to study the stability of the box section with a cross member. Finally, the stability of the system under this type of loading is also shown to be acceptable. Additional details can be obtained from the report by Burnside (1992).

Two initial geometric models, with a constant cross section as shown in Figure 3.5.7, (dimensions shown in Table 3.5.2A) were identified as possible designs that could feasibly be manufactured by using the pultrusion manufacturing process. The straight box was found unfeasible because of buckling problems in the webs. The box with single cross brace was optimized for different support and loading conditions and for two kinds of fibers (glass and



Note: Pultrusion is not the acceptable production process in the aircraft industry; therefore, the production rates are not available.

Figure 3.5.5 Production Rate (lb/hr) and Cost ($/lb) of Typical Aerospace Parts Produced by Various Methods



Note: Four times the production time of the pultruded part was used as a reference time.

Figure 3.5.6 Production Time and Cost Relative to Pultrusion of Aerospace Parts Produced by Various Methods.

carbon). The analysis was conducted using two different sets of boundary conditions, simply supported (SS) and fixed end (CC), as shown in Figure 3.5.8. The jointless (fixed/almost-fixed) bridge was simulated by constraining the translational and rotational degrees of freedom as illustrated in Figure 3.5.8.

The structural model has been optimized with reference to volume so that structural material costs could be minimized. Several design constraints were used in the structural analysis to control the number of possible solutions. First, the Tsai-Wu failure criteria is the most accepted criteria for strength evaluation of composites. It is an interactive criteria in the sense that all stress components (σ_x, σ_y, σ_z, σ_{xy}, σ_{yz}, τ_{xz}) are used simultaneously to predict failure against a set of strength values. The mathematical description is given in Tsai (1989) and Jones (1975).

$$Tsai\text{-}Wu=\left(\frac{1}{X_t}+\frac{1}{X_c}\right)\sigma_x+\left(\frac{1}{Y_t}+\frac{1}{Y_c}\right)\sigma_y+\left(\frac{1}{Z_t}+\frac{1}{Z_c}\right)\sigma_z$$

$$-\frac{(\sigma_x)^2}{X_tX_c}-\frac{(\sigma_y)^2}{Y_tY_c}-\frac{(\sigma_z)^2}{Z_tZ_c}+\frac{(\sigma_{xy})^2}{(XY_{xy})^2}+\frac{(\sigma_{yz})^2}{(YZ_{yz})^2}+\frac{(\sigma_{xz})^2}{(XZ_{xz})^2}$$

$$+\frac{C_{xy}\sigma_x\sigma_y}{\sqrt{X_1X_cY_1Y_c}}+\frac{C_{yz}\sigma_y\sigma_z}{\sqrt{Y_tY_cZ_1Z_c}}+\frac{C_{xz}\sigma_x\sigma_z}{\sqrt{X_tX_cZ_tZ_c}}$$

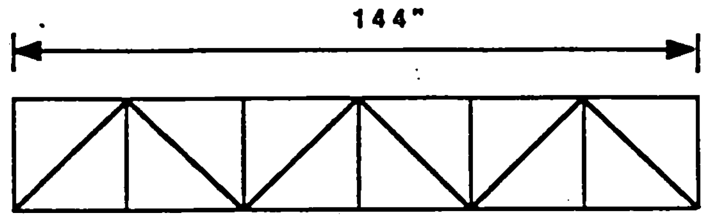
$$+\frac{C_{xy}\sigma_x\sigma_y}{\sqrt{X_tX_cY_tY_c}}+\frac{C_{yz}\sigma_y\sigma_z}{\sqrt{Y_tY_cZ_tZ_c}}+\frac{C_{xz}\sigma_x\sigma_z}{\sqrt{X_tX_cZ_tZ_c}}$$

The strength values used in this study are shown in Table 3.5.2. These strength values revealed that the possibility of first ply failure occurring anywhere in the structure can be prevented.

Table 3.5.2

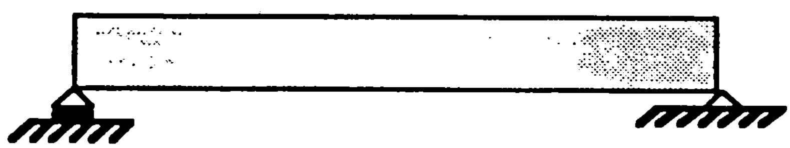
Material Properties of the Lamina

Material Property for a Lamina	E-Glass/ Polyester(GPa)	Carbon/ Polyester
Young's Modulus in the Direction of the Fibers	44.730 GPa	132.288 GPa
Young's Modulus Orthogonal to the Direction of the Fibers	7.737 GPa	8.158 GPa
Major Poisson's Ratio	0.25	0.25
Density of Laminate	2.547 Mg/m^3	2.021 Mg/m^3
Shear Modulus (G 12)	3.0 GPa	3.259 GPa
Ultimate Tensile Stress in the X Direction (Xt)	2.067 GPa	1.137 GPa
Ultimate Compressive Stress in the X Direction (Xc)	2.067 GPa	1.137 GPa
Ultimate Tensile Stress in the Y Direction (Yt)	64.311 MPa	63.808 MPa
Ultimate Compressive Stress in the Y Direction (Yc)	64.311 MPa	63.808 MPa
Ultimate Shear Stress (S)	32.156 MPa	32.156 MPa

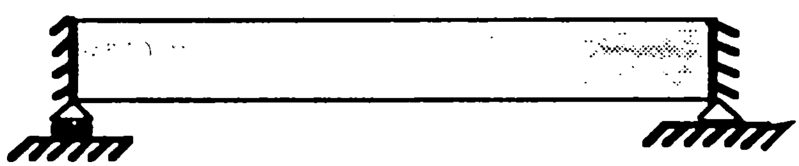


Box with a Single Cross Brace

Fig. 3.5.7 Cross Section of Proposed Bridge Designs



Simply Supported Bridge (SS)



Fixed/Almost-Fixed Bridge (CC)

Fig. 3.5.8 Support Conditions for Bridges

Second, the maximum deflection of the structure was not allowed to exceed the allowable limit of L/2000. Finally, the total thickness of the top, the bottom, and web laminates were constrained to a maximum thickness of 25.4 mm (1 in) so that pultrusion is feasible. The results of the optimum process are shown in Table 3.5.2A.

The buckling analysis conducted by Burnside (1992) showed that a simple box section would not be stable. Therefore, a box section with a cross member was chosen for the optimization. In this optimization, it was shown that for distributed load of a Maglev system 24.82 kN/m (1700 lb/ft), 20 percent less material was needed to carry the load in the jointless design over the simply supported system.

Burnside (1992) has shown that a carbon fiber structure must be at least six times smaller in cross section than the E-glass structure to justify its cost. Although E-glass/polyester structures required more material, it was still less expensive than a carbon/polyester structure.

A linear buckling analysis was performed by Burnside (1992) to determine the stability of the structure under Maglev loading conditions. Since the analysis employs an eigenvalue solution, the results are actually load multipliers for the different buckling failure modes. Therefore, the results presented in Table 3.5.3 are actual loads that will cause failure. A review of the results shows that compared to the normal load of 24.82 kN/m (1700 lb/ft), all the structures could handle more than twice the loading with respect to buckling, with the exception of SS carbon polyester that showed a 1.276 safety factor. The material properties used in computing buckling forces are given in Tables 3.5.1 and 3.5.2.

3.5.5.2 Hybrid Truss

In this section, the geometry of the hybrid truss system is discussed, (Fig. 3.5.9), to illustrate the simplicity of such a structure. Then, three types of support conditions (simply

Table 3.5.2A. Optimized Geometry of Box with a Single Brace

	FIBER			
	CARBON		GLASS	
	SS	CC	SS	CC
Depth mm (in)	2380 (93.7)	1072 (42.2)	2350 (92.5)	1420 (55.9)
T top mm (in)	9.754 (0.384)	18.19 (0.716)	27.18 (1.070)	21.84 (0.860)
T bottom mm (in)	17.374 (0.684)	20.88 (0.822)	42.45 (1.672)	26.31 (1.036)
T web mm (in)	18.186 (0.716)	29.77 (1.172)	44.91 (1.768)	29.81 (1.174)
T diag mm (in)	17.424 (0.686)	41.50 (1.634)	33.93 (1.336)	36.02 (1.418)
Cross Sect. Area mm^2 (in^2)	689031 (1021.5)	554940 (860.158	1487804 (2306.1)	738192 (1144.2)

Table 3.5.3 Results of Buckling Analysis Under Maglev Loading

Cross Section	Boundary Conditions	E-Glass Polyester	Carbon Polyester
Box with One Cross Member per Section	Simply Supported	18,892 N/m	30,044 N/m
	Fixed/Almost-Fixed	35,373 N/m	63,345 N/m

supported at the bottom of a deck, simply supported at the top of a deck, and fixed/almost fixed-jointless) are examined. The optimization of the truss members is presented with minimum stiffness levels. To verify the accuracy of the finite element modeling of the reinforced concrete deck, strength of materials solutions are developed. Finally, the results of the hybrid truss system are presented to show that the best solution is one in which vertical and diagonal tubes are optimized separately.

The loading of a magnetic levitation train on a guideway results in a uniform load that is about 12.41 kN/m (850 lb/ft), per truss. This load is placed on the top deck directly over the truss system to get the maximum use of the material. In addition, because the guideway is fully loaded with uniform load, the maximum deflection effects are studied. The impact loading is taken into account in the analysis by a factor of 1.8.

Optimization of the Truss System

The model was optimized to minimize the volume of material in the truss members for a given thickness of the reinforced concrete decks. The wall thickness and the diameters of the different tubes in the truss system were set as design variables within the program to optimize the required thickness and diameters of each tube while meeting the various design criteria. The tubes making up the vertical truss members and also the diagonal members were allowed to vary independently. The fiber angle of the layers of the laminate was also defined as a design variable. Several design constraints were used in the structural analysis to determine the feasibility of possible solutions. First, the maximum value of a two dimensional Tsai-Wu failure criteria for a representative section of a tube was checked (Burnside, 1992). This prevented the possibility of first ply failure from occurring anywhere in the structure. Second, the maximum deflection of the structure was not allowed to exceed the Maglev standard of L/2000 as specified

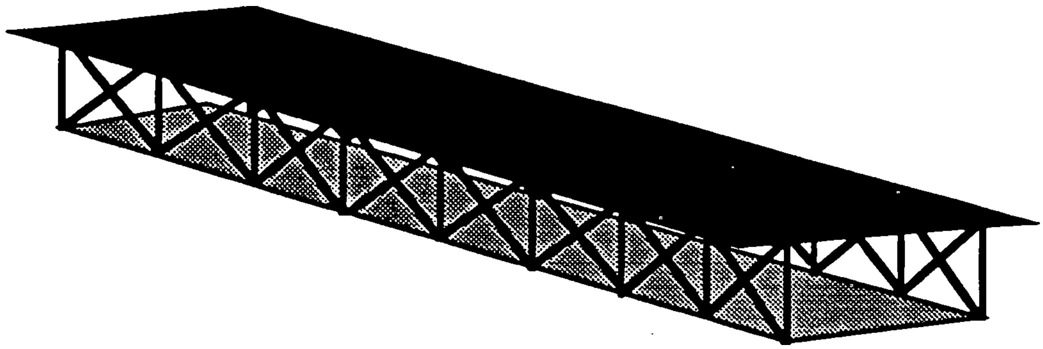
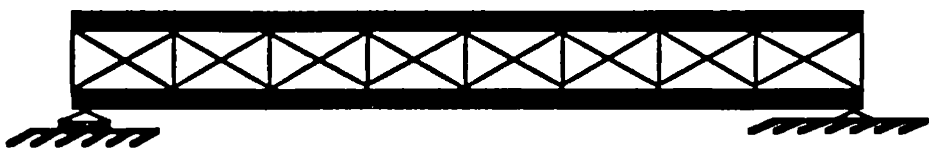
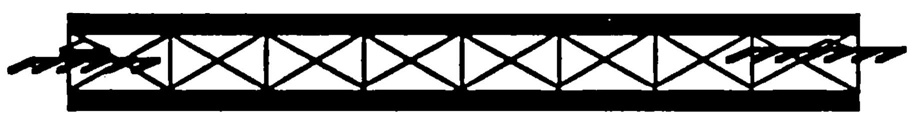


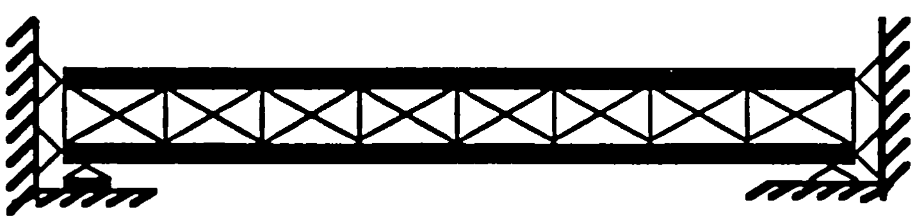
Illustration of the Hybrid
Concrete and Composite tube Truss System



Simply Supported at Bottom of Truss System



Simply Supported at Top of Truss System



Fixed/Almost Fixed Truss System

Fig. 3.5.9 Support conditions used for truss system

in Table 3.2.2. Finally the maximum compressive force and stress were checked against theoretical formulas for compressive forces and stresses that would cause buckling failure (Burnside, 1992).

Verification of Modeling of the Stiffness of Concrete Deck

In order to verify that reinforced concrete was modeled accurately in a hybrid truss system, a strength of materials solution for deflection was used in the analysis and compared with the finite element solution. The decks were modeled using shell elements. The nodes directly above each other in the top and bottom decks have their translational displacements coupled with simple supports on the bottom. A very good correlation between the two methods of analysis has been established.

The details associated with the strength of materials solution for finding the maximum deflection of constant cross section beam under a uniform load are presented below.

The initial values of the geometry for the Maglev guideway cross section as shown in Fig. 3.3.5 are:

Thickness of concrete bottom deck	t_2 = 254 mm (10 in)
Thickness of concrete top deck	t_1 = 216 mm (8.5 in)
Width of the top deck in.	b_1 = 2794 mm (110 in)
Width of the bottom deck in.	b_2 = 2032 mm (80 in)
Cross sectional area of the top deck	$A_1 = t_1 \times b_1$
Cross sectional area of the bottom deck	$A_2 = t_2 \times b_2$
Distance between the C.G. of top and bottom deck	d_1 = 1524 mm (60 in)

Half the top deck thickness d_2 = 107.95 mm (4.25 in)

Span of the guideway system L = 24.4 m (960 in)

The following equation for the Z component of the location of the centroid is derived geometrically from Figure 3.5.10, where $\bar{Z}_c = d_2 + d_1 \left(\frac{A_1}{A_1 + A_2} \right)$

The Z component of the centriod defines e_1 and e_2 from the geometry of the system. The moment of inertia of the cross section is computed on the basis of the second moment of the area of the cross section given in Fig. 3.5.10. The maximum displacement for the deck under a uniform load was then approximated with a strength of materials equation for deflection at the center of a beam, and the deflection value of 13.513 mm (0.532 in.) for live load is given in Table 3.4.2. This compared favorably with the finite element model which predicted a displacement of 13.33 mm (0.52 in) under the same loading; however, one should note that the above deflection value does not satisfy the vertical deflection limit state and the design needs to be reviewed.

Results of the Optimization of the Tubes

In this optimization, unlike the box sections, the amount of material needed to carry the distributed load was significantly affected by the boundary conditions. A 25 percent savings in material in the jointless design over the simply supported system has been realized for both E-glass and carbon fibers. This is illustrated for E-glass/polyester in Tables 3.5.4 and 3.5.5. The carbon/polyester is illustrated in Tables 3.5.6 and 3.5.7. A second optimization on the

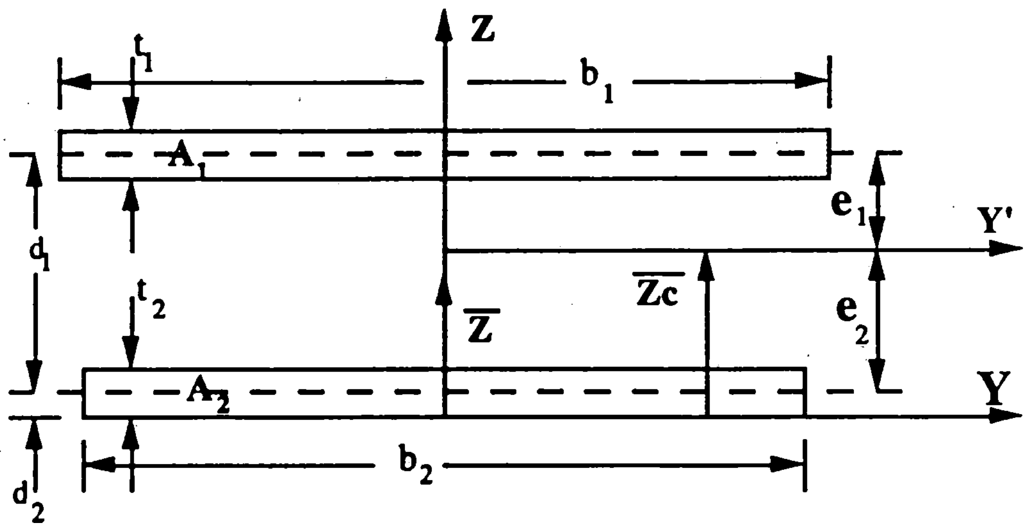


Fig. 3.5.10 Geometric Representation of Concrete Deck

hybrid truss model was performed with the added constraint that the diameters of the tubes for the vertical and diagonal members be equal. The results are shown in Tables 3.5.4 and 3.5.6. This would simplify the manufacturing of the these members. However, after reviewing the data, a significant increase in material requirements is noted for the best solution to resist the Maglev loads. Finally, E-glass (\$1.76/kg and a density of 2.547 kg/m^3) is compared with carbon fiber systems that have average strength, average modulus of elasticity with a cost of \$10.4/kgs, and a density of 2.021 kg/m^3. It can be observed from this comparison that the increased material cost of a carbon/polyester structure (Burnside, 1992) is not justified over E-glass/polyester structure, i.e., increase in cost because of the use of carbon fiber composites does not off-set the decrease in the volume or weight of carbon fiber composites for Maglev guides when compared with the costs of glass fiber composites.

Table 3.5.4
Results of an E-Glass/Polyester Truss System
With the Tube Diameters Equal in All Sections

Boundary Condition	Inner Diameter for Both Tubes mm (in)	Vertical Tubes		Diagonal Tubes		Volume of Truss System (mm^3)	Cost $
		Fiber Angle Degree	Wall Thickness mm (in)	Fiber Angle Degree	Wall Thickness mm (in)		
SS at Bottom	127 (5)	24.3	2.95 (0.17)	3.2	6.12 (0.24)	411000	
SS at Top	88 (3.46)	24.8	2.74 (0.11)	1.1	8.56 (0.34)	381000	
Fixed/Almost Fixed	117 (4.6)	40.2	2.87 (0.11)	1.4	2.87 (0.11)	203000	

Table 3.5.5
Results of an E-Glass/Polyester Truss System with Varying Tube Diameters

Boundary Conditions	Vertical Tubes			Diagonal Tubes			Volume of Truss System mm^3 (in^3)	Cost $
	Fiber Angle Degree	Inner Diameter mm (in)	Wall Thickness mm (in)	Fiber Angle Degree	Inner Diameter mm (in)	Wall Thickness mm (in)		
SS at Bottom	8.8	32 (1.26)	5.7 (0.22)	2.1	285.8 (11.25)	3 (0.12)	404000 (24.65)	
SS at Top	4.3	170 (6.69)	2.7 (0.11)	1.1	185.7 (7.31)	4 (0.16)	161000 (9.82)	
Fixed/Almost Fixed	19.9	30 (11.81)	2.7 (0.11)	1.1	113.8 (4.48)	2.7 (0.11)	98440 (6.0)	

Table 3.5.6
Results of a Carbon/Polyester Truss System
With the Tube Diameters Equal in all Sections

Boundary Condition	Inner Diameter for Both Tubes mm (in)	Vertical Tubes		Diagonal Tubes		Volume of Truss System mm^3 (in^3)	Cost $
		Fiber Angle Degree	Wall Thickness mm (in)	Fiber Angle Degree	Wall Thickness mm (in)		
SS at Bottom	83.8 (3.3)	7.8	10.2 (0.40)	5.7	4.5 (0.18)	315000 (19.22)	
SS at Top	27.9 (1.1)	26.0	2.7 (0.11)	1.3	8.3 (6.33)	129000 (7.87)	
Fixed/Almost Fixed	42.7 (1.68)	27.8	4.3 (0.17)	2.5	2.7 (0.11)	123000 (7.51)	

Table 3.5.7
Results of a Carbon/Polyester Truss System

Boundary condition	Vertical Tubes			Diagonal Tubes			Volume of Truss System mm³ (in³)	Cost $
	Fiber Angle Degree	Inner Diameter mm (in)	Wall Thickness mm (in)	Fiber Angle Degree	Inner Diameter mm (in)	Wall Thickness mm (in)		
SS at Bottom	23.9	164.8 (6.49)	4.9 (0.19)	2.1	93.7 (3.69)	2.7 (0.11)	244000 (14.89)	
SS at Top	1.3	25.7 (1.0)	2.7 (0.11)	1.1	83.1 (3.27)	2.8 (0.11)	121000 (7.38)	
Fixed/Almost Fixed	4.0	25.7 (1.0)	4.4 (0.17)	2.6	54.9 (2.16)	2.6 (0.10)	83000 (5.06)	

3.6 COMPARATIVE ASSESSMENT OF CONVENTIONAL AND INNOVATIVE MATERIALS

Sixteen conceptual guideway systems were developed, and seven systems were selected for further study based on Maglev guideway performance requirements. Simple design guidelines were used, whenever possible, to evaluate the performance of the selected seven systems. Finite element analyses were used to design and optimize the trapezoidal concrete box with FRP reinforcement, hybrid systems with concrete upper and lower decking stiffened by FRP truss members, and all FRP box systems (Figs. 3.3.2, 3.3.6, and 3.3.7), and conventional analysis was used to design the remaining four systems. The advantages and disadvantages of the structural materials used for the design of the most promising systems were evaluated with respect to the performance of the systems. To minimize corrosion and electromagnetic effects from an elevated guideway, the four guideway systems that use composite materials, (Figs. 3.3.2, 3.3.3, 3.3.6, and 3.3.7), should be further evaluated.

3.6.1 Selection of Candidate Systems

The sixteen guideway systems (see Appendix A) are grouped as beam and frame systems, beam systems stiffened with cables, and truss systems. These systems are further classified in the following manner for the convenience of technical discussions:

1. Single and continuous span systems
2. Balanced cantilever systems
3. Rigid frame systems
4. Truss systems

5. Beam systems stiffened with cables

6. Cable supported systems

7. Systems with different cross sectional shapes

8. Systems with different construction materials

1. Single and continuous span systems (Figs. A1, A9, A10, and A12)

Single span guideway systems offer the advantage of ease of design, fabrication, transportation, erection, and construction over the continuous systems. However, single-span systems are less efficient in strength and stiffness than continuous systems. Guideways designed as a two-span continuous system are of lengths 20 percent longer than guideways designed as simple spans with nearly identical cross sections. Such guideway systems with proper continuity will increase the structural efficiency of a guideway. However, field joining will impose greater maintenance and serviceability demands.

2. Balanced cantilever systems (Figs. A2 and A4)

Balanced cantilever systems are more efficient and economical than single-span systems because these systems behave like continuous systems after the placement of field joints at appropriate locations and the completion of construction of a superstructure. However, the required field joints at the inflection points of the superstructure do lead to maintenance and serviceability problems.

3. Rigid frame systems (Figs. A8, A11, and A13)

The rigid frame systems are more efficient and economical than the single span, balanced cantilever, and continuous span systems. The rigid frame systems can be designed to half the bending moment of simple spans. The rigid frame is four times stiffer than simple single span system. However, the joint detailing between the sub- and super-structure is complicated, resulting in a system more susceptible to soil settlements. The rigid frame systems are commonly referred to as jointless bridges, which are becoming popular in highway construction, but their long-term performance, due to environmental loads and soil settlement effects, is not well understood. No specific design and construction specifications are yet available.

4. Truss systems (Figs. A3, A4, A15, and A16)

Truss systems are considered for Maglev guideway applications because they are strong and stiff in the span direction yet weak in lateral bending and torsion. To improve the lateral bending and torsional resistance, a truss system needs to be stiffened with deck or slab components. These components are stiffened also with trusses at certain intervals in the lateral direction. The fabrication costs are relatively high for truss systems.

5. Beam systems stiffened with cables (Figs. A5, A6, A7 and A14)

Systems in this category deal with superstructural guideways that are stiffened by providing cables outside of a structure, not inside, i.e. this category does not include pre- or post-tension operations. Beam systems stiffened with cables increase the strength capacity of the system, but increase in the stiffness of the system is limited. A maglev guideway system design is controlled mostly by stiffness criterion, not by strength criterion. Therefore, strengthening the system with cables is not advantageous. Moreover, the cost of cables, anchorage systems, and protective devices increases the cost of the structure while being difficult to maintain.

Although cable stiffened systems are advantageous for span lengths of more than 152 m (500 ft.), such long span structures are not suitable for the present Maglev application. These structures are inefficient under aerodynamic forces.

6. Systems with different cross sections (Figs. A17, and A18)

Closed sections such as trapezoidal, rectangular, and circular are more efficient in resisting torsional and lateral moments than are open sections. Asymmetric sections about the strong axis (e.g., trapezoidal section) are more efficient than symmetric box and circular sections because higher magnitudes of lateral loads can be accommodated (i.e., larger top flange width), with modest webs and bottom flange widths.

7. Systems with different construction materials (Fig. A17)

Conventional and innovative composite materials were considered for Maglev guideway systems. The advantages and disadvantages of various construction materials were also studied (Section 3.5), and emphasis is given to the composite materials with nonmagnetic properties.

Based on these considerations, seven systems were selected for further study, as described in Section 3.6.2.

3.6.2. Selection of most-promising systems

The following seven guideway systems were selected for further analysis from sixteen guideway systems (Refer to Appendix A):

1. Trapezoidal concrete box system with steel reinforcement (Fig. 3.3.1)
2. Trapezoidal concrete box system with FRP reinforcement (Fig. 3.3.2)

3. Rectangular concrete box system with FRP reinforcement (Fig. 3.3.3)

4. All steel trapezoidal box (Fig. 3.3.4)

5. Hybrid system with concrete upper and lower decking stiffened by steel truss members (Fig. 3.3.5)

6. Hybrid system with concrete upper and lower decking stiffened by FRP truss members (Fig. 3.3.6)

7. An all FRP box system (Fig. 3.3.7)

These systems are shown in Fig. 3.3.1 through 3.3.7. The design loads for the systems are discussed in Section 3.2. The overall response of the guideway systems have been checked for various load combinations. The stresses and deflections are summarized in Tables 3.4.1 and 3.4.2.

3.6.3 Simplified Design of Most Promising Systems

The seven selected systems were designed for the loads specified in Table 3.2.1. The spans of the systems considered were 24.4 m, all of which were analyzed as simply supported. The deflection limit for live load is L/3600 and for live load plus impact is L/2000. Thus, for a 24.4 m span, the allowable live load deflection is 6.6 mm and for live load plus impact is 12 mm. The seven systems were evaluated on the basis of deflection for the specified construction materials. A brief description of the design of these systems is presented.

3.6.3.1. Design of Trapezoidal and Rectangular Concrete and Steel Box Sections (Figs. 3.3.1 through 3.3.4)

The design of the concrete and steel trapezoidal and rectangular box sections followed the design guidelines that are well established and available in the literature (AASHTO, 1989, ACI, 1989). The design details are given by Wendlik (1992). For example, the concrete guideway has been examined to evaluate the induced stresses and deformations affecting the overall design. The governing design aspect of the guideway is the vertical deflection. All design and performance criteria have been kept at the minimum tolerances to allow the system to perform satisfactorily. The stringent serviceability limits have been established from ACI, AASHTO, AREA, and other relevant specifications from the Transrapid designs. The guideway design substantiates the component behavior in terms of its strength, stability, stiffness, durability, and fatigue.

3.6.3.2. Design of Hybrid System with Concrete Upper and Lower Decking Stiffened by Steel or FRP Truss Members (Figs. 3.3.5 and 3.3.6)

The design of the concrete deck with steel or FRP trusses hybrid-system required a finite element (FE) analysis approach. The hybrid system is described in detail in Section 3.3 and in the thesis by Burnside (1992). It consists of two concrete decks connected by a truss of steel or composite tubes. Two versions of the same system were considered, with and without concrete inside the FRP composite tubes. The concrete filling improves the strength and stiffness of the FRP tubes and reduces the member and system buckling and natural frequency of vibration. A special joining detail must be used to join the FRP members to the top and bottom concrete slabs, as shown in Fig. 3.3.6A. In the design of the hybrid system with concrete filled FRP tubes the material for the truss members is assumed to be unidirectionally reinforced with the E-glass fibers aligned with the axis of the member. For the system without concrete inside the tubes, an optimization formulation was used to efficiently orient the fibers to prevent global and local member buckling. Some design details of the FRP truss system are presented by Burnside (1992).

3.6.3.3. Design of All FRP Box Deck (Fig. 3.3.7)

Based on the conclusions of Section 3.3, prismatic composite sections must be analyzed in depth for structural members so that they can be produced economically by the pultrusion process. In order to study the feasibility of using composites for the guideway, an all composite system was studied. The system is based on a repeated box structure suggested by McGhee (1990) for bridge decks.

Although there are some simplified methods for the design of composite members (Sotiropoulos and GangaRao, 1993, Barbero, 1991), they have not been demonstrated for larger structures. Some of the problems are:

a. Lack of an accurate computation of the shear correction factor.

b. Lack of an accurate computation of bending-extension warping (shear lag).

c. Lateral torsional buckling and local buckling models are just now being developed (Barbero, 1990, Barbero and Tomblin, 1992, Tomblin, 1992).

Therefore, the analysis was accomplished with a finite element program (Burnside, 1992), which accounted for the above three factors.

3.6.3.4. Comparisons

The weight of each of the systems is shown in Table 3.4.1. The concrete trapezoidal section is about three times heavier than the steel trapezoidal section. The system consisting of concrete decks with trusses weighs about the same when either steel or FRP trusses are used.

The maximum stresses for all systems are relatively low (Table 3.4.1), and the maximum live load deflections are within the specified limits (Table 3.4.2).

All of these systems are simply supported and single module units and, therefore, a span-by-span erection technique can be used for the trapezoidal systems. The erection of the hybrid systems can be accomplished by installing the bottom deck, attaching the truss system to the deck, and placing the top deck over the truss system. The bottom deck can serve as a working platform to construct the system.

3.6.4 Evaluation of Conventional and Hybrid Materials

Fatigue can be an important factor in the design of guideway systems. The induced fatigue stress depends on the number of load cycles, the service load stress range, the type of induced residual stress, and the initial size of a flaw. Steel has good strength and stiffness properties and higher fatigue strength than concrete or FRP. However, the performance of Maglev guideway systems based on our designs, does not appear to be controlled by fatigue considerations, since the stress range is very low (19.77 N/mm^2 [2.83 ksi]).

The cost of a guideway system depends on material availability, design and construction experience on related engineering projects, transportation, and construction methods. The availability of technical know-how, ease of fabrication and erection, simplicity of details, and ease of maintenance and repairs are more favorable for steel structures than for concrete and FRP structures. Fabrication of a steel section is done by means of welding. Efficiency and accuracy of welding is achieved by using robots. Thus, a simple unit to span 24.4 m (80 ft.) can be fabricated meeting all functional, design, and tolerance requirements. Modularization of guideway sections is recommended as will be discussed in Section 3.7.

Concrete deforms continuously under sustained loads, a phenomenon known as creep. The volume change due to the change in water content in the concrete is known as shrinkage. The change in deflections due to creep and shrinkage affect the ride quality. The creep and shrinkage deflections can be controlled by leaving unstressed prestressing cables in the guideway which can be stressed in the future to induce upward deflection.

Concrete itself does not exhibit any corrosion problem, but embedded steel reinforcement in concrete is susceptible to corrosion. Corrosion of steel results in volume increases due to oxidation. Such volume changes can induce tensile stresses in the concrete. Oxidation also leads to reduction in the effective cross-sectional area of steel rebars, and loss of strength and stiffness of the structural system. FRP rebars are non-corrosive, and their application in structural engineering is gaining importance over conventional steel rebars.

Concrete structures show better dynamic response over conventional steel structures because of their higher weight. Modularized precast concrete units can decrease costs and erection time, while providing better quality control. Simple span precast concrete units can be used to minimize the effects of soil settlements and replacement time. However, the ride quality suffers as the number of structural joints increases. The structural joints can be reduced by converting the simple spans into two- or three-span systems, but thermal stresses and deflections are more critical in continuous structures and must be accounted for in design by providing expansion joints.

FRP composite materials have several advantages over conventional construction materials. First, FRP is lighter than steel and concrete, so that the erection and transportation costs and time for construction are greatly reduced. Modular units fabricated at the shop can be easily assembled at the site. Composite materials are corrosion resistant, saving maintenance cost. Since composite materials are nonmagnetic, there are no electromagnetic field effects.

The main disadvantages of composite materials are their high initial cost and low stiffness. Even though composite materials have high strength-to-weight ratio, their stiffness is low, so the design of the section is governed by stiffness in most of cases. However, innovative guideway shapes, such as honey-comb cross sections, can improve the stiffness and provide a balance between strength and stiffness. High quality carbon fibers can improve the stiffness properties of a guideway, as well. The higher damping of composite materials may improve dynamic response but the reduced mass may cause vibrational problems. To avoid high material costs and buckling problems, composite sections with foam-like or wood cores should be considered rather than solid cross sections. The lack of technical know-how to apply composite materials to civil engineering structures and the lack of information on joint behavior are areas of concern when using composite materials. The manufacturing technique for modular units, which is a significant cost reduction factor, is quite attractive with composites.

3.7 FEASIBILITY OF UTILIZING PROTOTYPE COMPOSITE SYSTEMS

Recent advances in construction have shown a definite trend away from labor intensive and time consuming field operations to increase speed and ease of construction. The development of "optimized" guideway construction evolves from a comprehensive understanding of the inter-relationship between function, design, production, erection, and life-cycle costs. In addition, the functional component arrangement (which are stator packs, lateral guide rails, slide strips) and their flexibility in joining with a guideway system constitute an important criterion for constructing guideways on a systematized basis. Thus, the efficient utilization of available human and material resources could lead to economic, structural, and functional optimization of a guideway superstructural system. Such an approach is referred to by GangaRao (1978) as the "Systems Approach" to the construction of guideway systems.

The concept of prefabrication fits in well with the high-volume and mass production of Maglev guideway superstructural components and their assemblage, leading to system construction. Owing to the increasing demands for stringent tolerances on guideway structural and functional components; for reductions in initial, maintenance, and operational costs; and for energy savings, we are on the threshold of the "prefabrication era" in modern construction technologies (Sheppard and Phillips, 1989). The beginning of these innovations is apparent in terms of monorail structures, mass transportation structures and people movers. Three important trends highlight developments in prefabrication:

1. Standardization of structural shapes and systems for varying span lengths and load intensities,
2. Mass production of structural components with different materials as steel, concrete, timber, fiber reinforced composites, or hybrids - a combination of the above or other materials,
3. Mass transit usage in different modes, including the Maglev mode, requires mass production of structural components in a prefabrication form for the reasons of economics, environmental awareness, and energy savings.

Prefabrication technologies have many advantages including mass production of high quality components which are typically plant-manufactured under ideal quality control conditions, allowing delivery and erection of guideway structures on precise construction schedules. Many other advantages are listed elsewhere (Merritt and Ambrose, 1990).

In view of the above trends in modern construction techniques, we selected the simply supported single span guideway structure from the most promising Maglev guideway systems for detailed design. This structure was designed for strength, serviceability, stiffness, and stability and the results were reported by Wendlik (1992). Emphasis was placed on production of guideway system parts and their erection, maintenance, and replacement. Production of modular units through mass production techniques, connection details for structural integrity, and other advanced construction techniques were evaluated for the prototype guideway system.

Herein, seven prototype Maglev guideway systems are designed for a span of 24.4 m (80 ft.). The designs were prepared as a part of our research effort and are presented in reports by Wendlik (1992) and Burnside (1992). The structural components are such that they lend themselves well to prefabrication and modular construction. The most promising guideway system is an economical system that meets Maglev functional requirements and is suitable for mass production. Such systems can be made of different construction materials. Design constraints such as size, shape, and weight of a module as well as the methods of transportation and erection of those modules can be accounted for in the design process. In addition, the selection of material and cross sectional shape(s), simplicity of design and detailing techniques, construction assemblies, and low self-weight of the modules resulting in easy handling, transportation, and erection are some of the factors that are evaluated herein for cost reduction purposes.

3.7.1 Identification of Prototype System

The present study has been limited primarily to the guideway superstructural systems with right-angled supports and simple spans of 24.4 m (80 ft.). The detailed analyses of several guideway systems were carried out and cross sectional shapes are shown in Figs. 3.3.1 through 3.3.7

The most promising systems (shown in Figs. 3.3.1 to 3.3.7), are designed for the loads specified in Table 3.2.1. The deflection limits for the live load and live load plus impact are taken as L/3600 and L/2000, respectively. Thus, for a 24.4 m (80 ft.) span guideway, the allowable deflection is 7.77 mm (0.2667 in). Different cross sections were evaluated by using different construction materials with live load deflection limit established as L/3600. The behavior of hybrid and FRP box sections is not as well established as the behavior of a steel and concrete guideway structure. In general, the guideway superstructural systems that evolved through this research are subject to several system constraints. These include size and weight of the superstructure modules for transportation, crane limits for handling, and erection techniques. Typically, most superstructural systems in public works outlive their usefulness. Therefore, a minimum service life of fifty years is considered as another system constraint, and this constraint has been incorporated in our evaluations.

Before evaluating the guideway systems in-depth, broad issues dealing with module selection and their transportation and erection are discussed first:

Module Selection: A variety of prefabricated modular shapes must be conceptualized from the viewpoint of mass production to take full advantage of prefabrication. It should be noted, however, that these shapes will lead to a conceptual system after the modules are assembled in the field. In other words, the modules must be selected based on ease of mass production and erection, in-plant handling, economics of production, and transportation. The module selection is subject to the limitations of width, depth, span, and weight of a module.

Transportation: Prefabricated units are normally shipped by truck. The units are typically transported with two-point supports; hence, the units have to be checked for the stresses due to transportation and handling. Any special requirements such as stacking supports or handling hardware on the modules should be considered in the design. Also, it is important to check the possible routes through which modules can be transported to the construction site. Transportation limits on vehicle width, height, length, and load height have to be checked. These limits vary somewhat from one state to another, but are given in the "Overweight Vehicles - Penalties and Permits" (FHWA, 1992). It should be noted that permits for oversize and overweight vehicles and loads may be issued by the appropriate governing bodies under certain conditions. In addition to the highways, other modes of transportation such as railways, waterways, and airways also should be evaluated as alternate modes of transportation of the modules.

Erection: Properly thought-out erection schemes of guideway systems can save time and money through speed and minimization of field errors. Therefore, good coordination between the designer, manufacturer, erector and the general contractor is vital to the success of the erection phase. Designers normally make decisions on sizes and weights of prefabricated elements early in the project. Realistic design tolerances must be established from the erection viewpoint along with the connection requirements.

Although all the guideway systems are technically feasible, they differ in terms of fabrication, erection, durability, and life-cycle costs. To evaluate the merits and demerits of these systems, selection criteria based on eight items as given in Table 3.7.1 have been developed.

For purposes of relative comparison, a weighting technique, as shown in Table 3.7.1, has been applied. The weighted values for each of the evaluation criteria are based on sound engineering judgement and previous experience with structural systems similar to the guideways. It should be noted that the proposed ratings, at best, serve only as guidelines and such evaluations are based on a degree of subjectivity.

The ratings of the proposed systems involve complex inter-relationship of several unknowns, such as construction and maintenance costs, performance levels, long-term degradation rates, and others. Due to the above uncertainties, the rating indices may have to be lowered to account for these uncertainties. If, on the other hand, the full potential of these systems is realized, through "hands-on" experiences, the indices of these guideways would be higher and rating indices can be altered accordingly.

The results of our internal survey of ten technical personnel on evaluation of six Maglev guideway systems are reported in Table 3.7.1. The steel box system received the highest rating of 73.6%. This can be attributed to the familiarity of the material and the past usage. However, the lowest rating (68.6%) was given to the prestressed concrete deck with steel trusses. Obviously, the spread between the six proposed systems is very narrow for any meaningful delineation of the best possible guideway system. It is interesting to note that the composite systems received as good a rating as the well established steel systems. This implies that the composite guideway systems may be favored more than others, if their long term performance,

Table 3.7.1. Proposed Weighting Technique to Evaluate Maglev Guideway Systems

PROPOSED RATING SCALE: **E-Excellent; (5)** **V-Very Good; (4)** **G-Good; (3)** **F-Fair; (2)** **P-Poor (1)**

NO.	CRITERIA FOR WEIGHTING IN TERMS OF COST	WEIGHTING FACTORS	CONCRETE TRAPEZOIDAL OR RECT. BOX		STEEL TRAPEZOIDAL BOX	HYBRID		FRP
			STEEL REIN.	FRP REIN.		STEEL TRUSS	FRP TRUSS	
1	MATERIAL	35%	3.9	3.7	3.7	3.7	3.7	3.1
2	FABRICATION	10%	4.2	4.1	4.1	3.9	3.7	3.7
3	TRANSPORTATION	5%	3.0	3.2	3.9	3.4	3.8	4.5
4	ERECTION	15%	3.6	3.6	4.1	3.9	3.7	4.4
5	FUTURE EXPANSION	5%	3.0	2.8	3.8	2.8	2.9	3.9
6	SPECIAL REQUIREMENTS	10%	3.0	3.1	3.4	2.9	3.6	3.6
7	MAINTENANCE	7%	3.0	4.0	2.8	2.8	3.8	4.2
8	REHABILITATION	13%	2.8	3.3	3.4	2.8	3.3	3.5
	Sum of 1 to 8	100%	3.50 or 70%	3.56 or 71.3%	3.68 or 73.6%	3.43 or 68.6%	3.61 or 72.2%	3.64 or 72.8%

NOTE: The values indicated in Table 3.7.1 are the averages based on our internal survey of ten technical personnel that are closely associated with the Maglev project or related activities which can be established through accelerated test procedures, is satisfactorily established and the guideway system designers are familiar with the design of structures with the FRP materials. Hence, we recommend that the concrete trapezoidal box system with glass FRP reinforcement, the hybrid system with prestressed concrete slabs and glass or graphite and composite cellular decks FRP truss be evaluated further for future construction of Maglev guideways. We recognize that this recommendation somewhat contradicts the rating values in terms of the FRP box system. Such a contradictory recommendation is based on the lack of experimental data of FRP boxes. Our current recommendation on the FRP box will be reevaluated, provided it performs to our satisfaction under accelerated testing conditions. Faza and GangaRao (1992) are working on accelerated test procedures to establish master charts for FRP materials so that aging of these composite materials and, consequently, the life of a structure with FRP can be predicted with reasonable accuracy.

3.8 SELECTION OF MOST-PROMISING HYBRID SYSTEMS

Based on the rating survey presented in Section 3.7, the following three systems are recommended for further study: the concrete trapezoidal box system with glass FRP reinforcement; the hybrid system with prestressed concrete slabs (reinforced with glass FRPs) and glass or graphite FRP truss system; and the glass or graphite FRP composite cellular deck with cross bracing (diaphragms).

The reinforcement of concrete with continuous glass FRP tendons has been previously investigated (Wolff and Miesseler, 1989). A significant number of structures have been built using this technology. The use of glass or carbon FRP tendons as reinforcing elements in

Maglev guideways appears feasible and can be readily implemented. The hybrid system with concrete decks and glass or graphite FRP trusses offers good damping, strength, and stiffness characteristics. However, the complexity of the connections and field installation are disadvantages that must be evaluated in order to establish its competitiveness with the other proposed systems. Since composites perform differently in tension and compression, the design must allow for optimization of fiber angle, tube diameter, and tube thickness. For this reason, previous attempts to design composite truss systems by simply applying steel-design rules have been unsuccessful. The composite truss system is capable of transmitting the shear forces from the top to the bottom deck with low shear deformation. An efficient system is the jointless design (built monolithically with the supports), but in this case, the concrete decks must be prestressed because of the inducement of tensile stresses.

The cellular glass or graphite FRP box section with cross members can be fabricated by pultrusion using bidirectional fabrics that can provide continuity between the web and the flange of the box. Burnside's stability analysis indicates that the cross members are needed to prevent buckling of the webs (Burnside, 1992). This cellular system offers several advantages over the stringer-and-deck systems (Sotiropoulos, GangaRao and Mongi, 1993).

A cellular composite section appears very promising for possible construction as a Maglev guideway system, but the long-term performance of the system must be established, and the cost of the structure must be evaluated by including life-cycle considerations.

3.9 ANALYSIS OF COSTS AND ASSESSMENTS OF ECONOMIC IMPACT OF MAGLEV GUIDEWAYS

3.9.1 Formulate Framework for Economic Analyses

Background

A review of the literature was conducted and practitioners were consulted relative to identifying key issues with respect to construction and maintenance of Maglev guideways and the decision tools and economic analysis techniques appropriate for evaluating these issues. At least two constraints became clear very quickly. Given the extremely small number of Maglev guideways which have been constructed and/or proposed around the world, accurate cost data are difficult to acquire. The task becomes even more difficult for "innovative" guideways. A second difficulty is that Maglev system research and development is still in a very dynamic state. As a consequence, the need for and the nature of certain system components have still not been resolved, e.g., guideway heating systems.

Evaluation Techniques

The following evaluation techniques were felt to be worthy of further consideration: present worth, benefit-cost ratio, rate-of-return, and annual worth approach. Each of these approaches is described briefly below:

With the net present worth (present value) approach, the stream of costs (and benefits) is discounted to its present worth (their value now) and then netted to determine the resultant net present value. The benefit-cost ratio method, when properly applied, is little different than the net present worth approach. The only differences are that additional computations are required and that proper interpretation of the ratios can be confusing in some instances. The final form of the benefit-cost ratio answer is an abstract number that represents the ratio of net benefits to net costs.

By definition, the internal rate-of-return is the interest rate for which discounted benefits over n years are just equal to discounted costs. The internal rate-of-return has been popularized by engineering economists, though it has often been improperly understood, explained, and used. The characteristic of the method, that of finding a discount rate, is the major objection offered to its use.

The annual worth approach is popular because many people, even decision-makers, are unfamiliar with the other techniques. If all the variations in cash flow can be eliminated and an investment can be said to result in an equivalent annual cost per year, it is assumed to be more easily understood.

To select an economic analysis technique for use in this project, five evaluation criteria were developed. Those criteria were: compatibility with existing models, data requirements, ease of understanding the method, clarity of results, and computational efficiency.

Using these five criteria, the present worth approach was chosen as the most appropriate evaluation technique. This technique is both simple and unambiguous in indicating the alternative with the highest economic potential. None of the other methods are as straightforward; in fact, some may give ambiguous or incorrect economic indicators as commonly applied (Au, 1983).

The economic analysis also incorporated life cycle costing. Life cycle costing is an approach to incorporating the total costs (initial, operational, and maintenance) involved over the lifetime of an asset. The present worth approach can incorporate life cycle costs.

As mentioned previously, the present worth approach easily allows for comparison of alternatives using varying values of opportunity costs. The approach requires an identified analysis period. With the Maglev project, that period is the design life of 50 years.

Uncertainty

The principles of classical economics are based on the assumption of perfect information. This leads to the belief that all alternative outcomes are known with certainty. However, in real life, uncertainty is present in almost all decision making activities. Economic analysis is no exception; because of its future orientation, it is an activity with a high degree of uncertainty (U.S. Army, 1974). It is generally accepted that within the practical limits of available resources, an attempt should be made to compensate for uncertainty; this project is no exception.

Uncertainty is frequently distinguished from risk through a delineation between subjective and objective probabilities. Risk prevails where enough is known to permit assignment of objectively determined probabilities to all possible outcomes. Uncertainty exists where the assignment is limited to subjective judgement. Objective probabilities for critical variables are generally not available for this type of systems analysis. Therefore, most studies have addressed situations containing uncertainty rather than risk.

The reason that uncertainty must be approached directly and analyzed is that the results may have a direct impact on the choice among alternatives. It is simply not enough to present a set of alternatives whose costs are based on "most likely" factors and assumptions. The decision maker needs to be aware of how well the rankings of the alternatives measure up under reasonable changes to factors and assumptions (U.S. Army, 1974).

Four of the traditional approaches to the problem of uncertainty are a fortiori analysis, contingency analysis, statistical uncertainty and sensitivity analysis (U.S. Army, 1974). A fortiori analysis involves deliberate attempts to formulate assumptions that tend to uniformly favor or disfavor a particular alternative. A contingency analysis is designed to identify significant uncertainties of a qualitative nature; it does not attempt to indicate the effect on study results. The statistical approach results in a number of regression-related statistics and associated tests to measure how good an estimator the regressions are on an overall basis. Sensitivity analysis considers factor values under various assumptions in order to determine the range of impact that changes in quantitative data will have on the costs of each alternative.

Because an uncertainty analysis can be very time-consuming, one of the more straightforward approaches was undertaken for this project. A sensitivity analysis was used to address the quantitative aspects of uncertainty that are associated directly with the Maglev system parameters. Sensitivity analysis was performed by formulating a variety of value estimates for the selected sensitivity variables.

3.9.2 Development of Construction Cost Data

Capital cost estimates are key ingredients in determining the cost effectiveness, financial capacity, and overall engineering feasibility of major capital investments, such as Maglev (UMTA, 1981). Sound methods and reliable cost information are particularly important when comparing cost effectiveness and financial impacts among alternative systems. This is especially critical with respect to a Maglev guideway system. Construction of the Maglev guideway has been estimated to account for as much as 80 percent of all capital costs involved with overall system construction (Phelan, 1990).

Capital Cost Elements

The construction and installation costs associated with the guideway element are functions of many factors, both design-specific and site-specific. In this report, unless otherwise defined, the term guideway will refer to the guideway structural components only. The capital costs developed for this evaluation included only those elements that comprise the guideway structural system. No costs associated with the magnetic or electrical components on the guideway are taken into consideration. The actual type of levitation (attraction or repulsion) and guidance system are concept specific and the cost of the magnetic and electrical components of any particular system is assumed to be equal across alternative guideway systems.

Innovative Systems

Capital cost data for a variety of structural configurations and subsystems and construction processes were developed. In many cases, suppliers of materials or services were contacted to provide reliable cost estimates. For those situations where there are no reliable existing data, standard cost estimating procedures and sourcebooks were employed (for example, Means Construction Cost guides). An extensive literature review in this area was completed. However, because of the scarcity of existing Maglev systems, very little historical data on Maglev guideway capital costs exist. Discussions with practitioners in the Maglev field resulted in a similar conclusion. With respect to the more traditional mass transit guideways, extensive capital cost information was obtained. As noted earlier in this report, seven guideway designs were identified for evaluation and development. Cost estimates were prepared for five of these. These include a concrete trapezoidal box section with steel rebar, the same concrete box section with FRP rebar, a steel trapezoidal box section, a hybrid concrete-FRP truss system and a steel truss (these are described in more detail elsewhere in the report). Note that cost estimates were not prepared for the two designs involving only FRP materials. The lack of existing data on materials and labor costs precluded the development of reliable cost estimates.

One of the more challenging problems in the estimation of capital costs arises from the fact that the innovative guideway designs being proposed in this project do not currently exist. Estimating labor costs involved in construction proved to be difficult. There is no actual data relative to the quantities of labor required for construction and installation, especially with the FRP truss system. Discussions were held with FRP manufacturers to help determine labor times for these systems. The labor costs for the trapezoidal concrete box section with FRP rebar were easier to determine since this system closely resembles a standard steel rebar box section.

Another issue relative to labor cost estimation is that of production/installation costs. The question of whether the guideways will be mass produced or if a new construction technique will be used significantly affects the costs. Economic analysis of different construction techniques was beyond the scope of this study. The costs presented in the economic analysis section are not meant to be used as actual construction costs; they should be used only for the purpose of comparing alternative guideway designs and providing a general estimate of the costs.

Construction Cost Estimates

Concrete trapezoidal box with steel reinforcement: The concrete trapezoidal box system for the proposed Maglev guideway is by far the most used section. The trapezoidal box section has been used in highway design for many years. As a result, the estimation of costs for this "common" system proved to be the most straightforward.

Because of the weight of the guideway, off-site modularization of a 24.4 meter (80 ft.) beam would not be feasible. As a result, the construction plan includes on-site construction of the beams. It is envisioned that a construction area directly adjacent to the permanent location of the beams will be utilized. As progress on the Maglev line continues, the construction area will move along the route. The capital costs developed for the trapezoidal box (Table 3.9.1) do not include advanced preparation of the construction area. It is anticipated that this area will be developed when construction of the guideway's footings and supports is undertaken.

After consultation with manufacturers of concrete structures, it was determined that steel forms would be used in the construction process. The initial stage includes the placing of concrete for the bottom and the two sides of the box. The second stage includes the placing of the top slab. In the second stage, steel-framed wood forms will be used in the interior of the box. These lighter forms will make removal much easier than if steel forms were lodged in the box's interior.

The detailed cost analysis for the single guideway concrete trapezoidal box with steel reinforcement is presented in Eck and Hyre (1992b). A summary of the major cost elements is presented in Table 3.9.1. Unless otherwise noted, all of the prices, man-hours, etc. used in this analysis were obtained from Mean's 1992 pricing catalogs. All material quantities were provided by other team members.

Concrete trapezoidal box with FRP reinforcement: The only difference between this box system and the first box system discussed is the reinforcing material. This guideway was

Table 3.9.1. Cost Elements of Concrete Trapezoidal Box with Steel Reinforcement

SUMMARY OF CAPITAL COSTS	HIGH	LOW
Material Costs		
Formwork	$54,125	$41,125
Concrete	$131,355	$131,355
Reinforcing Steel	$13,144	$13,313
Stressing Tendons	$122,430	$69,960
Labor Costs		
Formwork	$287,224	$287,224
Concrete	$95,246	$95,246
Reinforcing	$13,044	$13,044
Tensioning	$53,873	$41,993
Installation	$200,125	$200,125
TOTAL (per km)	$970,566	$893,385
TOTAL Average	$931,976	
plus 10% for contingencies =	$1,025,200/km	

designed to take advantage of the electromagnetic advantages of FRP. In terms of construction costs, the reinforcing material cost and reinforcing-associated labor costs are the only differences. The material costs increase, while the labor costs decrease. The reduction in labor costs is due to the elimination of a crane from the work crew. The light weight FRP can be easily handled without the use of a crane. A summary of capital costs for material and labor is given in Table 3.9.2.

Steel trapezoidal box: While keeping the same trapezoidal shape as the previous two guideways, the steel box section will require a major variation in construction. None of the steel manufacturers contacted by the project team had ever dealt with such a large flat steel structure. As a result, the construction technique proposed may not be entirely accurate. The technique outlined will, however, be adequate for cost estimating purposes, and the capital costs summary is given in Table 3.9.3.

It was assumed that each 24.4 meter (80 ft.) side, top, and bottom element can be shipped intact to the site. Since the costs of the steel are based on smaller quantities, the savings from large quantities will be offset by the higher transportation costs. Once at the site, cranes will be utilized to hold the plates in place until welded together. Steel supports will be used to support the structure until the entire beam has been welded together.

Steel truss system: The construction of this guideway system is not extremely complicated. The bottom concrete deck would be placed first with the steel studs protruding from the finished grade. The top deck would be constructed upside down at the same time. The next step is the placement of the steel truss members on the bottom slab. The final step is the placement of the top slab onto the steel truss system. The capital cost summary is given in Table 3.9.4.

Table 3.9.2. Cost Elements of Concrete Trapezoidal Box with FRP Reinforcement

SUMMARY OF CAPITAL COSTS	HIGH	LOW
Material Costs		
Formwork	$54,125	$41,125
Concrete	$131,355	$131,155
Reinforcing	$54,822	$54,822
Stressing Tendons	$98,464	$98,464
Labor Costs		
Formwork	$287,244	$287,244
Concrete	$95,246	$95,246
Reinforcing	$9,471	$9,471
Tensioning	$53,873	$53,873
Installation	$200,125	$200,125
Total (per km)	$984,705	$959,825
Total Average	$972,265	
plus 10% for contingencies =	$1,069,500/km	

Table 3.9.3. Cost Elements of Steel Trapezoidal Box

SUMMARY OF CAPITAL COSTS	HIGH	LOW
Material Costs		
Steel	$787,504	$787,504
Braces	$3,500	$3,500
Labor Costs		
Steel Work	$637,189	$637,189
Installation	$200,125	$200,125
Total (per km)	$1,628,318	$1,628,318
plus 10% for contingencies	$1,791,200/km	$1,791,200/km

Table 3.9.4 Cost Elements of Steel Truss System

SUMMARY OF CAPITAL COSTS	HIGH	LOW
Material Costs		
Steel	$366,589	$366,589
Formwork	$28,613	$20,438
Concrete	$125,730	$125,730
Labor Costs		
Steel Work	$229,144	$229,144
Formwork	$157,039	$157,039
Concrete	$95,246	$95,246
Installation	$200,125	$200,125
Total (per km)	$1,202,486	$1,194,311
Total Average	$1,198,399	
plus 10% for contingencies	$1,318,250\km	

FRP truss system: The construction of this system is as unconventional as its design. The FRP truss system is filled with concrete at the same time the bottom deck is placed. This arrangement provides for continuity in the concrete. The bottom deck will be entirely enclosed with a steel form. The FRP truss system will then be erected on top of the steel form. The actual members will be fitted through openings in the form while the entire FRP structure is supported by wood braces. Concrete will be pumped into the steel form and into the FRP members. Quality control will be particularly important, but at this time no other method of construction is available. Once this system is in place, the top concrete slab will be placed, and the cost elements of FRP Truss system are shown in Table 3.9.5.

3.9.3 Development of Maintenance Cost Data

If estimating the capital costs of a Maglev guideway is a challenging task, estimating maintenance costs is even more difficult. Not only is there no history of experience to draw upon but, in some cases, the detailed configuration of system components has not yet been determined.

A potential wealth of maintenance data is available from conventional transit systems. The types of data available have been identified and evaluated for their appropriateness to the Maglev situation. Of particular interest is how the approaches used by other investigators can be verified with data from conventional systems.

Maintenance Cost Elements

Many elements need to be considered when discussing the maintenance cost of a guideway. The type and number of elements vary from guideway to guideway. Regardless of

Table 3.9.5 Cost Elements of FRP Truss System

SUMMARY OF CAPITAL COSTS	HIGH	LOW
Material Costs		
FRP	$715,205	$715,205
Formwork	$42,000	$30,000
Concrete	$139,838	$139,838
Braces	$16,633	$16,633
Labor Costs		
FRP Work	$89,141	$89,141
Formwork	$230,379	$230,379
Concrete	$82,170	$82,170
Bracing	$95,164	$95,164
Installation	$200,125	$200,125
Total (per km)	$1,610,655	$1,598,655
Total Average	$1,604,655	
plus 10% for contingencies	$1,765,000/km	

the type, the largest element in guideway maintenance typically is the labor cost. The other guideway maintenance cost element is materials cost.

During normal operations, guideway maintenance consists principally of inspections and scheduled preventive maintenance tasks and repair of components or subsystems which have failed. As noted by Bechtel (1990), guideway maintenance should be scheduled, whenever possible, to be performed by the late-night shift or to coincide with low passenger demand periods to provide maximum system availability during peak demand. The overall goal should be to maintain the guideway structure (piers, beams, etc.) in a safe and reliable operating condition for maximum system performance.

Preventive maintenance programs (e.g., inspection and cleaning) for guideways should be based on calendar time and controlled by life cycle data. Bechtel (1990) has proposed preventive maintenance frequencies for different aspects of the guideway structure; these are shown in Table 3.9.6. The differences between the different types of inspections were not described in the report.

Corrective maintenance involves two aspects. Failures which affect passenger service and which require immediate attention in order to restore normal operations will be performed immediately. Defects or failures which do not immediately affect passenger service should be corrected as quickly as possible to prevent future interruption of operations.

There are two basic approaches to estimation of maintenance costs for Maglev guideway systems. The first determines labor costs on the basis of a maintenance activity plan for each guideway component. The activity plan should permit evaluation of labor hours/costs by type of repair and item, frequency of repairs per item, and material costs per item. The materials

Table 3.9.6 Labor Requirements for Guideway Structure Maintenance as Proposed by Bechtel (1990).

	Duration (h/km)	Deployment (persons)	Frequency per year	Labor exp (mh/year /km)
Periodic Visual Inspections	0.75	3	4	9
Inspection	1.25	3	1	4
Structure Inspection	4	3	0.33	4
Main Inspection	4	6	0.17	4
Rustproofing	50	8	0.05	20

costs are then determined as a function of the capital costs. The calculation of material costs is based on capital costs, service life, and share of substitute material. For guideway structuremaintenance, Bechtel (1990) has estimated a service life of 80 years and a maintenance material cost of one percent of capital costs.

The second approach, in addition to using a function of capital costs for the material costs, also expands this function to include labor costs. This procedure applies an annual percentage maintenance factor against the initial capital cost of each element to arrive at a gross annual maintenance cost for that element which includes both material and labor. This procedure is used by Transrapid and is based on the methodology specified under Germany's "Federal Traffic Act" for use in project evaluations for the German National Railways. The Transrapid percentage labor/materials disaggregation is 0.08 percent. In a review and revision of capital and operating costs for the Las Vegas-Southern California Maglev corridor, the Canadian Institute of Guided Ground Transport (1986) revised the percentage upward to 0.12 percent for guideway maintenance. This was done because of site specific conditions - the more demanding seismic and climatic conditions in the Southern California corridor.

The problem with all Maglev guideway maintenance estimates is the lack of a historical record. Even data from the Transrapid system demonstration line in Germany (not available for this project) would not provide a total validation due to its relatively brief existence. Because of the large initial capital costs, a small change in the maintenance factor percentage creates a significant change in the maintenance cost estimates. For example, the CIGGT change from 0.08 percent to 0.12 percent for the Southern California corridor increases the annual guideway maintenance costs by 50 percent.

Applicability of Conventional Transit System Data

Because of the lack of detailed cost data for Maglev guideways, and consequently the ability to validate the percentages being used, the modification and application of conventional guideway transit system maintenance costs to Maglev appears to be an approach which deserves close examination. The merits of this approach include the ability to validate the rule-of-thumb percentage approach and the identification of guideway components that may contribute to high maintenance costs.

One such conventional transit system, the Morgantown, West Virginia, Downtown People Mover (DPM), has a wealth of detailed and long-term maintenance data. Thus, this project used conventional transit system maintenance data to help estimate the maintenance costs for proposed Maglev guideway systems.

The Morgantown DPM involves small rubber-tired vehicles (8 seated passengers, 20 standing passengers) operating over a concrete guideway. The system operates in either an on-demand mode or a fixed schedule (short headways) mode, 16 hours per day, 6 days per week. The original system (approximately 8 km [5 miles] in length) was opened to passengers in 1975. A second phase, which increased the system length to about 12.8 km (8 miles), was completed around 1980.

The process of gathering the guideway maintenance data from the Morgantown DPM required considerable time. Since the focus of this effort was on only the guideway, it was necessary to manually examine a printout highlighting the entire system maintenance records and select only those maintenance items judged to be pertinent to the Maglev guideway situation. Next, each individual maintenance record had to be located and examined. In a typical year, almost five thousand maintenance records are created. From the individual maintenance records, items of interest were reviewed to determine date, location, task, type of materials used and man-hours of labor involved. An item of major interest not on the individual records is the quantity of material used for each repair. Normally, this information can be found from a second database. However, due to the nature of repairs made to the guideway, this information generally was not recorded in the second database. The type of information stored in the second database was concerned more with vehicle maintenance, such as quantity of computer chips changed or tires replaced, as opposed to the guideway maintenance items, such as number of bags of cement used. Typically, a maintenance worker would only use a portion of a bag of cement or bucket of concrete patching material. These materials would be taken from storage and when the amount of cement would run low, more would be purchased. Therefore, the material costs had to be obtained from purchase orders. Although overall material costs per year were determined, it is impossible to break down the amount of material used for each individual maintenance job.

The guideway maintenance costs associated with the Morgantown DPM are relatively low. In the system's twenty-year history, deterioration of the guideway structure has been minimal. At this juncture, it is important to recognize the inherent differences between acceptable tolerances with a Maglev system and a DPM transit system. One major element of concern in certain Maglev systems is the differential elevations of connecting spans at their joints. Due to the strict tolerances in some Maglev systems, the alignment of this joint is critical. In the DPM system, the alignment is critical only with respect to ride comfort. Therefore, maintenance costs of this joint will be higher with the Maglev system than with the DPM system.

In addition to those elements mentioned previously, another area of guideway maintenance concern, developed from examination of the DPM system, includes the use and maintenance of embedded sensors or communications loops in the guideway and how that will affect the guideway surface. Other minor maintenance issues include debris falling on the guideway and vandalism.

Data from the Morgantown DPM have been compiled for calendar years 1989 and 1991 and summarized in Table 3.9.7. Because of the significant amount of time required in obtaining the data and difficulties in compiling the information, only these two years could be used for this project. However, based on discussions with DPM officials, it is fair to say that the amount of maintenance activity for 1990 is similar to that of 1991 and likewise that 1988 is similar to 1989. Based on preliminary investigations, maintenance activity for the two years preceding 1988 was slightly less than the 1991 activity. Note that the maintenance costs are shown with and without the heating system (i.e. embedded pipes in guideway.)

The 1989 data demonstrate the influence of system rehabilitation on maintenance costs. As can be seen from Table 3.9.7, the guideway maintenance cost (excluding guideway heating elements) for 1991 was just over \$10,950 or \$850 per kilometer (\$1,360 per mile). For 1989, the guideway maintenance cost was \$20,450 or almost double that of 1991. The difference in annual guideway maintenance costs for the two years is due to major rehabilitation of pier pads during 1989 (and 1988 as well). The rehabilitation of pier pads is labor intensive work done at heights (on scaffolding) in tight spaces; thus, the high costs for the procedures.

As a function of the original capital costs, the 1991 maintenance percentage was 0.02 percent without the heating system and 0.03 percent including the heating system. For 1989,

Table 3.9.7. Summary of Morgantown DPM Cost History.

System Length = 12.9 kilometers (8.1 miles)

Total Capital Costs (1992) : $268,000,000

Guideway Capital Costs (1992) : $ 63,100,000

Annual Guideway Maintenance Costs

Item	1991		1989	
	Total Cost	Per Km Costs	Total Costs	Per Km Costs
Excluding Heating System	$10,950	$850	$20,450	$1,580
With Heating System	$19,250	$1,490	$20,590	$1,595

Maintenance Costs As Percent of Capital Costs

Item	1991	1989
Excluding Heating System	0.02%	0.03%
With Heating System	0.03%	0.03%

the percentage was 0.03 percent for both scenarios. Although these percentages are very low, they are closer to the Transrapid (Las Vegas to Los Angeles) maintenance cost percentage estimates than those proposed by CIGGT and Bechtel. The effects of maintenance of guideway joints for Maglev systems would cause an increase in the percentage. One conclusion from the Morgantown data (and examination of the Transrapid (Las Vegas to Los Angeles) and CIGGT data) is that the Bechtel estimates appear to be extremely high.

The Morgantown DPM system was built in two phases. The first phase, which is approximately twenty years old, consists of concrete piers, steel beams, and a concrete running surface. The second phase, which is just over twelve years old, consists of concrete piers, concrete beams, and a concrete running surface. From examination of the maintenance data, it can be concluded that approximately ninety percent of all maintenance activity has focused on the first phase guideway. The concrete in the second phase is in excellent condition and shows no sign of wear. One advantage which the second phase had is that any design "flaws" found in the first phase were corrected in the construction of the second phase.

Overall, for the Morgantown system, maintenance activity system-wide appears to be stabilizing. Preliminary analysis of 1990 data and data up to May, 1992, support this conclusion. As a result, it is concluded that after twenty years of operation, a guideway's annual maintenance cost as a percentage of capital costs will become stable. This is shown conceptually in Figure 3.9.1. The only change would come from any rehabilitation done on the system. However, it is extremely difficult to predict accurately at what times in a particular guideway's life major rehabilitation will be required. This depends on the actual design and construction. A "flaw" requiring major rehabilitation, may arise after a few years of operation or the guideway may complete its estimated life with little or no rehabilitation required.

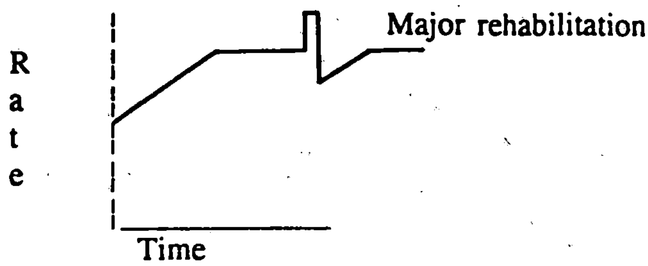


Figure 3.9.1. Guideway Maintenance Costs as a Percentage of Capital Costs Maintenance Cost Estimates

In terms of Maglev, the project team is confident that the 0.08 percent figure for the Transrapid system is more realistic than others proposed. However, the initial annual maintenance costs will likely not be this high. It is proposed that the annual maintenance cost of the guideway will initially be close to zero but will gradually increase, as time passes, to the 0.08 percent level as indicated for Transrapid. Once reaching this level, the annual costs will remain constant (neglecting inflationary increases). It is important to note that this analysis deals only with the guideway structure itself. These annual maintenance cost figures do not include any of the other features of a Maglev system (e.g., guideway heating, footings, etc.).

An important question is what will be the difference in annual maintenance costs for the five guideway systems identified in the preceding section. That is, is there a difference in how each system approaches the 0.08 percent annual level, or is it possible that the non-conventional guideways may not even reach the 0.08 percent level or may, in fact, exceed that level? The Transrapid value of 0.08 percent was based on a concrete trapezoidal guideway. It was assumed that the two concrete trapezoidal guideways (one with steel reinforcement the other with FRP) will reach the 0.08 percent level. The analysis for the other systems, however, is not as straightforward. Since the steel trapezoidal guideway will not involve any concrete maintenance, there should not be the high maintenance costs associated with concrete. The last two systems - the steel truss and FRP truss - involve concrete, but not as extensively as the two trapezoidal guideways. While intuitively it would appear that the FRP truss system would require slightly less maintenance than the steel truss system, the unique design of concrete-filled FRP trusses complicates this issue. The authors are not certain about the long term performance of FRP materials even though preliminary results indicate much better FRP performance than concrete or steel. As a result, it is felt that these two systems will have similar maintenance cost requirements. However, since the future annual maintenance is based only on engineering judgement, the economic analysis includes life-cycle costs with various maximum maintenance percentages for the guideways ranging from 0.08 to 0.12 percent. As a reference when examining the maintenance costs in the economic analysis section, the total estimated annual guideway maintenance costs for the 370 kilometer (231 miles) Los Angeles to Las Vegas Maglev system is $888,000. (CIGGT, 1986)

3.9.4 Economic Analyses

The purpose of the economic analysis is to examine how the life-cycle costs of the five guideway systems under consideration vary with respect to changing variables. Not only is it possible to compare the guideways with each other, it is also possible to determine the sensitivity of the guideways to specific maintenance costs and interest rates. The results provide decision makers with the information necessary for the selection of a course of action.

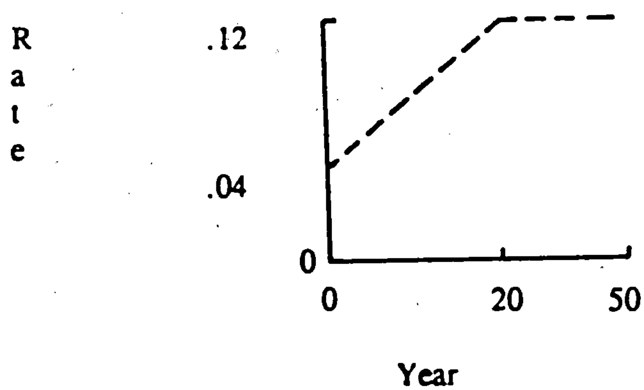
It should be noted that the maintenance costs obtained from the economic analysis are based on "bare" capital costs. Contractor overhead and profits plus engineering fees are not included. As a result, the annual maintenance costs appear to be low.

Project Scenarios

This section presents a sample calculation for the economic analysis of a steel trapezoidal box system. Calculations for the costs of the other systems presented were performed in an identical fashion.

Capital cost = $179,125/km (111,955/miles)

At 8% interest rate-

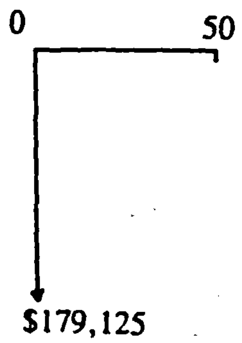


This run will have the annual maintenance costs beginning at .04% and reaching 0.12% at year 20. After that, the annual maintenance costs will remain at 0.12% of the initial capital costs for the life of the system.

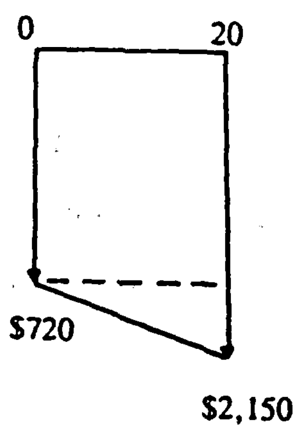
At 0.04% annual costs, maintenance costs = $720/km

0.06%	=$1,075
0.08%	=$1,440
0.10%	=$1,795
0.12%	=$2,150

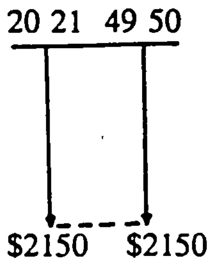
Capital Costs:



"Increasing" Maintenance Costs (years 0-20):



"Stable" Maintenance Costs (years 21-80):



Note: Money for annual maintenance costs needs to be available starting January 1 of the year in question, thus maintenance money for year 1 must be available at time 0, and money required for year 80 must be available at time 79.

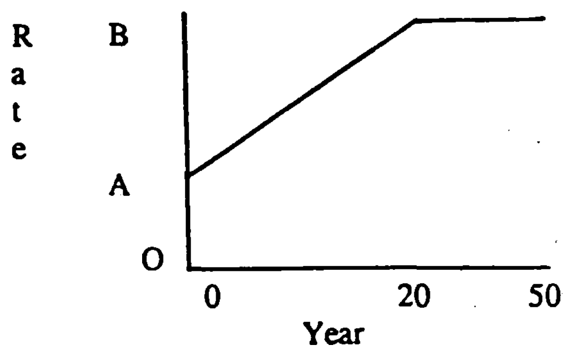
$$\text{NPW} = \$179{,}125 + \$78.75 + \$78.75(P/A,8,20) + \$71.56(P/G,8,20)$$
$$+[\$2150(P/A,8,59)(P/F,8,20)]$$

Using standard engineering economics tables.

$$\text{-NPW} = \$179{,}125 + \$718.75(9.8181) + \$71.56(69.0898)$$
$$+ \$2150(11.1584)(.2145) = \$1{,}809{,}116/\text{km}$$

The remaining runs were calculated using the same procedure. The results are shown in Tables 3.9.8 through 3.9.12.

Annual Maintenance Cost Percentage Scenario Conceptual Graph



Conventional Versus Innovative Designs

The life-cycle costs, as implemented, were found to have very little influence on the cost differential among the alternatives. Three distinct ranges of costs of the five guideway systems were evident. The concrete trapezoidal boxes (both steel reinforced and FRP reinforced) represent the low end, the steel truss system represents mid-range, and the steel trapezoidal box and FRP truss system represent the high end of costs. One interesting finding from the data is that the steel truss system appears to be more cost effective than the steel trapezoidal box system (Tables 3.9.8 and 3.9.9). The large quantity of steel required for the trapezoidal box is the cause of the higher cost.

As expected, the more traditional trapezoidal concrete box guideways appear to be best in terms of cost effectiveness (Tables 3.9.11). It should be noted, however, that factors other than cost play a role in the final selection process. The issue of electromagnetic interference from steel could eliminate the three steel guideways from further consideration.

The analysis examined only two interest rates, 8 and 10 percent. Initially, many more rates were planned to be examined. However, after two iterations, it became apparent that as the interest rate increased, the difference in costs at the various maintenance percentages was less important. In other words, the higher the interest rate, the less influence maintenance costs have on the total costs. Conversely, lower interest rate levels and changes in the anticipated annual maintenance costs can have a major effect on the total cost.

Role of Diagnostics

As discussed elsewhere in this report, guideway diagnostics and monitoring are very important aspects of the operation and maintenance of a Maglev guideway. In terms of costs, the use of these nondestructive testing and monitoring methods will certainly increase construction costs. While the costs are considerable, such systems have the potential to save money in terms of the ability to detect problems early, thus avoiding major repair costs.

However, a great deal of study needs to be done in this area before meaningful cost estimates can be made and economic analyses performed. Two items are especially important from an economic standpoint. First, the sensors to be used need to be determined. Several possible sensors are outlined in the next chapter. It is not likely (nor feasible) that all of these techniques would be utilized on a particular Maglev system. However, the optimum combination needs to be determined. Secondly, once the system(s) to be used has been identified, the details of the monitoring system must be specified so that realistic cost estimates can be prepared. Only when such data are available can the life cycle cost consequences of guideway diagnostics and monitoring be assessed.

Table 3.9.8 Net Present Worths for Steel Trapezoidal Box

Maintenance Rate		Interest Rate	
A	B	8%	10%
.04%	.12%	$1,809,116	$1,805,048
.04%	.10%	$1,807,033	$1,803,564
.04%	.08%	$1,804,950	$1,802,081
.04%	.06%	$1,802,830	$1,800,573
.06%	.12%	$1,811,740	$1,807,449
.06%	.10%	$1,809,656	$1,805,967
.06%	.08%	$1,807,553	$1,804,484
.08%	.12%	$1,814,409	$1,809,894
.08%	.10%	$1,812,326	$1,808,412
.08%	.08%	$1,810,242	$1,806,928
.10%	.10%	$1,814,948	$1,810,813
.12%	.12%	$1,819,655	$1,814,698

Table 3.9.9. Net Present Worths for Steel Truss System:

Maintenance Rate		Interest Rate	
A	B	8%	10%
.04%	.12%	$1,331,115	$1,328,200
.04%	.10%	$1,329,604	$1,327,134
.04%	.08%	$1,328,094	$1,326,049
.04%	.06%	$1,326,306	$1,324,966
.06%	.12%	$1,333,071	$1,330,010
.06%	.10%	$1,331,559	$1,328,926
.06%	.08%	$1,330,049	$1,327,841
.08%	.12%	$1,335,004	$1,331,780
.08%	.10%	$1,333,493	$1,330,694
.08%	.08%	$1,331,982	$1,329,082
.10%	10%	$1,335,425	$1,332,465
.12%	.12%	$1,338,869	$1,335,320

Table 3.9.10 Net Present Worths for FRP Truss System:

Maintenance Rate		Interest Rate	
A	B	8%	10%
.04%	.12%	$1,782,584	$1,778,580
.04%	.10%	$1,780,519	$1,777,111
.04%	.08%	$1,778,456	$1,775,641
.04%	.06%	$1,776,393	$1,774,172
.06%	.12%	$1,785,184	$1,780,961
.06%	.10%	$1,783,119	$1,779,492
.06%	.08%	$1,781,056	$1,778,023
.08%	.12%	$1,787,784	$1,783,343
.08%	.10%	$1,785,719	$1,781,873
.08%	.08%	$1,783,638	$1,780,403
.10%	.10%	$1,788,320	$1,784,254
.12%	.12%	$1,792,673	$1,788,104

Table 3.9.11 Net Present Worths for Concrete Trapezoidal Box with Steel Reinforcement:

MAINTENANCE RATE		INTEREST RATE	
A	B	8%	10%
.08%	.12%	$1,031,661	$1,029,253
.08%	.10%	$1,030,509	$1,028,418
.08%	.08%	$1,029,357	$1,027,583
.10%	.10%	$1,032,009	$1,029,792
.12%	.12%	$1,034,662	$1,032,000

Table 3.9.12 Net Present Worths for Concrete Trapezoidal Box with FRP Reinforcement:

MAINTENANCE RATE		INTEREST RATE	
A	B	8%	10%
.08%	.12%	$1,076,657	$1,074,121
.08%	.10%	$1,075,451	$1,073,249
.08%	.08%	$1,074,246	$1,072,378
.10%	.10%	$1,077,015	$1,074,682
.12%	.12%	$1,079,786	$1,076,987

3.10 DEVELOPMENT OF TEST PLAN

3.10.1 Test Plan Preparation

A test plan is proposed herein with a view to aid the future development in the areas of:

(1) Maglev guideway design,

(2) uses of various construction materials for structural components,

(3) fabrication/manufacturing processes, and

(4) nondestructive evaluation techniques (NDT)

In order to investigate the parameters affecting Maglev guideways and to assess the safety and reliability of the guideway systems, the test plan is proposed in terms of laboratory testing, field experiment, and field demonstration phases (see Figure 3.10.1)

3.10.1.1 Laboratory Phase

Prior to field exposure, testing under controlled conditions is required. Therefore, the laboratory testing phase should include the following:

I. Building and testing of several structural components in the laboratory to determine static, thermal, dynamic, and fatigue responses.

   A. Structural response studies of thermal, creep and shrinkage of the material, and study of the fatigue response of various components and numerical evaluations using numerical techniques.

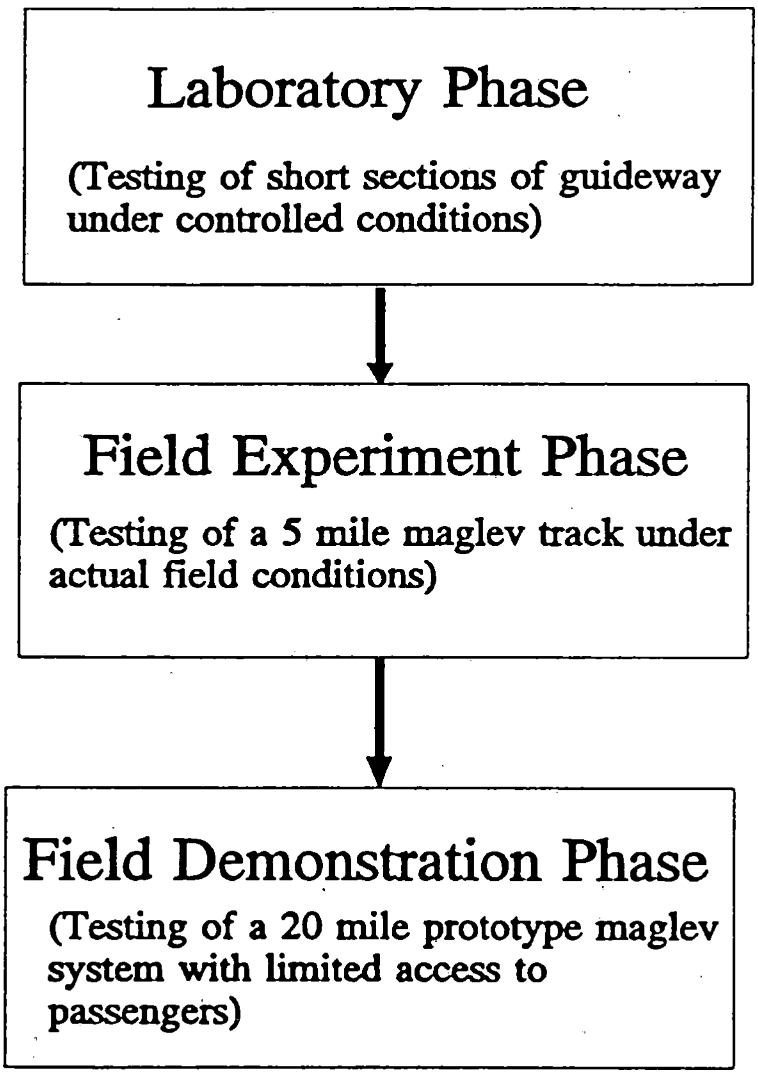


Fig. 3.10.1 Three Phases of the Proposed Test Plan

B. Evaluation of methods for rehabilitation of damaged main components and replacement of secondary components with reference to the structural performance of a Maglev system.

C. Detailed cost analysis of elevated guideway systems and development of economic models for various manufacturing/fabrication processes of guideways.

II. Building of experimental structural components with embedded sensors (such as ultrasonic, acoustic emission, and fiber optic sensors) which can be used for nondestructive monitoring.

A. Evaluation of various NDT sensor techniques for their accuracy and reliability, sensitivity, ease of data acquisition, and quality control of the curing process (monitoring strength increase with curing time) under controlled conditions of the laboratory.

B. Evaluation of NDT methods using embedded fiber optic cables and microbending/deforming teeth.

C. Design and detailed cost analysis of the operational system for nondestructive monitoring, which includes a remote data acquisition system using cellular phone, state-of-the-art data analysis, and interpretation concepts.

III. Construction of a Magnetic Influence Laboratory to study the effect of magnetic field on various components and the magnetic field influence on various appurtenances.

A. Establishment of magnetic drag forces as a function of area, cover and type (open vs. closed loop) of steel reinforcement.

B. Study of the effect of magnetic fields on various sensors which will be used to monitor guideway systems.

3.10.1.2 Field Experiment Phase

The full scale field experiment phase involves testing under actual field conditions, with exposure to the environmental loads and should include the following:

I. Construction and testing of an experimental track approximately five miles in length with a view towards field testing the proposed modular units and appurtenances associated with the guideway.

   A. Study of modularization and mass production techniques for composite guideways and accessories.

   B. Study of the interaction of the vehicle guideway foundation and soil to establish tolerable limits for operation, ride quality, human comfort, and settlement.

   C. Field measurement of noise, aerodynamic forces, and forces due to track irregularities and integrate them in the Maglev guideway design.

   D. Evaluation of alignment, switching, rehabilitation of main components, and replacement of secondary components with reference to structural performance of the guideway system.

   E. Measurement of magnetic drag forces as a function of the amount of ferrous material in the guideway.

   F. Establishment of magnetic drag forces as a function of vehicle speed, distance of reinforcement from the stators, and switching mechanisms for lane changing.

   G. Study of the viability of various NDT methods (including embedded fiber optic cables and microbending deforming teeth) as a complete monitoring system for Maglev by conducting experiments on the experimental track.

   H. Acquisition of remote data based on real-time, on-line services using devices such as cellular phones. Analyses and interpretation of the data collected from NDT sensors embedded in the guideway using information management systems (computer science fields).

I. Feasibility studies to prove the assumptions in the economic models regarding the manufacturing/fabrication processes.

3.10.1.3 Field Demonstration Phase

After extensive testing of the Maglev components in the laboratory and the whole system in the field, a prototype (e.g., 20 mile long test track) will have to be built as a demonstration system with limited access to passengers and exposure to actual field conditions to evaluate performance.

3.10.2 Diagnostics and Monitoring Techniques for Maglev Guideways

3.10.2.1 Introduction

The state-of-the-art in nondestructive testing (NDT) technology has advanced significantly over the past fifteen years and has reached a stage where continuous monitoring of structures can be successfully achieved. The adoption of advanced NDT technology for Maglev is absolutely essential because of the Maglev system safety considerations and high cost of guideway construction. Therefore, several monitoring methods have been evaluated (Sections 3.10.2.2 to 3.10.2.7) in terms of their possible use in a Maglev system.

3.10.2.1.1 General Monitoring Concept

The general monitoring concept for the Maglev system has two major objectives:

* Early detection of damage to the guideway system.
* Prevention of catastrophic structural failures.

These objectives can further be integrated into two different stages of the life of a guideway:

* During construction.
* Post-construction period.

Monitoring methods can either be real-time (i.e., continuous with embedded sensors) or periodic (i.e., intermittent surveying).

The essential steps in the monitoring process are:

1. Identification of defects or damage.
2. Determination of suitable methods to predict distress.
3. Determination of steps to minimize, prevent, or eliminate impending distresses.

3.10.2.1.2 Guideway Defect and Damage Identification

During construction, the monitoring requirements are as follows:

* Curing of the construction material (e.g., maturity and heat of hydration measurements in concrete);
* Time-dependent strength variation (e.g., ultimate growth of concrete strength with time);
* Geometric alignment, with tolerance needs defined; and

* Structural integrity with respect to member joints.

In addition to material aging, the structures are exposed to harsh loading and environmental conditions causing deterioration. Monitoring during the service life of the structure should be focused on:

* Guideway stiffness variations;
* Differential settlements of the foundation;
* Integrity of geometric alignment; and
* Integrity of the material including strain variations.

The main concerns in the applications of NDT to monitor Maglev guideways are:

1. Development of maintenance procedures and testing methods based on the design details of the guideway. For example, joints between two sections of the guideway may have to be evaluated with the aid of different NDT techniques.
2. Due to the high degree of heat generated during Maglev operations, NDT techniques with adequate resistance to heat may have to be emphasized.
3. The magnetic field in the guideway is not known but can be of the order of 0.5 Tesla (proposed Canadian Maglev system). Effect of this magnetic field on the piezoelectric sensors was not found in the literature study and needs further study.

3.10.2.1.3 NDE Technology Applicable to Maglev Guideways

Nondestructive evaluation (NDE) techniques can be classified broadly into two types:

1. Strength estimation;
2. Material properties determination.

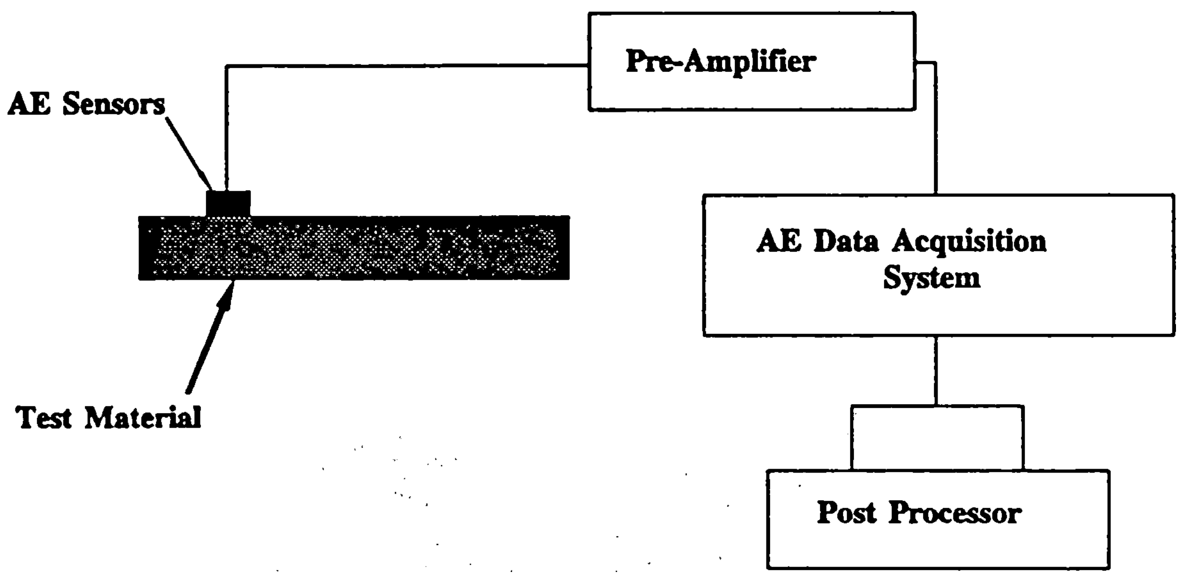
Strength estimating techniques are more traditional and include the surface hardness methods (such as test pistols, rebound hammers, etc.), the penetration resistance methods (e.g., windsor probe, pin penetrator, etc.), the pullout test and the break-off test methods. These methods are very slow and cause minor localized damages in the structure. Hence, they are not suitable for monitoring Maglev systems.

Material property determining techniques, on the other hand, cause no significant disturbances in the structure, can be easily automated, and used as long-term monitoring methods. Some of the property determining methods are acoustic emissions, laser alignment, ultrasonic, ground penetrating radar, thermograph, fiber optics, and others. These methods are more fully elaborated in the following sections.

3.10.2.2 Acoustic Emission

Acoustic emissions (AE) can be defined as the stress wave released by a material that undergoes irreversible changes. AE sensors detect audible or sub-audible stress waves to find the deteriorating conditions of a structure. For example, acoustic emissions due to the release of internal energy from the cracks in construction materials or from debonding in the case of reinforced concrete, can be picked up by piezoelectric transducers.

Parameters most commonly used in AE analysis include the number of events, the peak amplitudes, the rise times, the event duration, and the ringdown counts. Common analyses conducted in AE include: energy or slope determination, amplitude distribution, frequency analysis, and location determination. AE sensors, amplifiers, data acquisition system and post processor required to conduct an AE test is identified in Fig. 3.10.2.



AE Diagnostic Set-Up

Fig. 3.10.2 Acoustic Emission Set-up Technique

Currently at WVU, studies have been conducted involving crack propagation, yield strength determination, ultimate strength prediction and plastic zone locations ahead of the crack-tip in concrete material. Delamination, fiber fractures, and damage location studies on FRP composites are being conducted and the results evaluated.

Acoustic Emission Monitoring System

Figure 3.10.3 shows a proposed design of an AE system applied to the Maglev guideway. The AE sensors can be embedded in the structure at the critical locations and can perform continuous monitoring. However, due to the high cost of the sensors, it is advisable to apply metal waveguides to conduct the waves to the sensors. The waveguides are integrated into the structure, particularly over the locations where damages are most critical, and are linked to embedded AE sensors. Hence, a good waveguide would be one that can transmit the signal the farthest and involve the least attenuation.

Research is currently underway at WVU to study the behavior of waveguides. One of the suggestions for reinforced concrete structures is that the reinforcement within the concrete structure can be used as waveguides. Waveguides will not, on the other hand, be necessary for a steel structure.

3.10.2.3 Geometric Alignment Using Laser

Track geometric variations can provide information on the movement and damage of guideway sections. On a macro-scale, issues such as differential settlements, ground heavings, and horizontal land movements will all result in guideway geometric alignment deviation. On a micro-scale, interior cracks or expansions of a guideway section may result in surface

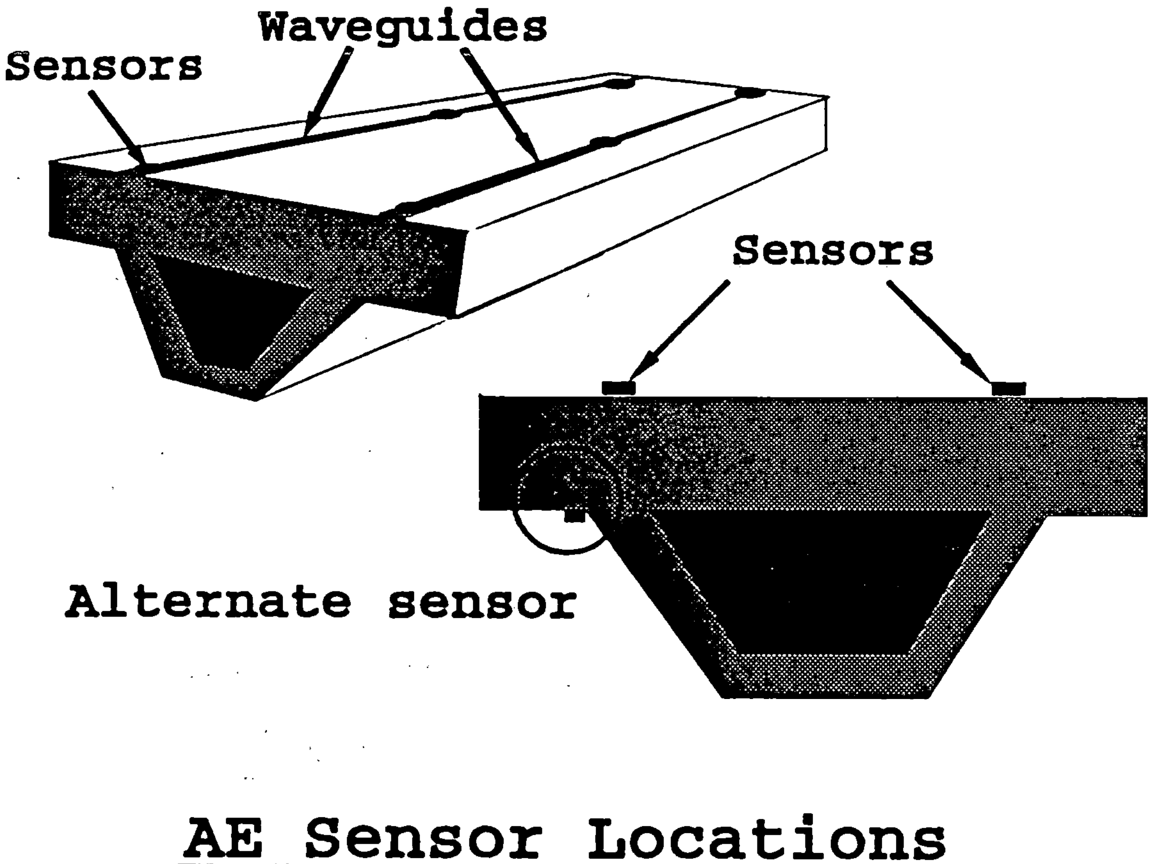


Fig. 3.10.3 Proposed AE Sensor and Waveguide Locations

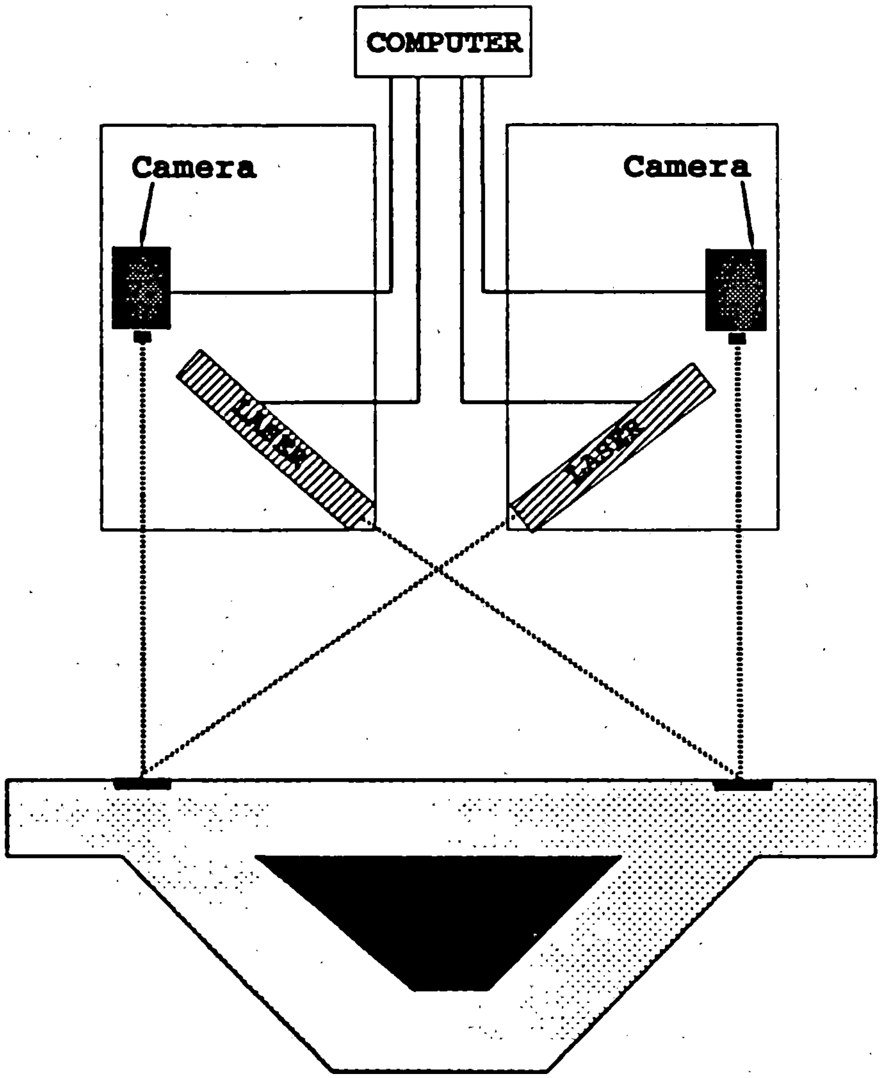
irregularities. These deformations can sometimes be identified by visual inspection. More accurate methods involve the application of a high-tech laser tracking method.

Defined as the emission of molecular and ionized beams, laser can be useful for monitoring the alignment of structural geometry. The system consists of a laser light source, reflectors, receiver, and a date acquisition system. It involves the emission and reception of molecular/ionized particle beams with the reflected wave pattern giving out useful information. Compared to conventional surveying techniques, laser has its advantages in high precision data measurements and in the ease of its application.

The laser guideway application can be distinguished as either a local system (mounted on a test car), or a global system (placed at a fixed station). The global system may be directly placed on the guideway or at a certain distance away from the guideway.

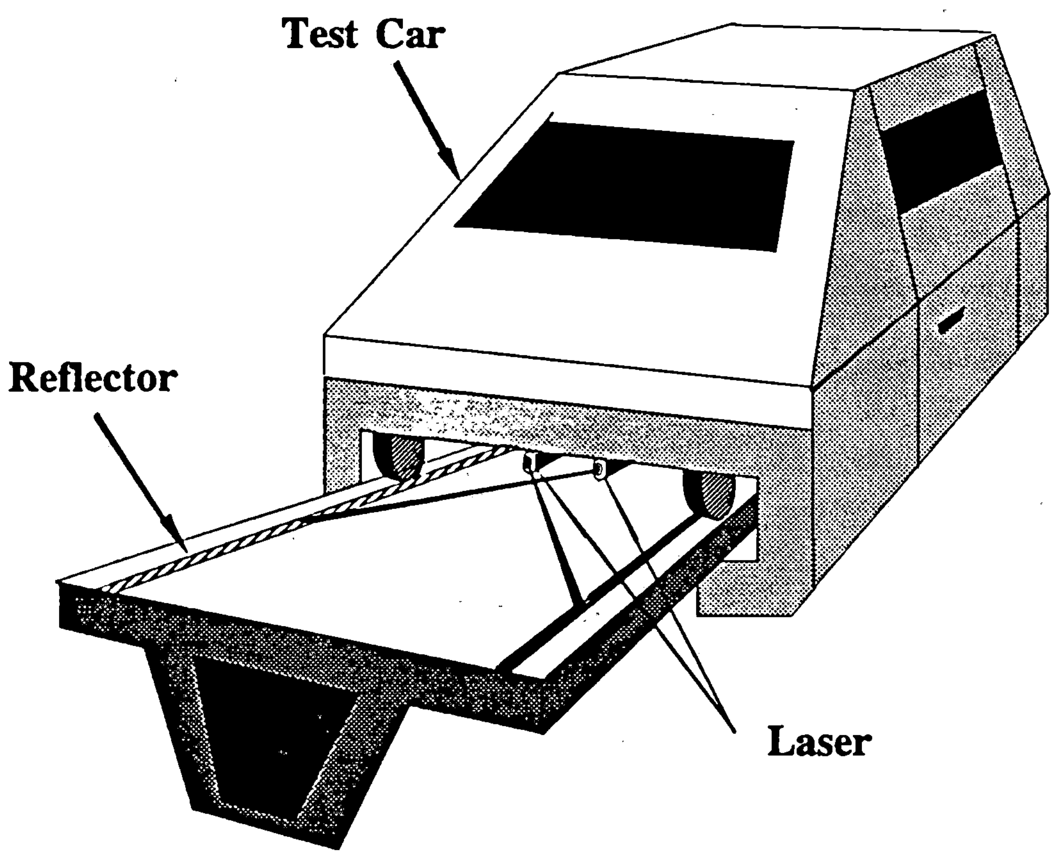
The test car technique is currently available and has been applied for the purpose of monitoring the alignment of railway systems (CSX Report, 1990). In this application, a test car is equipped with a laser emitting apparatus along with an electronic video camera for receiving the reflected beam. The reflector is placed permanently on the track (railway). A proposed setup for Maglev systems is shown in Figure 3.10.4. The test car is allowed to travel at a designated speed, typically about 80 kmph (50 mph). Similar test cars can be designed for Maglev applications (Figure 3.10.5). Another alternative is to install the laser source and camera directly onto the Maglev vehicle.

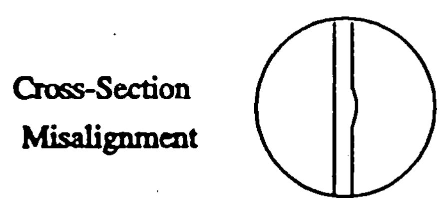
Figure 3.10.4 shows a Maglev test car similar to the CSX test car with two reflectors fixed along the guideway. By receiving the reflected laser beam by two high-speed cameras,



Track Alignment Car

Fig. 3.10.4 Proposed Track Alignment Car Scheme





Test Car for Geometric Alignment

Fig. 3.10.5 Proposed Test Car Mounted on Guideway

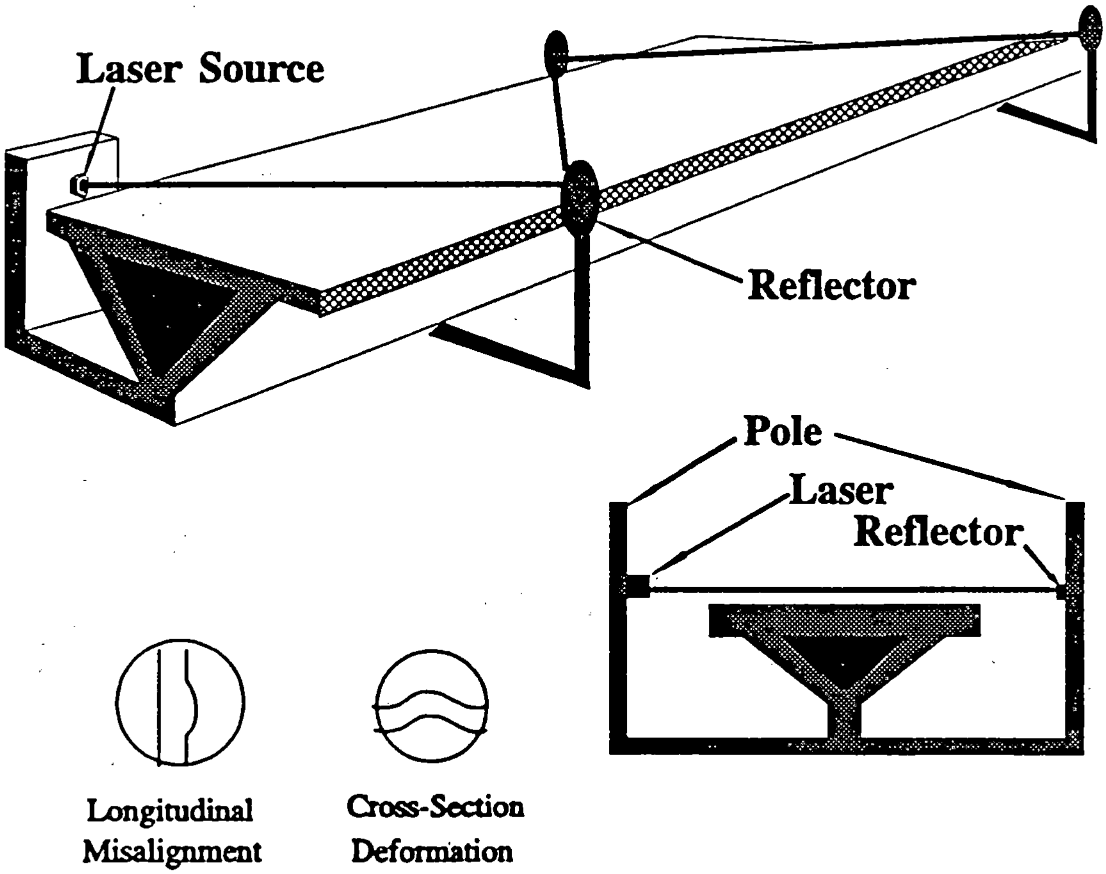
the deformation of the cross section can be determined. This method is more efficient than the other proposed methods but is limited to detection of cross sectional misalignment.

Figure 3.10.6 shows the global laser system for geometric alignment. The laser source and the reflectors are fixed on some extensions on the guideway. By reflecting the light source over the surface of the guideway, adequate information regarding track geometry can be retrieved, information which can be used to detect both longitudinal (along track length) and cross-sectional misalignment. This system may also be used for the detection of debris on the track. Fixed laser systems that can be placed underneath a guideway have certain advantages, such as no need to be set up every time.

3.10.2.4 Ultrasonics

The ultrasonic pulse velocity method is a good NDE technique for the condition assessment of concrete. In this method, an electronic pulse is generated and then transformed into complex mechanical waves (usually a combination of compression, shear, and surface waves), that are propagated through the specimen. The travel time and the wave velocity can be measured to determine the material properties of the concrete. Ultrasonic velocities are sensitive to material constituents, density, elastic modulus, moisture content, and internal cracks and voids.

This method has good reliability and accuracy in the case of steel structures, but the heterogeneity of concrete might pose some problems in the analysis. Research conducted at WVU and elsewhere (e.g., Limaye and Krauss, 1991) has shown that this technique is capable of detecting cracks and delaminations in concrete. However, ultrasonic sensors need to be in



Laser on External Wall and Zig - Zag above the the Guideway Surface

Fig. 3.10.6 Proposed Fixed Laser-Reflector Geometric Alignment System

contact with the test specimen (wet coupled or dry coupled), and may require the sensors to be fixed or embedded.

Ultrasonic transducers can be affected by the magnetic field caused by passing trains. This effect is temporary, and the interference will fade as the train moves away. In such a case, the output from the sensors will have to be ignored during the time the train is passing over the specific region. Magnetic fields can also cause permanent damage to the piezoelectric sensors in ultrasonic transducers. However, the effect of these magnetic fields on the ultrasonic sensors is not yet known. Additional research needs to be undertaken to determine these effects.

In the case of a steel guideway system, different types of distresses can occur over a period of time (e.g., cracks, corrosion). Ultrasonics can be used for detection of cracks up to 3 mm minimum thickness, and determination of their extent and orientation. Corrosion can be detected by determining the thickness of steel members using focussed ultrasonic transducers (Singh and McClintock, 1983). However, detection of incipient corrosion and evaluation of corrosion rates by ultrasonics is difficult.

Ultrasonic Monitoring System

The main components of the ultrasonic monitoring system are shown in Fig. 3.10.7. Significant advances have been made in the area of signal processing of ultrasonic data whereby analysis of the output in the frequency domain has led to improved results (Limaye and Krauss, 1991).

The various guideways designed for Maglev systems were thoroughly studied for possible distress locations. The levitation magnets are located below the overhang portion of the guideway and support the entire weight of the Maglev vehicle. This creates tension on the top

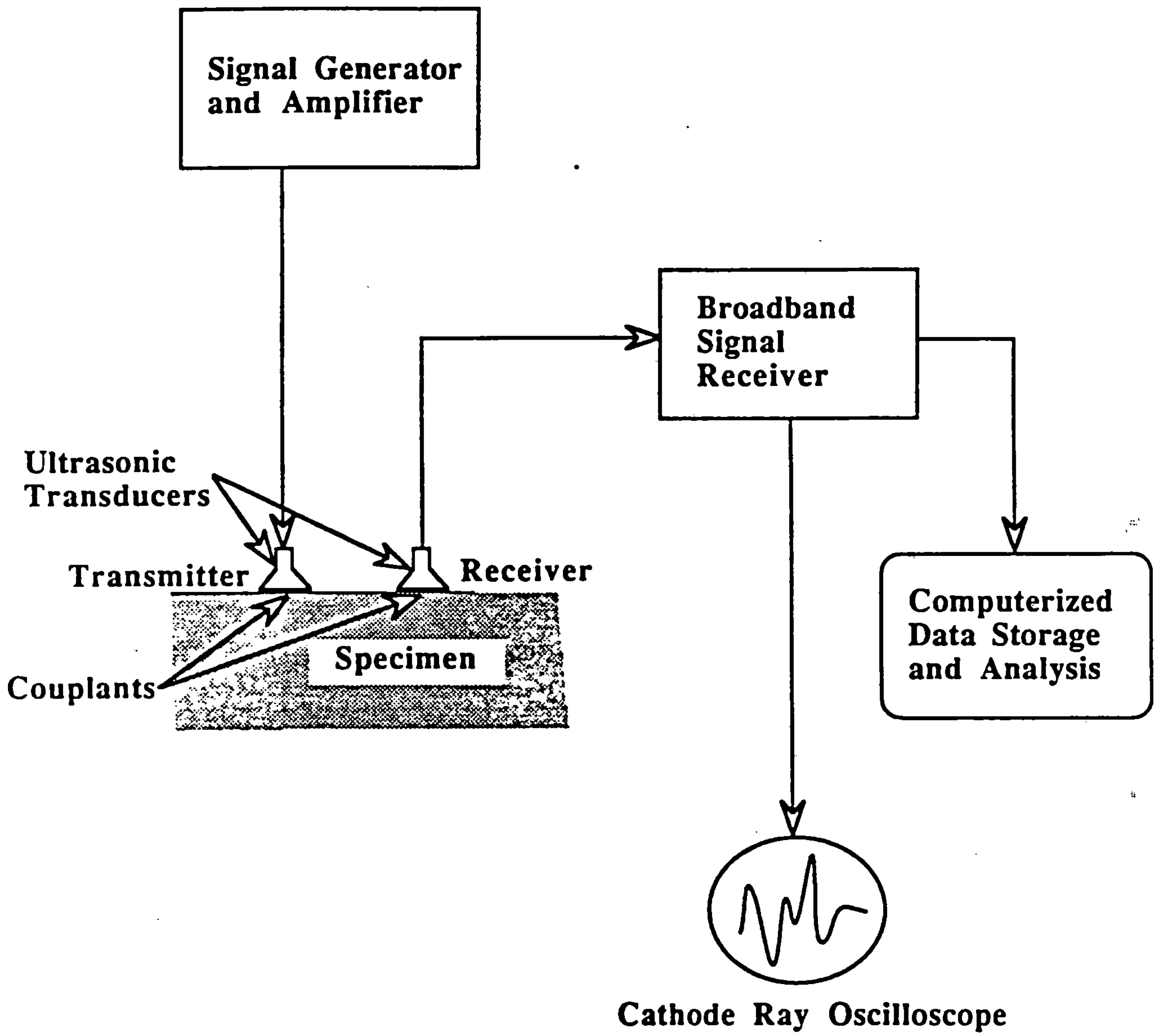


Figure 3.10.7 Components of an Ultrasonic Monitoring System

surface of the guideway near the support of the overhang portion of the guideway, causing the information of vertical cracks along that line. Vertical cracks are best detected by surface transducers, and two sensors are required for each location. With six possible locations (as shown in Fig. 3.10.8), 12 sensors are required for each section.

In addition, positive bending moment at the midspan of the guideway section leads to tension development at the bottom part of the box section. It is estimated that two surface transducers (not shown in Fig. 3.10.8) will be sufficient to detect any vertical cracks at the midspan, requiring a total of 14 sensors per section. Assuming an average span for each section to be around 24.4 m (80 ft.), there are approximately 40 sections per km (65 sections per mile) or 560 sensors per km (910 hundred sensors per mile). For the data acquisition and processing system, a single computerized data acquisition system can handle about 14 sensors, i.e., one system per section will be required. These systems are manufactured by several firms.

3.10.2.5 Ground Penetrating Radar (GPR)

The Ground Penetrating Radar (GPR) technique can be used effectively for condition assessment of concrete structures. This is a non-contact technique and has the advantages of fast and easy data acquisition. The GPR, which utilizes short pulse electromagnetic waves, has a common antenna for both transmitting and receiving the radar signals. It has the potential to detect water content and degree of hydration in fresh concrete, which is useful in predicting the durability of concrete as well as quality control in the manufacturing and curing stages.

It has also been widely used for the detection of subsurface conditions of concrete bridge decks and pavements (e.g., Maser and Roddis, 1990; Bomar et.al., 1988). Subsurface flaws, cracks, or voids in concrete produce reflections which appear as peaks in the radar signal as

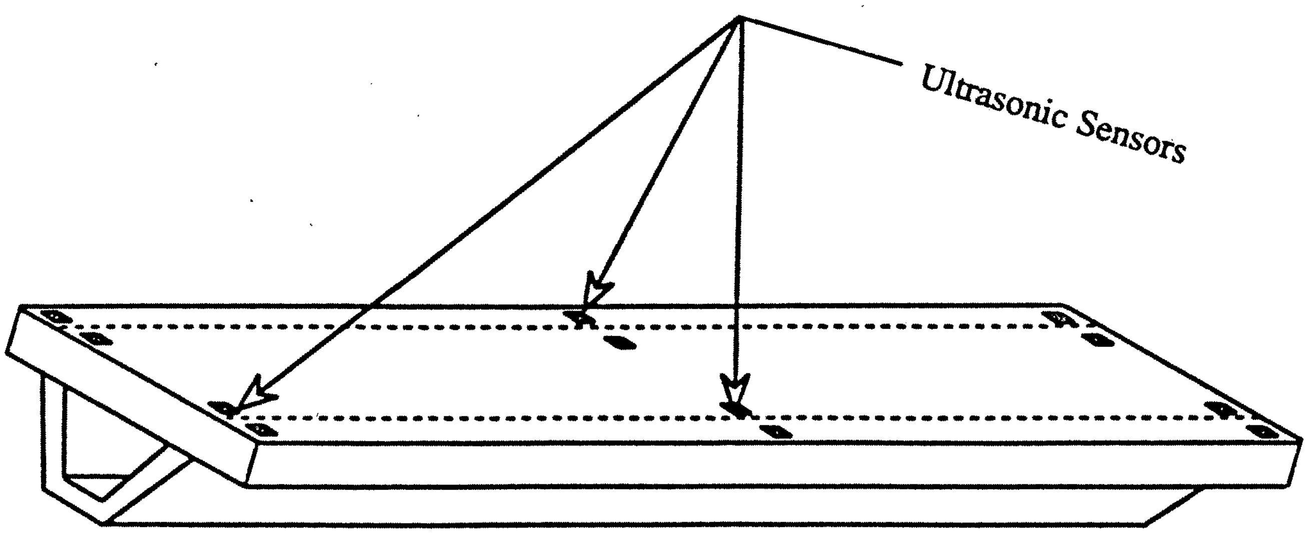


Figure 3.10.8 Positioning of Ultrasonic Sensors on Concrete Guideway

shown in Fig. 3.10.9. Analysis of these radar signals can provide valuable information about the condition of the guideway. However, the electromagnetic radar waves are greatly influenced by the magnetic fields in the Maglev environment, hence a separate non-Maglev test vehicle will be necessary for data acquisition in the field.

For GPR, metals such as steel and aluminum have a reflection coefficient of -1 and a transmission coefficient of 0, i.e. radar waves cannot penetrate through metals. Hence, GPR cannot be used as a NDE technique on steel guideways. Nor can GPR be used if the concrete/composite guideway is covered with aluminum sheets (for shielding of the magnetic radiation).

GPR Monitoring System

The main components of the GPR system are shown in Fig. 3.10.10. These components are generally housed in a van which is then run over the pavement of bridge deck at speeds varying from 16 to 32 kmph (10 to 20 mph). This system can be adapted for use on a Maglev guideway by using a special test vehicle.

Each radar antenna is about 203.2 mm (8 inches) wide and can scan an area of 0.093 m^2 (1 sq. ft.) at a time. Because the distresses will most likely occur along the line of support of the overhang (as explained in Section 3.10.2.4), two antennas will be sufficient to scan the guideway in a single pass.

3.10.2.6 Infrared Thermography

Infrared thermography senses the emission of thermal radiation from the specimen and produces a visual image of the surface from this thermal signal. Infrared thermography can be

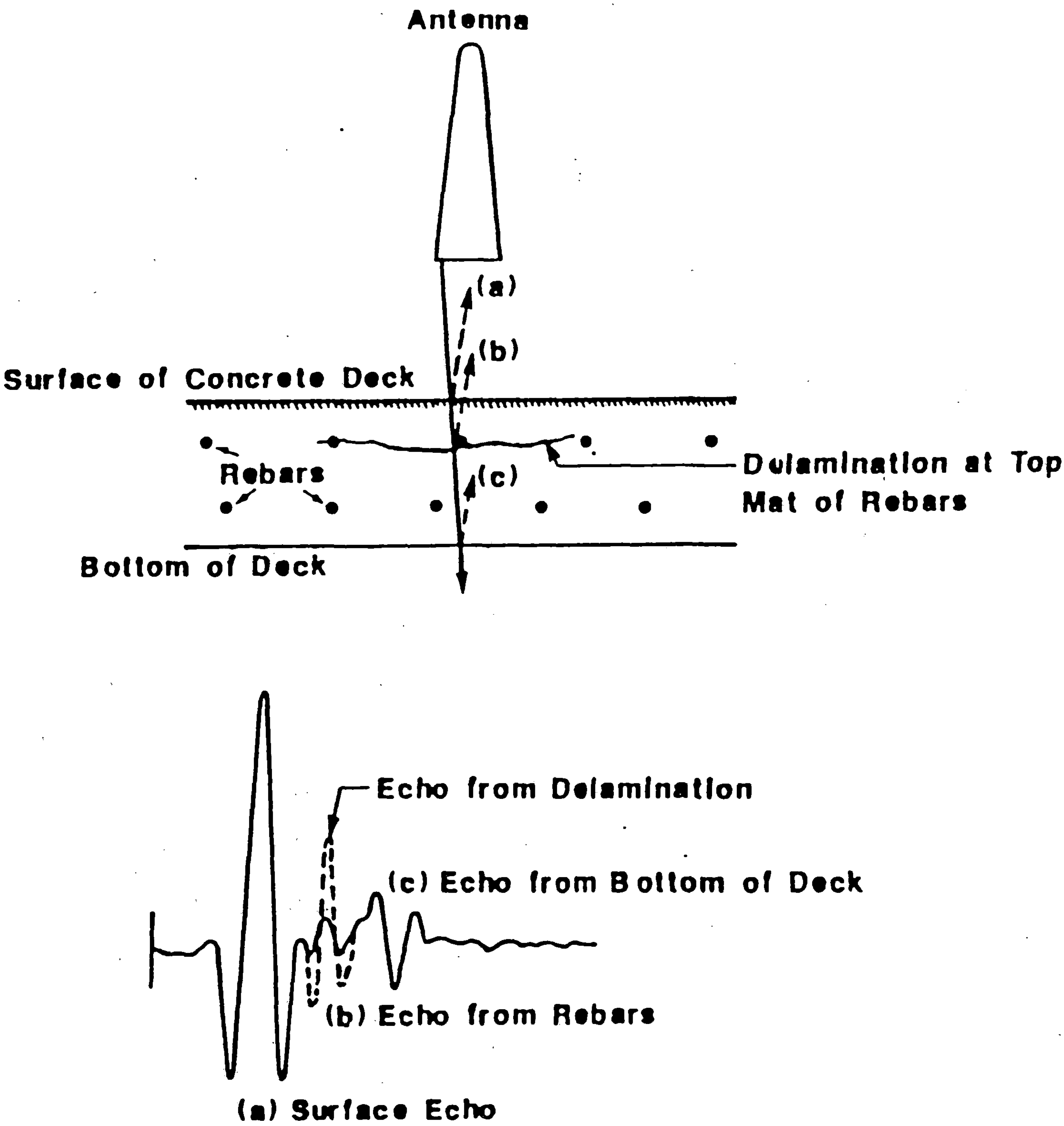


Fig. 3.10.9 Radar Response from Test on Defective Specimen (Clemena, 1991)

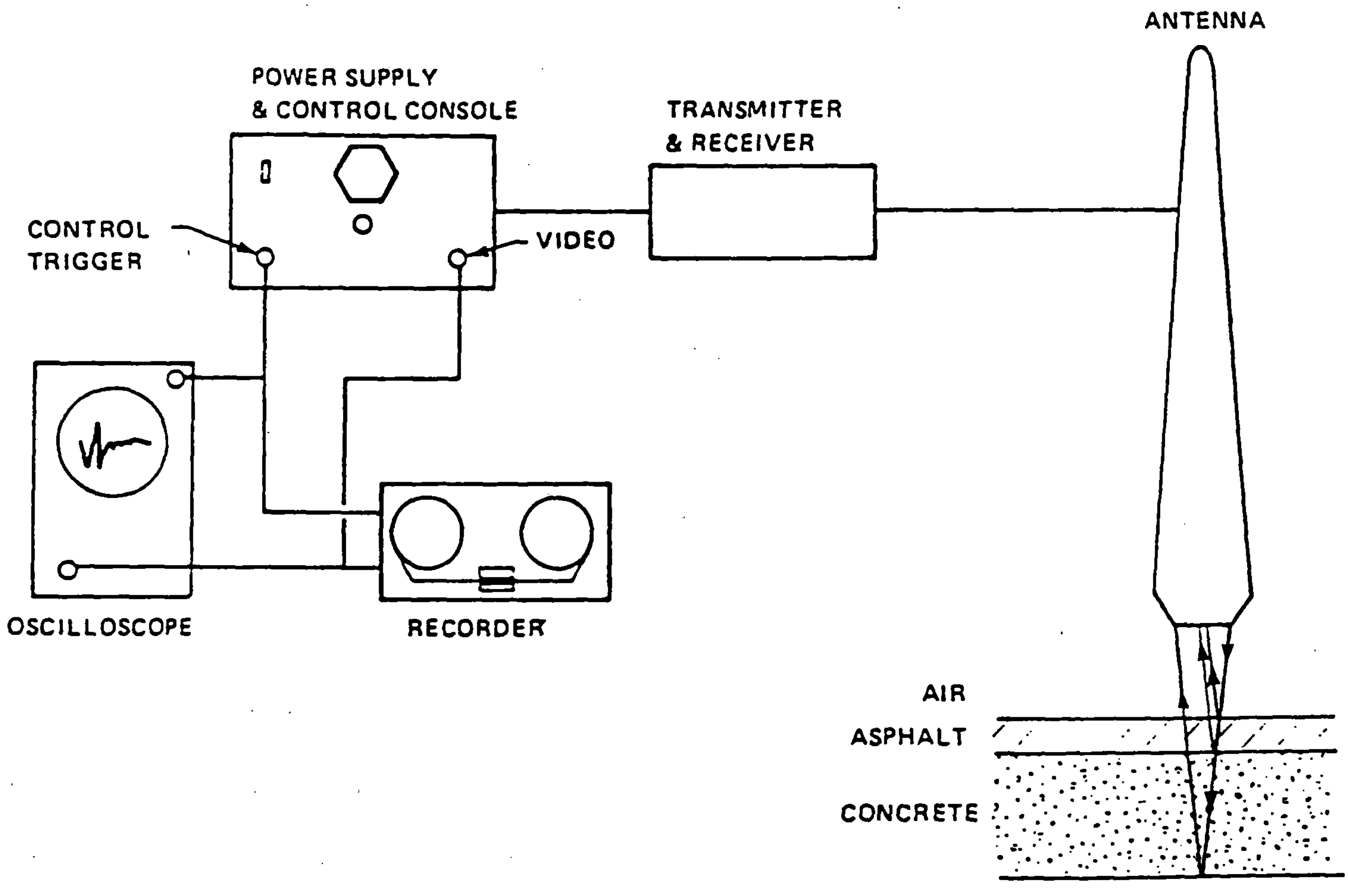


Fig. 3.10.10 Components of a GPR Monitoring System (Manning, 1985)

used to identify delaminated or debonded areas in concrete by measuring the temperature difference between these areas and the surrounding areas of sound concrete (Maser and Roddis, 1990)

Thermography has the advantages of relatively fast data acquisition and easy interpretation. However, infrared measurements are severely affected by the unpredictable changes in weather conditions. Defects can be identified only on bright sunny days (or nights following sunny days) during the solar heating cycle (around 11 a.m. - 3 p.m..) or the cooling cycle (around 11 p.m. - 3 a.m.). Furthermore, the magnetic fields existing in the Maglev environment may cause high temperature gradients and their effect on the infrared measurements has to be properly incorporated in the study.

Infrared Monitoring System

The main components of an infrared monitoring system are:

- Infrared camera and VCR;
- Regular video camera and VCR; and
- Digitization system for the infrared camera with computer and disk storage.

The IR system can be mounted on the Maglev vehicle for scanning the guideway. However, the speed of the Maglev vehicle is far too high for the camera to read and record distinguishable temperature differentials. Hence a separate test vehicle which runs at a slower speed (32-48 kmph [20-30 mph]) is necessary for the IR system. A test vehicle similar to that used for the GPR system can be used in the IR system. Some manual labor is necessary for data collection and supervision of the testing procedure.

3.10.2.7 Fiber Optic Sensors

Fiber optic sensors can be used to detect microcracks in the guideway, guideway misalignments, or obstructions on the guideway. For detection of the above, the sensors may be implemented separately or in conjunction with each other. The main advantage of using fiber optic sensors is that the strong magnetic field associated with Maglev does not affect the components of the system. The only components of the system which will be exposed to magnetic fields are the fiber optic cables, which are not affected by the field. Other electronic components have to be shielded and placed at a safe distance from the magnetic field.

Another advantage of the system mentioned above is the method of detection. The sensors only need to detect a decrease in light intensity to determine if a microcrack, misalignment, or obstruction is present. This feature makes the data analysis both easy and inexpensive. Modifications may be made to the microcrack detector system in order to detect strain and temperature, with a penalty of more difficult and expensive data analysis.

3.10.2.7.1 Embedded Fiber Optic Cables to Produce a "Smart Structure"

Fiber optic cables run from inspection stations to the guideway where they are embedded at critical stress areas, and then return to the inspection station. The inspection stations contain Light Emitting Diodes (LED) that transmit light through the fibers, phototransistors to detect the light intensity passed through the fiber, and support devices (i.e., operational amplifiers, transistors) that amplify the signal for interpretation. The inspection stations can be positioned either at every joint in the guideway structure, or at intervals of joints as necessary. At least two fibers run the length (about 24.4 m [80 ft.]) of the guideway. This length does not pose any major problem, since optical fibers with a length of several miles are being successfully used for telephone lines.

When the structure has cracks at the critical areas, the fiber embedded within the guideway will experience some deformation. This deformation in the fiber will allow light which is normally reflected within the fiber to be absorbed in the fiber cladding. This deformation is known as a microbending loss in the fiber and will decrease the intensity of light received at the photo-transistor. This decrease in light intensity will trigger a warning signal that some crack has occurred within that particular section of the guideway. However, experimental research to determine the minimum crack size that can be detected is yet to be conducted.

The embedded cables in the above configuration could also be used to sense temperature and strain. A change in either of these would cause a phase change in the light transmitted through the fiber optic cable. Using interferometric devices, the phase change with respect to a reference fiber can be determined. The measurement of these parameters would greatly increase the complexity of data analysis.

3.10.2.7.2 Fiber Optic Guideway Alignment Detector

Fiber optic cables run from inspection stations to the guideway joints, through deformers, and return to the inspection stations. The inspection stations contain Light Emitting Diodes (LED) that transmit light through the fibers, photo-transistors to detect the light intensity passed through the fiber, and support devices (i.e., operational amplifiers, transistors) that amplify the signal for interpretation. These inspection stations are usually very small units and can be positioned either at every joint in the guideway structure or at intervals of joints as necessary. Two fibers are placed at each guideway joint.

If the guideway becomes misaligned due to settlement or other causes, the deformers press against the optical fibers. The deformers have teeth that induce microbending losses when pressed against the optical fibers. The deformation in the optical fiber will cause light which is normally transmitted through the fiber to be absorbed by the fiber cladding. The amount of light absorbed by the cladding is proportional to the deformation of the fiber. The light received at the phototransistor will decrease, and a warning signal is generated.

3.10.2.7.3 Obstruction Detection on the Guideway

Fiber optic cables run from inspection stations to the guideway and terminate at lenses which focus the light and project it across the guideway to form light emitters. A second set of cables runs from inspection stations to the guideway and terminates in lenses which gather the light sent by the emitters. These light receivers carry the light back to the inspection station. The inspection stations contain Light Emitting Diodes (LED) that transmit light through the emitters, phototransistors to detect the light intensity passed through receivers, and support devices (i.e. operational amps, transistors) that amplify the signal for interpretation. The inspection stations can be positioned either at every joint in the guideway structure, or at intervals of joints as necessary.

An array of light emitters and receivers are positioned on the guideway as shown in Figure 3.10.11. Any large obstruction on the guideway will break one or more light beams, resulting in a decrease of light at the phototransistor. A warning signal will then be sent to the monitoring system. The number of emitters and receivers in the array can be adjusted as necessary.

4.0 SUMMARY, CONCLUSIONS, AND OPTIONS

The research described in this report represents one part of a comprehensive, long-term study to assess the engineering, economic, and environmental feasibility of Maglev in the U.S.

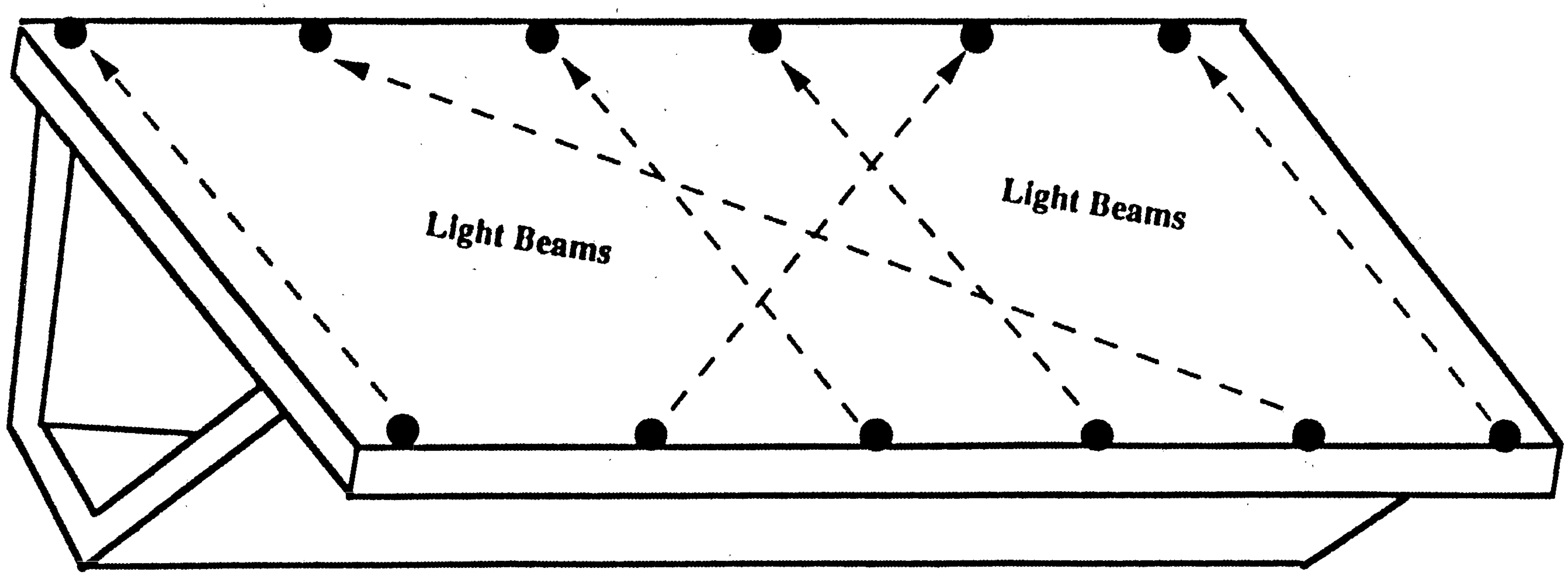


Fig. 3.10.11 Positioning of Guideway Obstruction Sensors

Previous work in Europe and Japan suggests that the concept is technically feasible and may offer substantial benefits in terms of certain types of intercity travel. There are, however, a number of concerns that must be addressed.

A Maglev system consists of essentially four major components: guideway, substructure, propulsion/guidance/levitation system, and vehicle. The guideway constitutes the major cost item for the system. The overall objective of this study was to examine existing and innovative materials and guideway systems and provide an assessment of the most promising systems for Maglev guideways in terms of performance and cost.

Several conclusions have been drawn and options presented as a result of the research effort. A brief summary will be presented first, followed by the conclusions and options for future work.

4.1 SUMMARY

The various Maglev systems under consideration for a ground transport system were reviewed, summarizing different magnetically-levitated propulsion technologies (e.g., EDS, EMS, LIM, and LSM). Each Maglev technology possesses distinct advantages and disadvantages. At this stage, it is premature to rate each system with regard to the overall technical and economical effectiveness. While all systems seem to be promising, German and Japanese efforts have seen the most extensive results to date.

The concrete, steel, FRP, and hybrid guideways have been designed under varying load and serviceability conditions. The governing design aspect of the guideway is the vertical deflection. For an electromagnetic (German) system, the vehicle is suspended only 10 mm above the guideway, thus allowing only a very limited vertical movement of the guideway under live load. However, the electrodynamic (Japanese) system has a 100 mm air gap. In general, all design and performance criteria have to be kept at minimum tolerances to allow the system to perform successfully. The stringent serviceability limits and performance requirements that have been established from ACI, AASHTO, and AREA testing and construction specifications, and other relevant materials should be satisfied during all design and operations and maintenance phases. The design of each Maglev guideway must account for material component behavior such as strength, stability, stiffness, fatigue, and flexibility. This should not only apply to the design of the guideway but also to the design of substructure, footings, vehicle, and functional components to allow a compatible interaction of each system's components.

Human response factors related to noise levels, environmental effects, and ride quality were established, based on the information available in the literature. The loads acting on a guideway system such as dead loads, dynamic, impact, braking, wind, thermal, centrifugal, aerodynamic loads, and others were identified. Furthermore, the effects of magnetic field interference were discussed. The resulting magnetic drag forces can be minimized by properly designing the reinforcement system, the electro-magnets (ferromagnets), and the conductor sheets. One way to minimize the magnetic drag forces is by replacing any steel components in the magnetic fields with non-conductive composite materials.

The Maglev guideway represents an excellent opportunity to incorporate fiber reinforced plastic rebars as reinforcement and prestressing tendons instead of conventional steel that is usually used for these tasks. The advantages of using composite materials in the design of a

Maglev guideway were highlighted. Composite materials appear to be feasible and highly compatible not only for use in the reinforcing system in a concrete guideway but also as a major structural component in a hybrid guideway system.

Consideration has been given to the fabrication, erection, and transportation processes, utilizing modular construction techniques which should be employed on a systematized basis to validate any economic feasibility of the construction of a Maglev guideway system. The construction of a prefabricated concrete guideway module appeared to be the most promising choice with regard to ease, speed, and cost efficiency of the fabrication and erection.

Modularized precast concrete units can decrease costs and erection time while providing a better quality end product. Simple span precast concrete units can be used to minimize the effects of soil settlements and replacement time; however, the ride quality suffers as the number of structural joints increases. The joints can be reduced by converting simple span guideways into two or three span guideways; but thermal stresses are more critical in continuous structures and must be accounted for in the design.

Superstructural guideway systems made of FRP composite materials have several advantages over conventional construction materials. First, FRP is lighter than steel and concrete, thus, the cost and time for construction and transportation are reduced. Composite materials and systems are corrosion resistant, which reduces maintenance cost. Since composite materials are nonmagnetic, there are no electromagnetic field effects. On the other hand, the principal disadvantages of composite materials are their high initial costs and excessive deflections. Even though composite materials have high strength-to-weight ratio, their stiffness is low; consequently, the design of the section is governed by stiffness in most cases. The higher damping of composite materials may improve dynamic response but the reduced mass may cause vibrational problems. To avoid high material costs and buckling problems, composite sections with concrete or wood cores should be used rather than solid cross sections. The lack of technical know-how to apply composite materials to civil engineering structures and the lack of information on joint behavior are areas of concern when using composite materials. The manufacturing technique for modular units, which is a significant cost factor, is quite attractive with composites.

Since the buckling analysis showed that a simple box section would not be stable, only box sections with cross members were chosen for the optimization. There are significant advantages in using a jointless clamped-clamped design as shown by the amount of material that is needed to carry the loads for a simply supported system versus a jointless system for Maglev loading. The depth of the guideway reduces significantly for a jointless system versus a simply supported system.

When the cost of carbon fibers is compared to the cost of E-glass fibers, the carbon system is at least six times more expensive. This fact indicates that, even though E-glass/polyester structures required more material, this was not enough to justify the increased material cost of a carbon/polyester structure.

In optimizing for weight, unlike the box sections, it was shown that as a result of the distributed load, the amount of material needed to carry the load was significantly affected by the boundary conditions. In addition, it was shown that up to a 50 percent reduction of material could be achieved with the jointless design as compared to the simply supported system for both E-glass/polyester and carbon/polyester laminates. A second optimization on the hybrid truss models was performed with the added constraint that the diameters of the tubes for the vertical and diagonal members be equal. A review of the data demonstrated that this caused a significant increase in the material needed to handle the load, indicating that the material is not being used to its maximum potential. Finally, when the E-glass and carbon fiber systems are compared, it is found that the materials are not used to their maximum potential even though E-glass/polyester structures required more material.

Based on a subjective rating survey, the following systems were recommended for further study: trapezoidal concrete box section with FRP reinforcement; hybrid system with concrete slabs (reinforced with FRPs); and FRP truss system; and FRP composite cellular deck with cross bracing (diaphragms).

The hybrid system with concrete decks and FRP trusses offers good damping, strength, and stiffness characteristics. However, the complexity of the connections and field installation are two of the disadvantages that must be further evaluated. A very efficient system is the jointless guideway design (built monolithically with the supports), but in this case the concrete decks must be prestressed because tensile stresses are developed in the negative moment zones.

The cellular FRP box section with cross members can be fabricated by pultrusion. The stability analysis indicated that the cross members are needed to prevent buckling of the webs. A cellular composite section is recommended for construction, but the long-term performance of the system must be established, and the cost of the structure must be evaluated by including life-cycle considerations.

After an extensive review and evaluation of economic analysis techniques, the net present value approach was chosen for the economic evaluation of Maglev guideways. This approach is considered to be superior to all others and provides great flexibility in an analysis.

Due to the extremely small number of existing Maglev systems, very little actual cost data needed for an evaluation are available. Thus, any cost estimates involve considerable judgment. In addition, the innovative nature of the designs being proposed also contributes to making the estimating process more difficult. In terms of capital costs, estimating labor costs associated with the new materials or construction procedures proved to be the most difficult step. The lack of available data on the materials and procedures contributes to the difficulty.

The development of maintenance costs for Maglev guideways is also hampered by the lack of historical data. To date, two basic approaches have been undertaken by estimators in formulating Maglev maintenance costs. Both techniques utilize a certain percentage of the capital costs in some form or another. Because of the lack of Maglev data, conventional mass transit system guideways were examined. This project examined maintenance data from the Morgantown DPM and applied it to the Maglev guideway situation. This application was in the form of verification of the rule-of-thumb percentage approach and identification of guideway maintenance problem areas.

From the study of the various NDT techniques and their applicability to Maglev systems for guideway monitoring, a number of issues were highlighted. First, the application of NDT methods for complete monitoring of Maglev guideway systems is very promising. Secondly, the use of a NDT monitoring system can lead to early detection of distresses, initiating proper repair steps and preventing the occurrence of disasters. From the study of the various NDT systems, it is evident that a combination of the various NDT methods will be necessary for a complete monitoring system. All NDT methods discussed are applicable to concrete structures whereas only a select number of NDT methods are applicable to composites. Finally, ground penetrating radar, infrared thermography, and optical fibers (embedded sensors) are not applicable to steel structures.

4.2 CONCLUSIONS

The following conclusions may be drawn from this research study:

1. Sixteen Maglev guideway superstructural systems with closed and open cross sections were identified, and they were reduced to the following seven systems for in-depth design evaluations of 80 ft. span length.
   a) trapezoidal concrete box section with conventional steel reinforcement;
   b) trapezoidal concrete box section with fiber reinforced plastic (FRP) reinforcement;
   c) rectangular concrete box section with conventional steel reinforcement;
   d) trapezoidal steel box section;
   e) hybrid-system with concrete decking stiffened by steel trusses;
   f) hybrid-system with concrete decking stiffened by concrete filled FRP trusses;
   g) all FRP box system.
2. In-depth design evaluations were carried out for the above sections using ten load conditions and three serviceability criteria.
3. Special emphasis is given to the design of Maglev guideway systems employing fiber reinforced plastic materials so that magnetic drag forces can be minimized.
4. Based on our internal rating, trapezoidal or rectangular concrete box with FRP

reinforcement, hybrid system with FRP trusses stiffened by concrete decks and all FRP box systems are found to be the best composite material alternatives for further study.

5. Our literature reviews revealed that modularized construction techniques should be employed on a systematized basis to attain ease, speed, and cost efficiency of the fabrication and erection.

6. A review of economic analysis techniques revealed that the net present value approach is the superior approach to all others.

7. Since the development of maintenance costs for Maglev guideways is hampered by the lack of data, maintenance data of conventional mass transit system guideways were examined and found that the guideway maintenance costs are very low, i.e., 0.03 percent of the original capital costs.

8. The use of a NDT monitoring system will lead to the early detection of distresses in Maglev guideways, and a combination of the various NDT methods will be needed for complete monitoring. The ultrasonic method can measure in-situ stresses in concrete and steel guideways whereas the acoustic emission technique was found to be most useful in measuring stresses in FRP composites.

4.3 OPTIONS FOR FUTURE WORK

Options for Future Work

This research has identified a number of areas where additional work is needed before the details of a Maglev guideway can be defined. Some of this effort involves "paper and pencil" type studies using data and/or information which was not available or could not be acquired during this project. Other issues can only be addressed through laboratory and field testing and experience. This section outlines the key needs in each of these areas.

A number of design factors were based on limited knowledge. Future research, it is hoped, will aid the Maglev guideway designers to fully understand some of these phenomena associated with a Maglev technology. The design examples that were developed as a part of this effort should be viewed as preliminary and not as in-depth guideway designs. Optimization of a guideway section, including detailed design specifications and construction drawings, should be carried out in the future.

Several issues need to be resolved so that the economic analysis can be refined. Follow-up work should address the following areas:

Climatic effects on guideway: It is not clear whether provisions need to be made for controlling snow and ice on Maglev guideways. If so, the question of whether such a system would be either internal to the guideway or external needs to be answered. The former may involve additional construction cost and would certainly mean additional maintenance costs (as indicated by experience with the Morgantown DPM system).

Future retrofitting of guideway system: As guideway-related components reach the end of their useful life, complete replacement or retrofitting of certain parts of the system may be necessary. This would certainly be a major expense that should be included in any economic analysis. Unfortunately, neither the nature nor the magnitude of this work is known. Additional information in this regard would be desirable.

Construction techniques: The issue of exactly how Maglev guideways will be produced and installed is a major issue that needs to be resolved. Due to the significant differences in the guideway designs being proposed, the construction technique being employed could have a significant influence on the capital costs.

Maintenance cost factor: Because of the lack of Maglev guideway maintenance data, the use of a maintenance cost factor (or percentage) appears to be necessary. The significant differences in proposed factors create problems. Additional information needs to be collected before this issue can be resolved.

NDT techniques: Research is needed to study applications of NDT methods to FRP structures. Application of Acoustic Emission and Ultrasonics to FRP structures appears very promising. Research also should be conducted on the effect of strong magnetic fields on NDT sensor/system response.

Test plan: In order to fully investigate all the parameters affecting Maglev guideways and to assess the safety and reliability of the guideway systems, a model test plan was developed in terms of laboratory, field experiment, and field demonstration phases, and testing under a variety of conditions is recommended.

Laboratory Phase

Prior to field exposure, testing under controlled conditions would be required. The optimal laboratory testing phase would include:

- Building several structural components (with embedded sensors) in the laboratory to determine: (1) performance behavior under static, thermal, and dynamic conditions; (2) thermal, creep and shrinkage of the material, and study of the fatigue response of various components and numerical evaluations using numerical techniques; (3) performance of various NDT sensing techniques for their accuracy and reliability, sensitivity, ease of data acquisition, and quality control of the curing process; (4) methods for rehabilitation of damaged main components and replacement of secondary components, and (5) design cost details of an operational system for nondestructive monitoring.

- Construction of a Magnetic Influence Laboratory to study: (1) the effect of magnetic field on various components; (2) magnetic drag forces as a function of area, cover and type (open vs. closed loop) of steel reinforcement; and (3) the effect of magnetic field on various NDT sensors.

Field Experiment Phase

The field experiment phase would involve testing under actual field conditions with exposure to the environmental loads. This phase should include:

- Construction of an experimental track to: (1) field test the proposed modular units and appurtenances associated with the guideway; (2) study the interaction between the vehicle guideway foundation and soil to establish tolerable limits for operation, ride quality, and human comfort and to establish tolerable movements of the guideway with respect to stress and safety of the track; (3) measure noise, aerodynamic forces, and forces due to track irregularities in the field and integrate them in the Maglev guideway design; (4) measure magnetic drag forces as a function of the amount of ferrous material in the guideway; and (5) study the viability of various NDT methods (including embedded fiber optic cables and microbending deforming teeth) as a complete monitoring system.

Field Demonstration Phase

After extensive testing of the Maglev components in the laboratory and the whole system in the field, a prototype (e.g., 20-mile-long test track) could be built as a demonstration system with limited access to passengers and exposure to actual field conditions to evaluate performance.

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APPENDIX A

CONCEPTUAL MAGLEV GUIDEWAY SYSTEMS

A review of literature has shown (GangaRao, 1978) how different materials (concrete, steel, others) lend themselves to a systems approach toward the construction of bridges or elevated guideways. Several innovative guideway systems (Figs. A1 through A16) have been identified from our literature review as feasible alternatives for elevated Maglev guideways. In addition, several feasible cross-sectional shapes (Figs. A17 and A18) have been selected for possible implementation with the guideway systems. The sixteen guideway systems have been broadly classified as beam or frame systems (Figs. A1, A2, and A7 through A13), cable stiffened beam systems (Figs. A5, A6, and A7 through A14) and deck stiffened truss systems (Figs. A3, A4, A15, and A16). Similarly, Figures A17 and A18 provide several conceptual closed and open cross sections that can be evaluated with respect to beam and frame systems. It should be noted that cable-stiffened beam systems and the space truss system have been eliminated from our study because structural complexities involved routinely maintaining such superstructural systems. Other superstructural systems such as the beam system with over hangs (Fig. A2) and the frame systems (Figs. A7 through A13) are considered to be variations of simply supported beam systems. Therefore, a simple beam type system (Fig. A1) for different cross-sectional shapes (rectangular and trapezoid) and materials (concrete reinforced with steel or FRP, and all steel) were selected for in-depth analyses and design under Maglev loads. In addition, guideway systems with steel truss or FRP tubular truss members filled with concrete (Fig. A15) were selected for in-depth analyses and design. Finally, an all FRP box system was selected, also for further investigation because of increasing use of composites in construction. Thus, a total of seven superstructural guideway systems were selected for final evaluations and presented in Section 3.3.

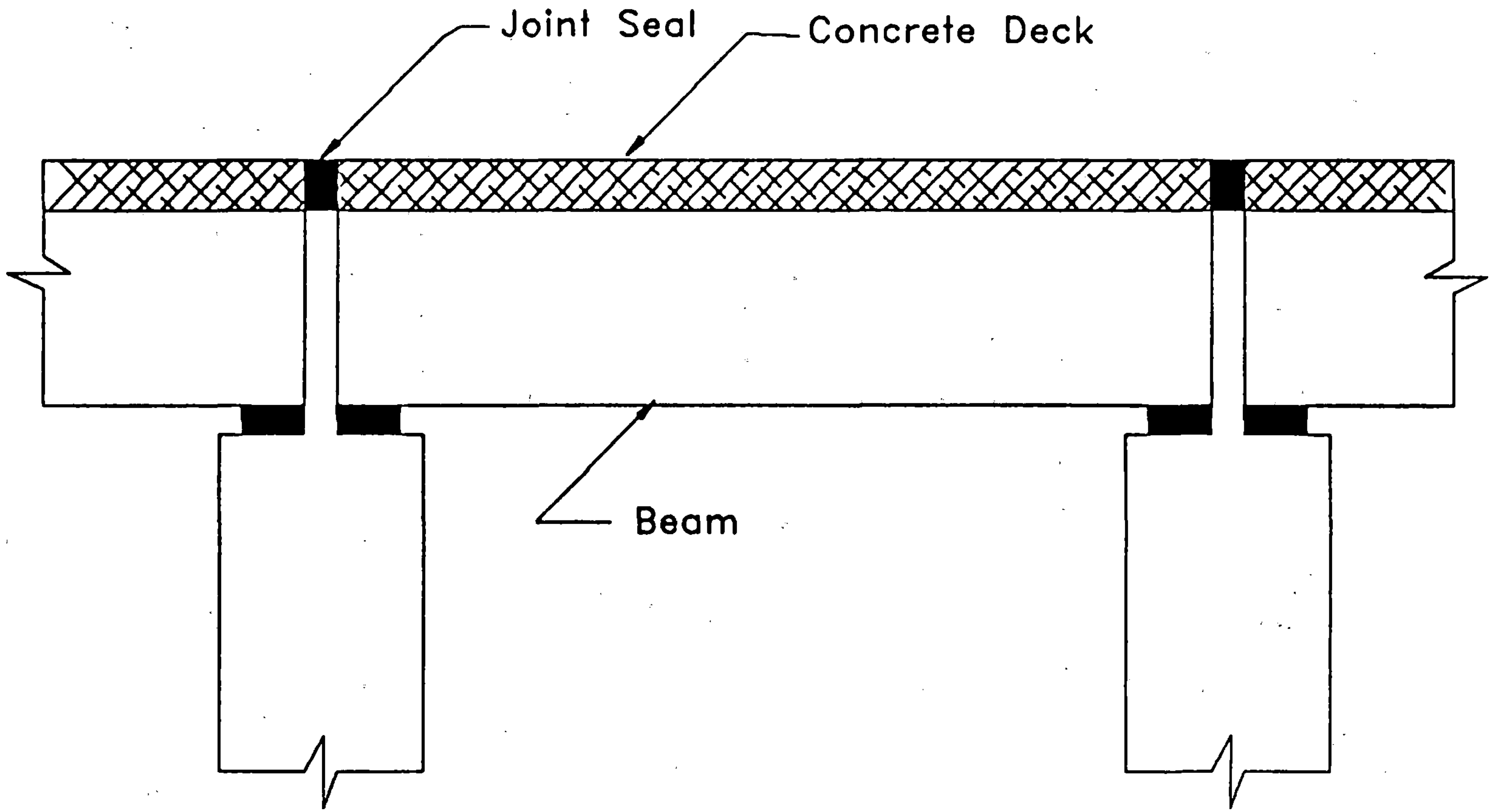


Fig. A1 Simple Beam System

Note: Refer to Figures A17 & A18 for Cross Section

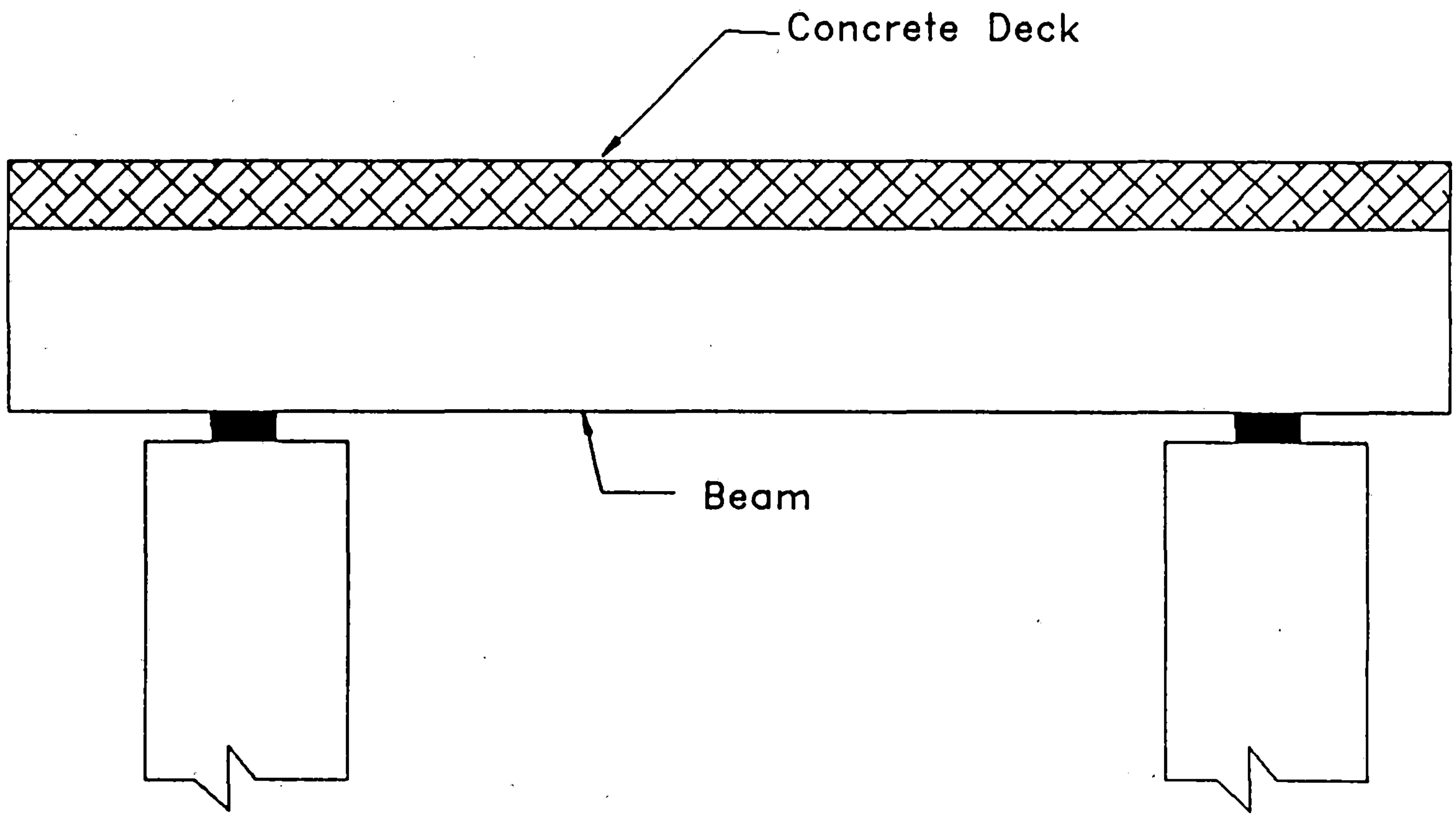


Fig. A2 Simple Beam System With Overhang

(Balanced Cantilever Construction)

Note: Refer To Figures A17 & A18 for Cross Section

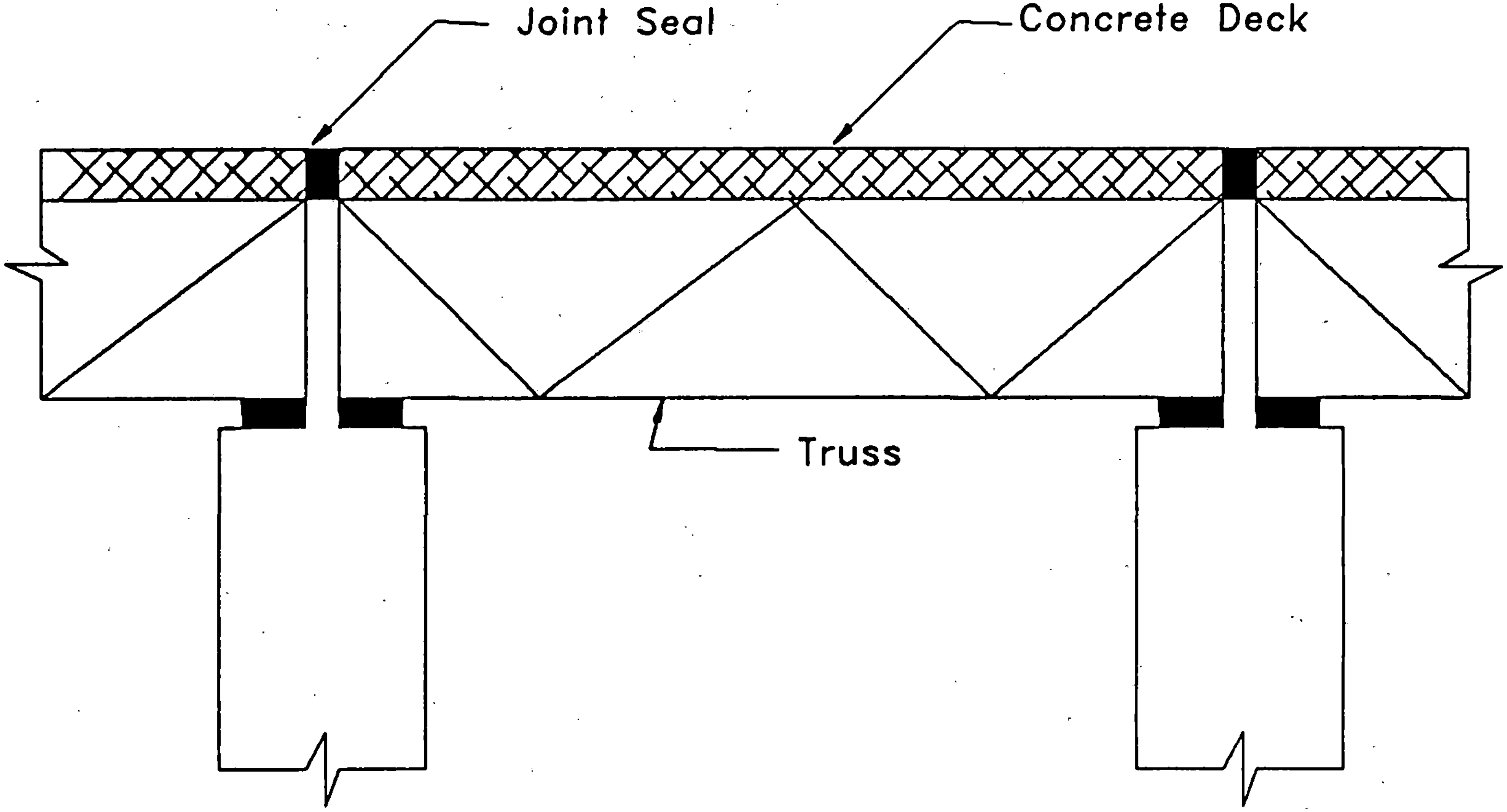


Fig. A3 Simple Truss System

Note : Refer to Figures A15 & A16 for Cross Section

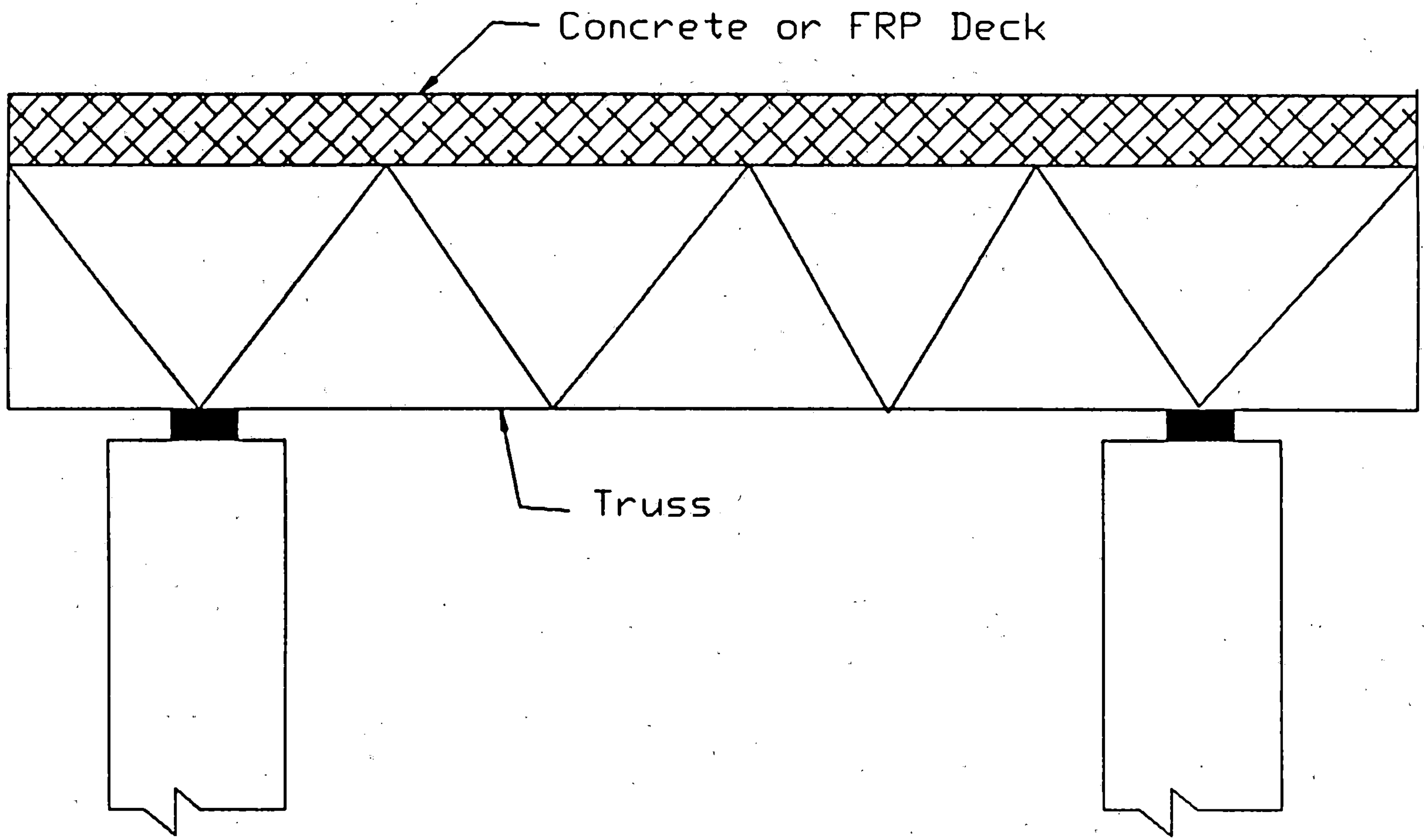


Fig. A4 Simple Truss System (Balanced Cantilever)

Note: Refer to Figures A15 & A16 for Cross Section

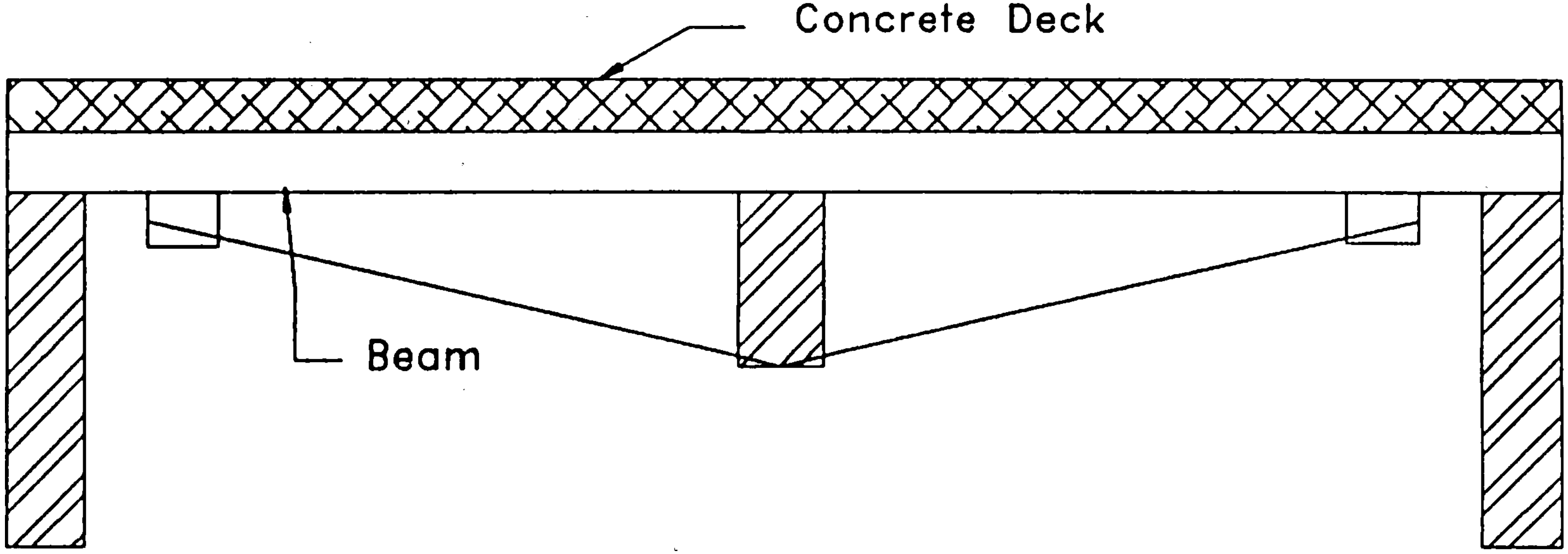


Fig. A5 Cable Stiffened King Post System

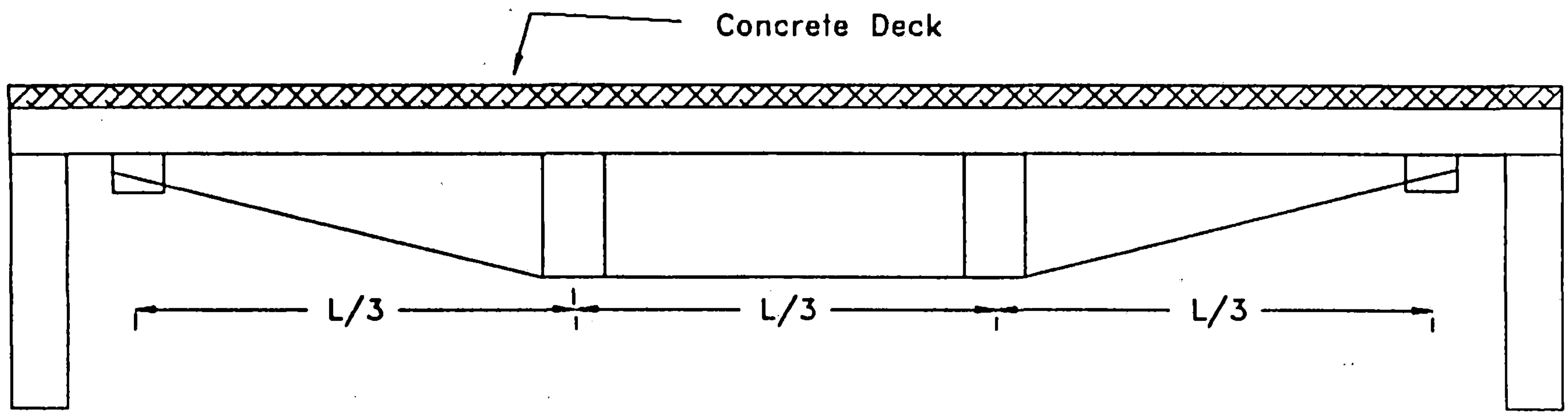


Fig. A6 Cable Stiffened Queen Post System

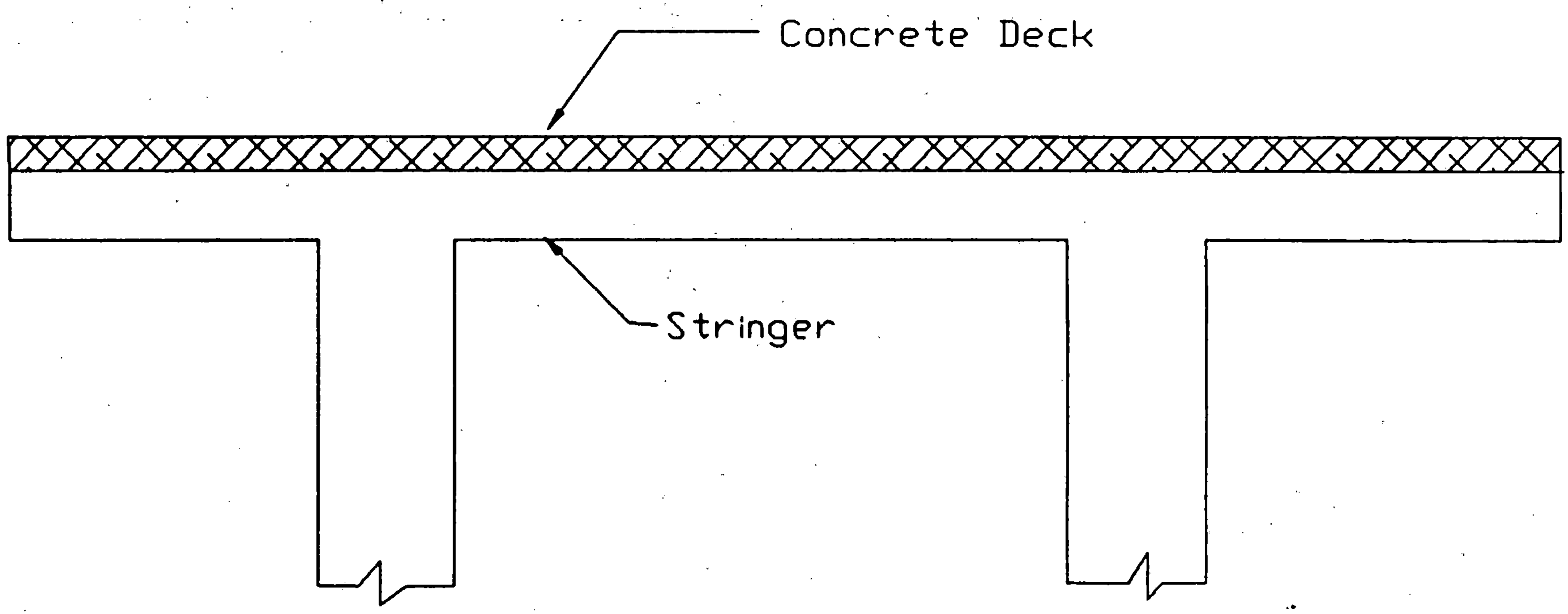


Fig. A7 Rigid Frame System with overhang

Note: The system is considered with or without overhangs

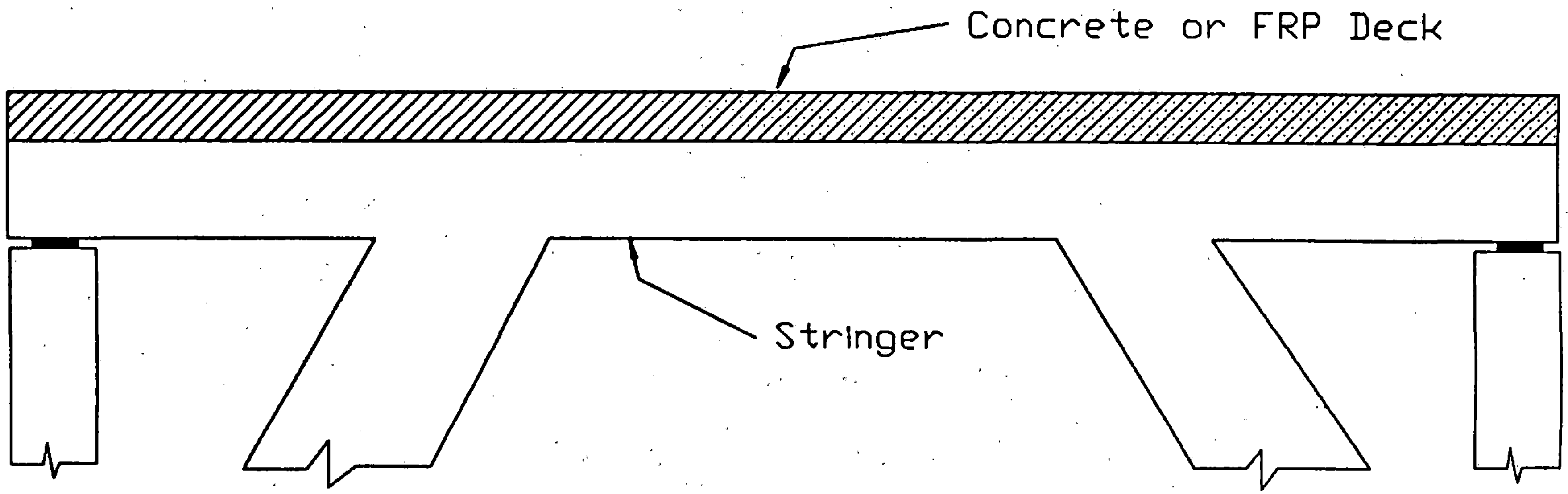


Fig. A8 Flat Arch with overhang

Note: The above system can be with end roller supports or hinge joint in the superstructure.

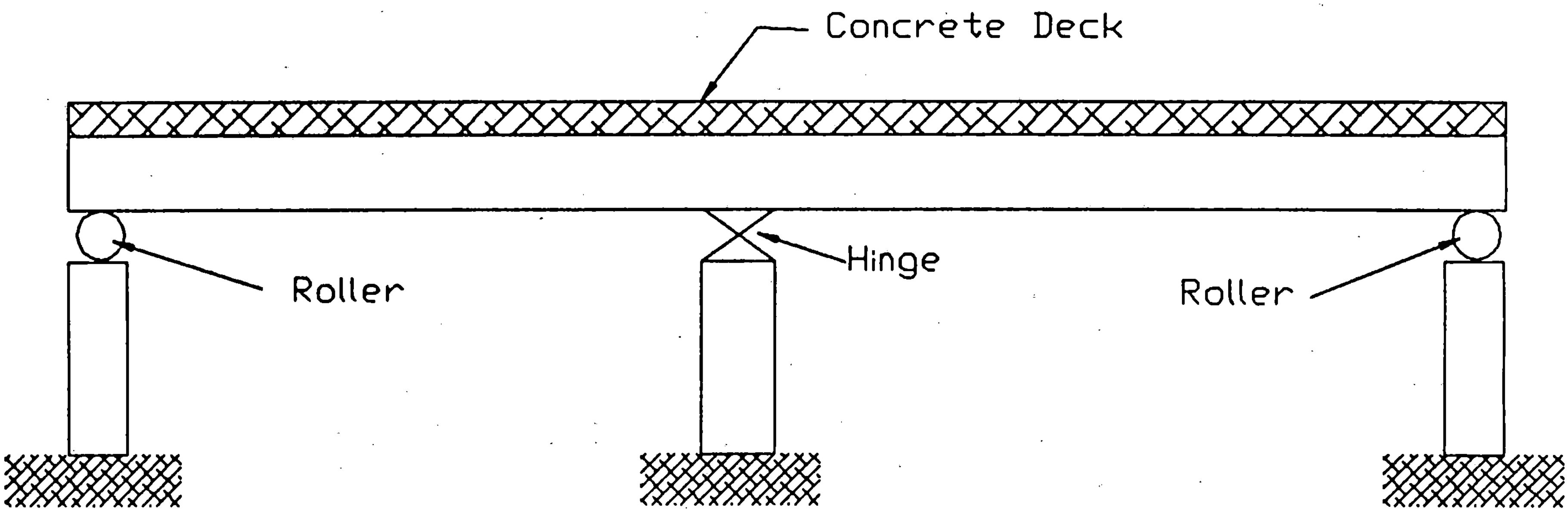


Fig. A9 Two Span Continuous Beam System

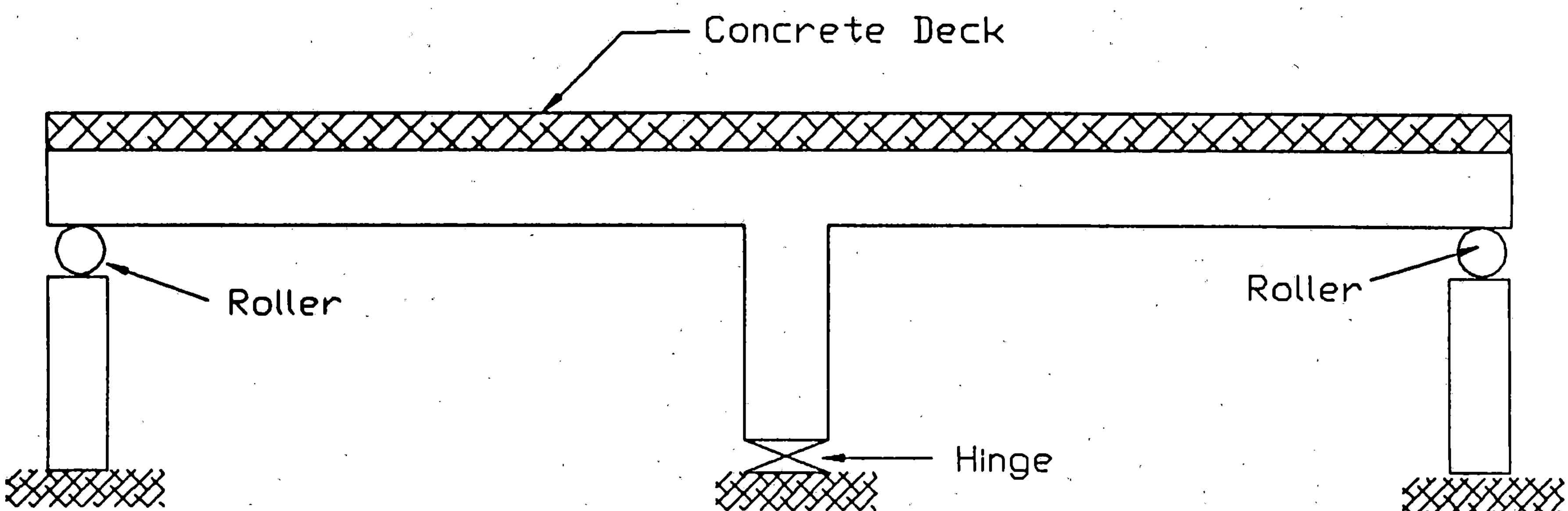


Fig. A10 Two Span Continuous System Without a Joint at Central Pier

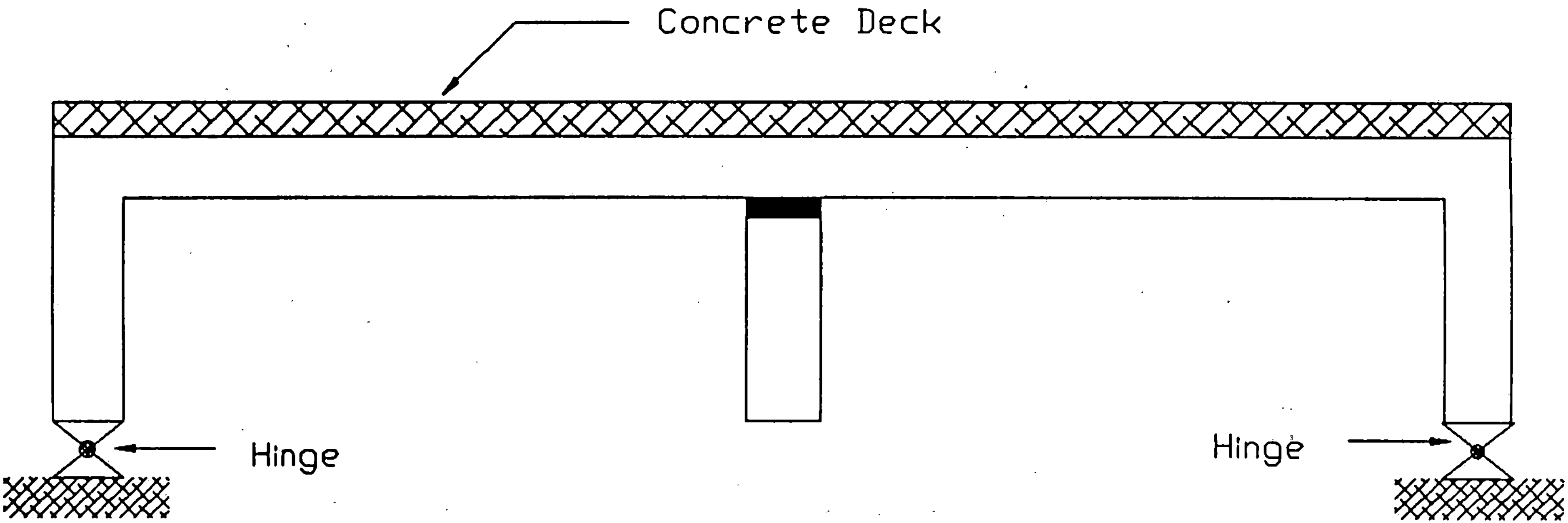


Fig. A11 Two Span Continuous Rigid Frame System

(No Lateral Restraint at Central Pier)

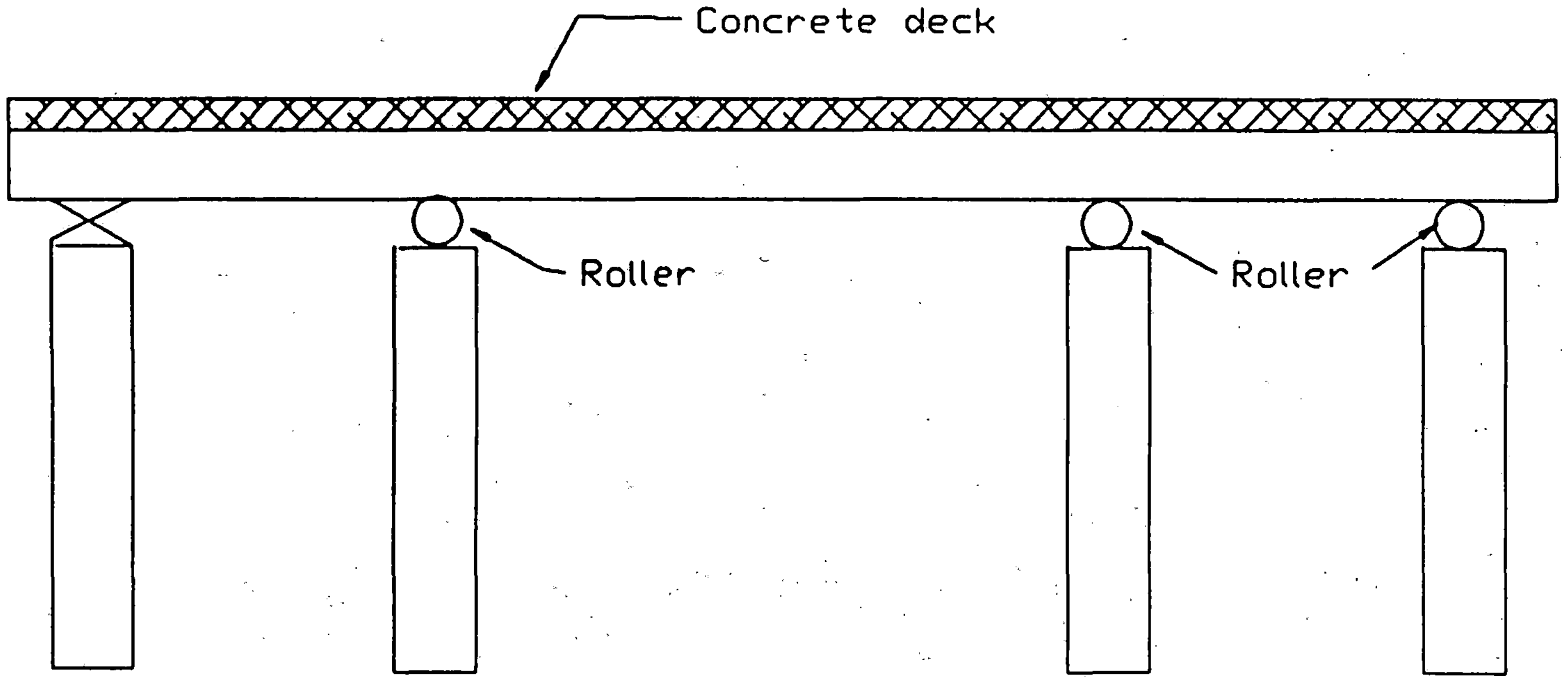


Fig. A12 Three Span Continuous Beam System

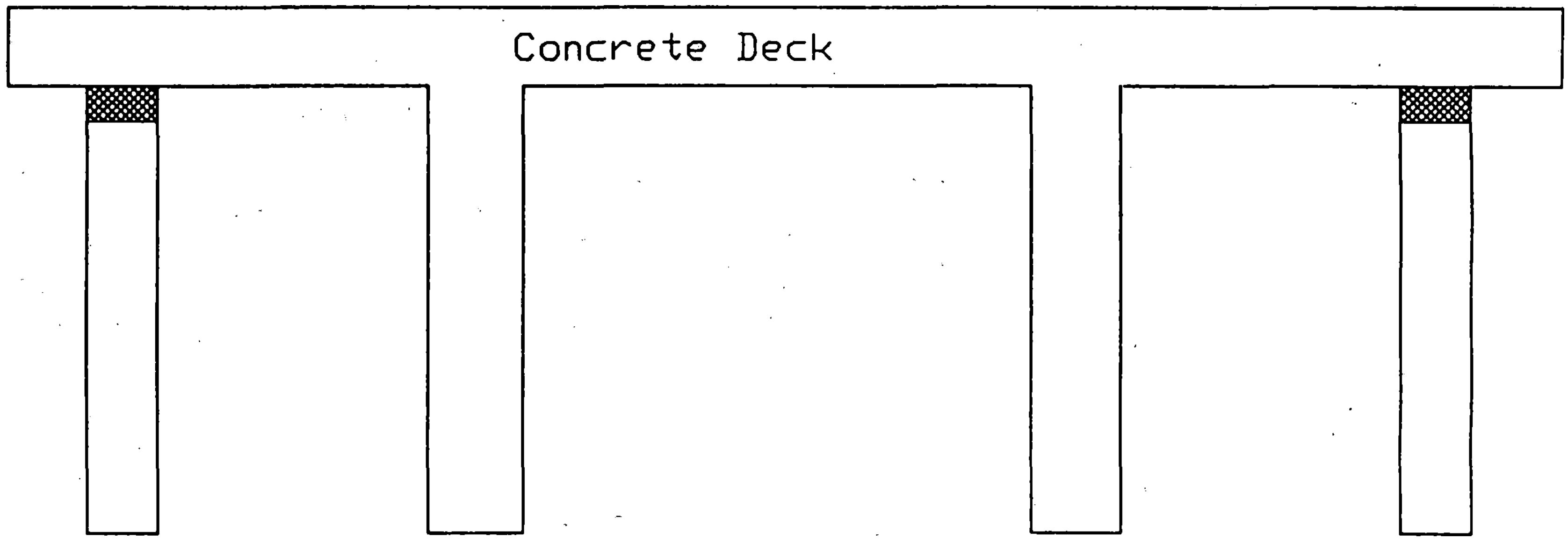


Fig. A13 Three Span Continuous Rigid Frame System

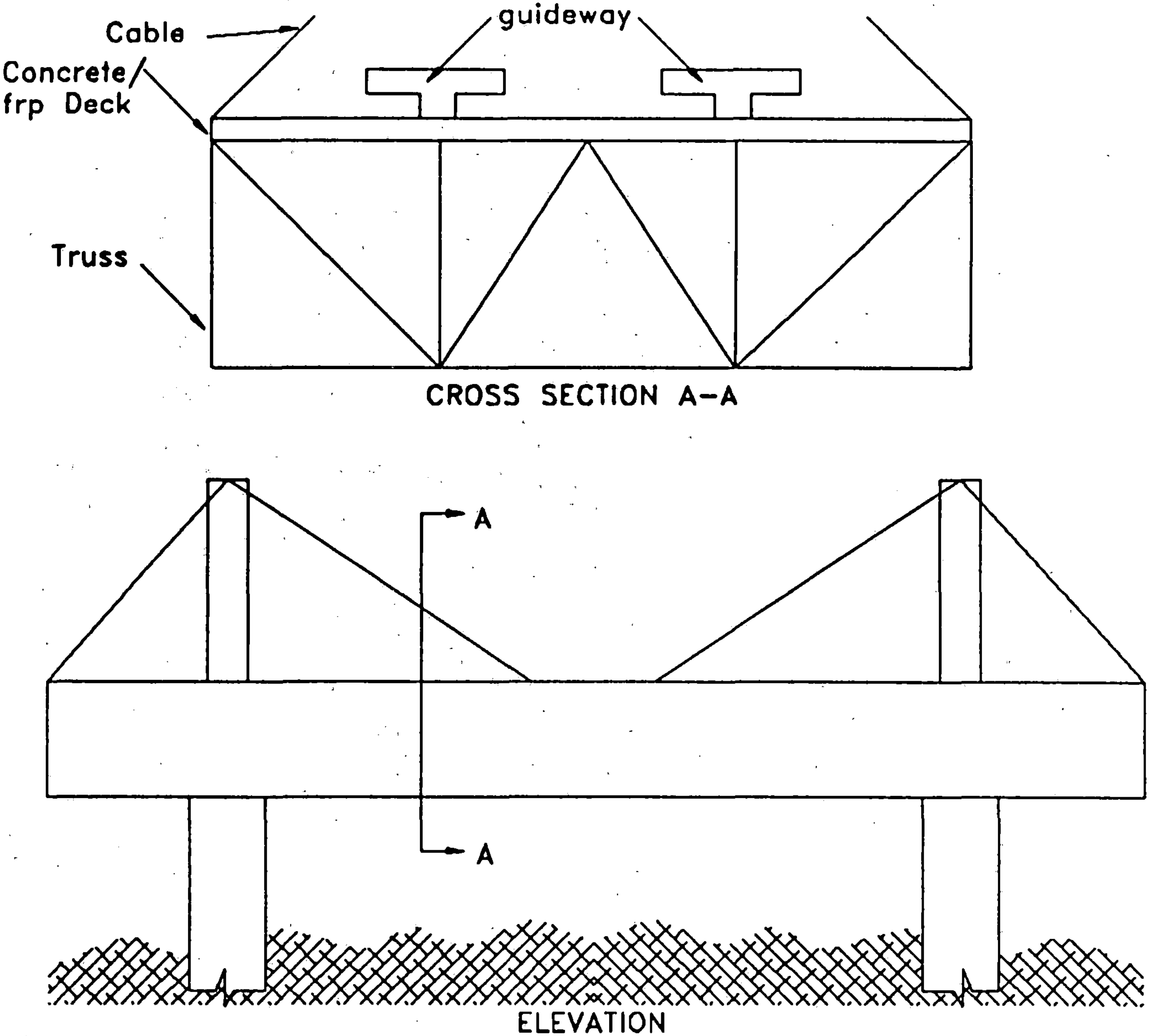


Fig. A14 Cable Supported System

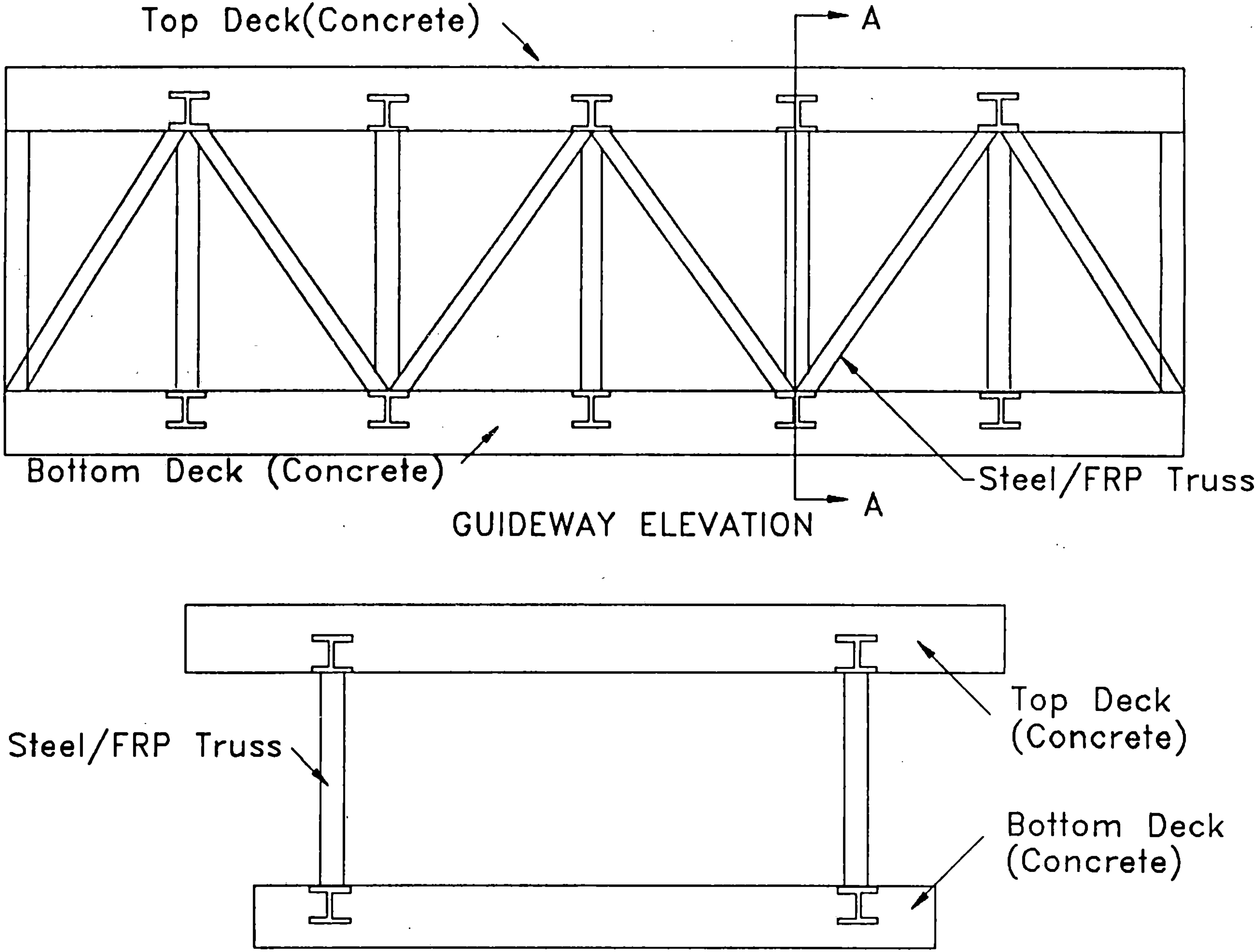


Fig. A15 Truss Type Guideway System with Cross Section

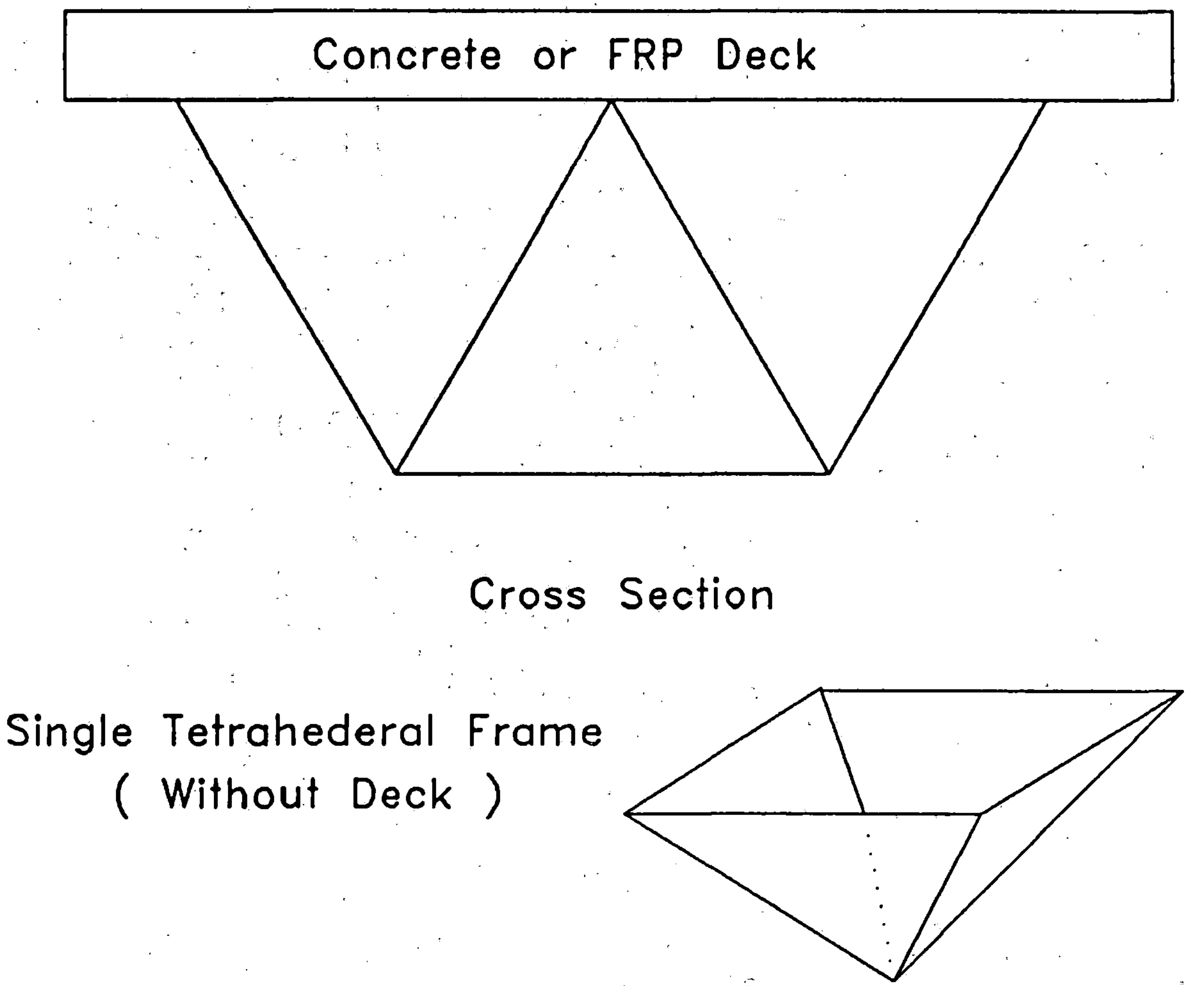


Fig. A16 Tetrahederal Space Truss System

Concrete - Prefab.

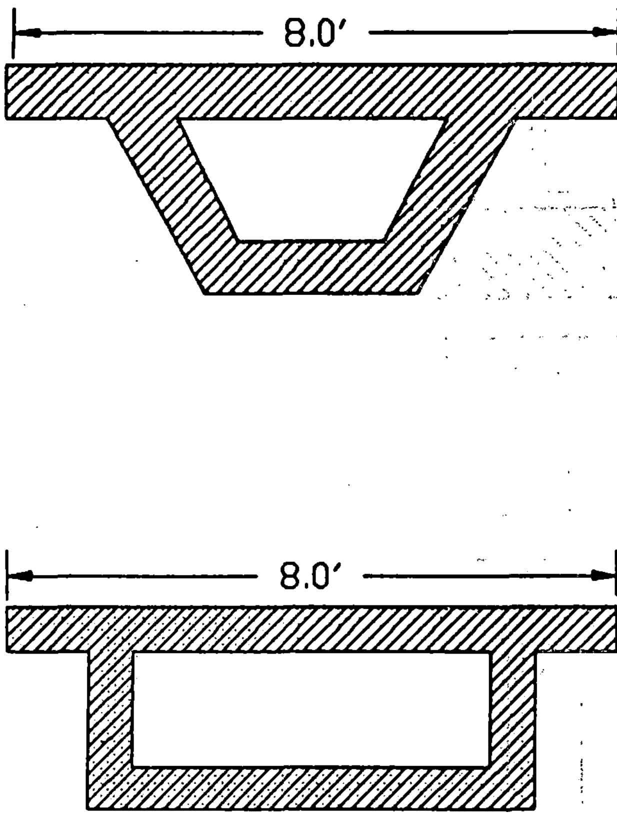
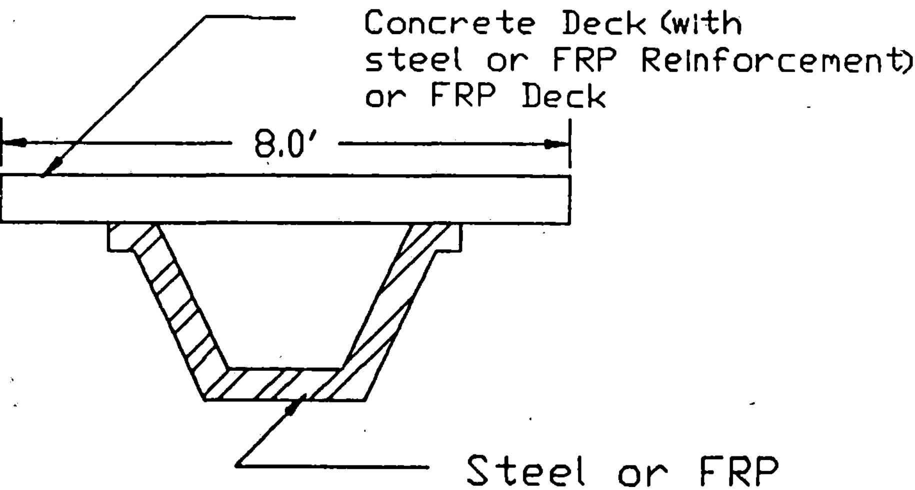
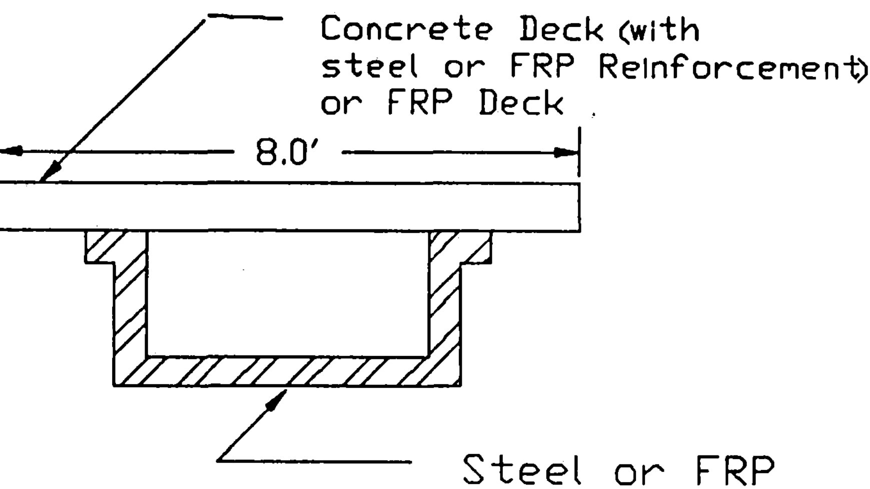


Fig. A17 Closed Cross Section





Not to Scale

s with or without overhangs

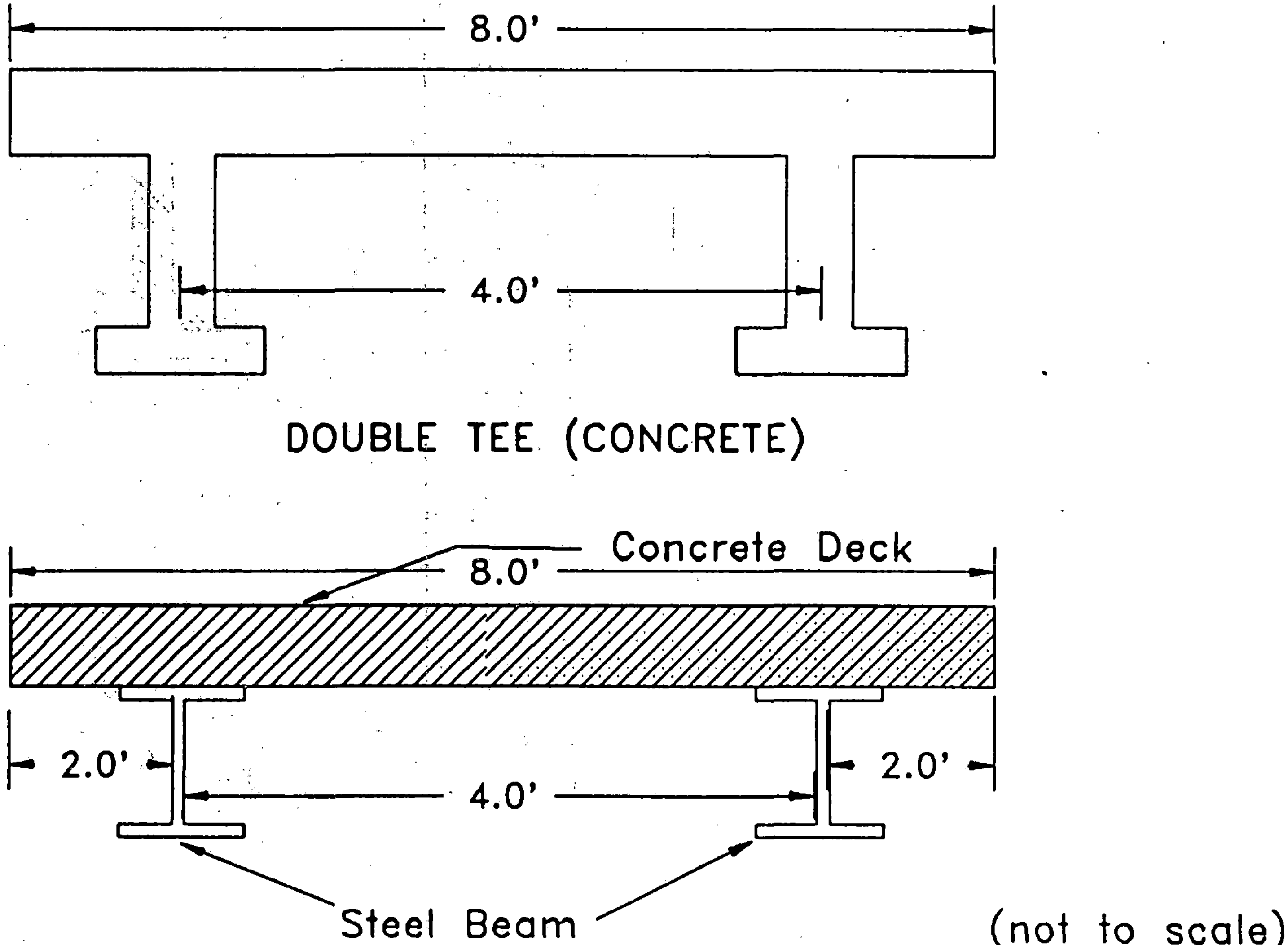


Fig. A18 Open Cross Sections