The MIT/Marine Industry Collegium

Opportunity Brief

ADVANCED COMPOSITES

for

OFFSHORE STRUCTURES

October 30-31, 1991
Cambridge, Massachusetts

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The MIT/Marine Industry Collegium
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INTRODUCTION

Defined in a broad sense, composites are not new. In fact, they date back thousands of years to the construction of adobe-like dwellings, which combined the use of straw, mud and clay. Composites today are found in a variety applications, from concrete sidewalks to polymer stealth aircraft. Composites also have broad applications for the offshore industry, as represented by offshore concrete structures, and the limited application of polymer composites for platform decking, low-pressure piping and chemical and water storage tanks.

The dramatic increase in deepwater leases with exploratory drilling, to depths of 2250 meters, as well as the leasing of sites in very hostile environments, e.g. the Arctic, has pushed the offshore industry to develop new design concepts for offshore platforms. Composites will play an important enabling role in the development of these future sites by providing four critical attributes to the design engineer: 1) corrosion resistance, 2) custom design profiles and strength, 3) high-strength to weight ratio and 4) fatigue resistance.

Despite the great promise composites may offer the offshore industry, several problems remain that will hinder the widespread acceptance of structural composites in offshore structures. Primary among these is cost. The manufacturing of composite structures depends on careful fabrication techniques, which oftentimes require close supervision, extensive human labor and associated high costs. Large-scale reproducibility remains a difficult manufacturing challenge, which in turn forces conservative design practices. In addition, accepted design protocol has yet to be developed for the application of structural composites. Nontraditional inspection and repair techniques must also be developed for composites in offshore structures. And there still remains a high-level of ignorance with regard to the long-term performance of composite materials (cyclic and thermal fatigue, environmental degradation, local impact damage, and failure mechanisms) in the marine environment.

The benefits that composites could offer the offshore industry warrant their continued investigation as future materials in offshore structures. Significant advances are made every year in the development of advanced composites and it will be only a matter of time before composites are widely accepted as a structural material.

This workshop will bring together the potential users and manufacturers of composite materials with MIT researchers to discuss some of the most promising applications of composites. The workshop will also identify those questions that must be answered for the successful use of composites in future offshore structures.

John Moore Jr.
Manager
MIT Marine Industry Collegium

WORKSHOP AGENDA

Advanced Composites for Offshore Structures

October 30, 1991

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9:45-10:30	**High-Performance Composites for Deepwater Risers** *Pierre Odru, Institut Francais du Petrole*
10:30-10:50	**BREAK**
10:50-11:20	**Failure and Damage Mechanisms in Composites** *Paul A. Lagace, MIT, Dept. of Aeronautics & Astronautics*
11:20-11:50	**Environmental Degradation of Composites** *David K. Roylance, MIT, Dept. of Materials Science and Engineering*
11:50-12:20	**Composites Manufacturing** *Timothy G. Gutowski, MIT, Dept. of Materials Science and Engineering*
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1:30-2:15	**Steel/Concrete/Steel Sandwich Composites for Permanently Floating Platforms** *Dale E. Berner, Ben C. Gerwick, Inc.*
2:15-2:45	**High-Strength Cement Composites for Marine Applications** *Oral Buyukozturk, MIT, Dept. of Civil Engineering*
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3:05-3:35	**Minimum Weight Design of Foam Core Sandwich Panels** *Lorna J. Gibson, MIT, Dept. of Civil Engineering*
3:35-4:(5	**Design of Fiber Reinforced Brittle and Quasi-Brittle Matrix Composites for Marine Applications** *Christopher K. Y. Leung, MIT, Dept. of Civil Engineering*
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5:30-7:00	**RECEPTION**, MIT Faculty Club

Advanced Composites for Offshore Structures

October 31, 1991

8:00-8:30	**LATE REGISTRATION**
8:30-9:15	**Offshore Applications & Requirements for Use of Advanced Composites** *Mamdouh M. Salama, Conoco*
9:15-9:45	**Polymer Composites in Structures** *Thanasis C. Triantafillou, MIT, Dept. of Civil Engineering*
9:45-10:15	**Non-Conventional Profiles of Composites for Structural Applications** *Andrew Green, Composite Technology, Inc.*
10:15-10:30	**BREAK**
10:30-11:00	**Composites and Construction Require a Structural Design System** *Richard E. Chambers, Simpson, Gumpertz and Heger, Inc.*
11:00-11:30	**Economic Evaluation of Composites for Offshore Use** *Frank R. Field, MIT, Dept. of Materials Science and Engineering*
11:30-12:15	**Where do we go from here?** *Open Discussion by all Participants*

SYNOPSES OF PRESENTATIONS

October 30

9:00
An Overview of Advanced Structural Composites
Douglas S. Barno, Society of Plastics Industry, Inc.

Composites are an unusually versatile family of materials which are used in a wide variety of industrial, transportation and consumer applications. Composites have come of age largely due to widespread recognition that these materials offer a unique combination of important performance benefits including:

- High Strength (both amount and orientation),
- Light Weight,
- Corrosion Resistance,
- Dimensional Stability (mechanical and environmental),
- High Dielectric Strength,
- Low Tooling Cost,
- Parts Consolidation,
- Finish and Color and
- Long Term Durability/Low Maintenance.

In many demanding industrial applications including marine and related waterfront service, composites have a forty-five year track record of successful performance. But in-depth knowledge and use of composites in offshore structures is largely confined to specialty products. Composites are an unusually versatile and valuable family of materials that can solve offshore problems such as corrosion, improve productivity or facilitate introduction of new products.

But, there are a few "tricks" to understanding and applying composite technology to a new or existing product. These new things to learn are not difficult, but they are important. Like any new material system, working in composites just takes getting familiar with the basics.

It is important to keep in mind that with "traditional" materials such as sheet steel, aluminum bar stock, magnesium die castings, etc., the fabrication process shapes the material into final product form without changing the basic properties of the materials themselves. This is not necessarily the case with composites. The properties and characteristics of composite materials are generally created at the same time as the product is being formed. In this way, composites are more like concrete than metals. That is, you create a typical concrete mixture system when the ingredients are mixed and allowed to set and cure.

There are great benefits inherent in the versatile family of all composite materials and particularly with advanced composites. But, there can also be real pitfalls if proper attention is not given to the initial design and testing phase, and if adequate materials, process and quality control procedures are not in place during manufacture. This requires knowledge of the materials behavior and process alternatives early in the design and evaluation phase of any composite application development project to assure that the properties and benefits of composites have been optimized. Ineffective application of composite materials or processes may result in cost/performance disadvantages or outright misapplication and product failure.

An additional benefit of working with composite materials is that models and prototypes can be produced which essentially duplicate the manufactured part performance of the desired production part. This allows comprehensive testing of the design in lab and service settings before committing to manufacturing investment.

Implicit in the composites application development process is that the practitioner must have adequate grounding in composite materials/processing/design considerations to make intelligent initial choices. Fortunately, this is not something that an engineer must undertake alone. There is already a well-developed network of resources including knowledgeable composites fabricators with off-the-shelf-items, composites consultants, CAD/CAM programs composites designers, prototype specialists, university/industry composites centers and alike. Such resources are readily available either through direct contact or by referral to appropriate parties as part of the new Composites Institute Market Development Program.

The necessary structural/design knowledge required to position composites as materials of choice in demanding structural applications in marine/offshore markets already exists in large degree within the composites industry. The problem is that such information is generally closely-held and is not readily available to practitioners. Another concern is that composites structural design information is not generally developed in traditional civil engineering materials design formats. Therefore, a long-term effort on the part of the composites industry to develop a composites Structural Design System (SDS) based on Total Structural Knowledge (TSK) will be required before composites can reasonably penetrate structural marine/offshore applications markets on other than a specialty basis. It is certainly valid and beneficial to use composites in specialized applications. However, until TSK/SDS is widely available to the marine/offshore industry, practitioners may not have the same degree of ease or confidence dealing with composites that they presently have with traditional materials such as steel, concrete and metallic alloys. Simply stated, until practitioners have a "Composites Handbook" sitting on the reference shelf alongside the steel handbook and concrete handbook, coupled with a number of years successful experience with the material, composites will probably continue to be "on the outside...looking in" at the mainstream of marine/offshore markets and applications.

At this writing, the Composites Institute is in the initial stages of market investigation as to the viability of using advanced multi-phase composites in the marine waterfront and offshore applications. If this program reaches full term within the next 45 to 60 days, a multi-faceted task group comprising composites industry resources, marine and offshore trade/professional organizations (TPO's), practitioners and selected academic resources will join forces to identify and develop new applications for composites in these markets. Such an effort will establish performance/cost targets, competitive materials shortfalls and probable response, demonstration projects, specifications/standards, education/training, etc. in a total technical/commercial package suitable for wide-spread commercialization.

The Composites Institute is pleased to be taking a leadership position in this effort. We would like to hear from any marine/offshore organizations that would be interested in participating in such a market development effort.

9:45
High-Performance Composites for Deepwater Risers
Mr. Pierre Odru, Institut Francais du Petrole

With increasing water-depth, the weight of offshore structures for drilling or production systems becomes a major problem and analysis shows that the weight of the risers is one of the critical contributors. This talk will summarize work that the Institut Francais du Petrole has performed to date in the offshore applications of composites. An overview of the results of the recent joint industry project devoted to the qualification of advanced composite tubes for tension leg platform use and an optimized tube structure will also be presented.

10:50
Failure and Damage Mechanisms in Composites
Professor Paul Lagace, MIT

Composite materials present a real opportunity to the structural designer due to their high stiffness-to-weight and strength-to-weight ratios as well as due to the ability to tailor the structure to the particular structural demands. However, with this increased flexibility comes increased complexity in the manner in which these materials, and structures made of these materials, fail. The "composite nature" of the material means that there are two components, the fiber and the matrix, which can fail. This introduces the various failure modes of fiber fracture, matrix fracture, and fiber/matrix debonding. The laminated nature of these structures introduces the failure mode known as delamination. Final failure of a structure can occur due to material effects, such as fiber failure, or due to structural effects, such as buckling of delaminated sublaminates whereby the overall structure loses its integrity.

It is therefore important for the structural engineer to understand each of these damage mechanisms and how they interact to cause the final failure of a composite structure. This is especially important in applications such as offshore structures where in site inspection and repair of the structure is difficult and the structure is expected to have a substantial lifetime.

The different failure modes associated with composite materials and the manner in which they contribute to final failure will be discussed. This includes damage accumulation under repeated loading. Techniques to assess the vulnerability of structures to various damage types will be presented. This is separated into two phases: techniques to assess the stress/strain state, and failure/damage criteria utilized. In addition, research needs will be identified.

11:20
Environmental Degradation of Composites
Professor David K. Roylance, MIT

Since their large-scale introduction as radome materials during the Second World War, fiber-reinforced composite materials have enjoyed a remarkable growth market, and are now being used in a wide variety of military and commercial applications. Excellent toughness, high strength, low density, microwave transparency, and many other attributes not present in more traditional materials provided much of the impetus for this growth. However, one must also include the excellent environmental resistance of composites as a feature sought by many designers. Composites are not totally immune to the outdoor environment, but they are less susceptible to corrosion than many other materials, and they are in many cases easier to stabilize against weathering.

Unless suitably stabilized and coated, fiber-reinforced composites are subject to photoinitiated oxidation that results in a degradation of the resin surface and an eventual reduction in the composite's mechanical properties. This photooxidation process, which is initiated by UV-absorbing oxidation products created during cure, is relatively amenable to detection by techniques of analytical chemistry. Mechanical test results, reflecting as they do a very wide range of material properties, are more subject to variability and misinterpretation.

Even though the vast majority of commercial items employing composites consist of chopped glass fibers in polyester matrices, applications requiring excellent performance usually specify epoxy resins and often more high-performance fibers (Kevlar, graphite, boron). While this review will deal in detail only with epoxy composites, many of the comments to be made will be germane to the polyester composites as well.

11:50
Composites Manufacturing
Professor Timothy.G. Gutowski, MIT

The purpose of this talk is to review composites manufacturing techniques with a particular emphasis on those applicable for the production of offshore structures. In the limited time we have, I will attempt to point out the advantages and limits of each process, current efforts to develop new processes, and the general economics of composites manufacturing processes. In the conclusion, I will outline some of the composites manufacturing research projects at MIT.

1:30
Steel-Concrete-Steel Sandwich Composite Construction for Permanently Floating Platforms
Dr. Dale E. Berner, Ben C. Gerwick, Inc.

Steel-concrete-steel, S-C-S, sandwich composite construction has been used for many years for such temporarily floating structures as bridge piers and immersed tubes. Since 1983, Ben C. Gerwick, Inc. (BCG) has been engaged in the physical testing, computer analysis, and/or the preliminary design of S-C-S sandwich constructions. This work has been primarily directed towards structures such as ice-resistant offshore Arctic Gravity Base Structures, (GBS's), and blast-resistant silo structures for which high-strength, high-ductility and high-shear capacity are of primary importance. Permanently floating platforms such as tension leg platforms, (TLP's), and semi-submersibles have somewhat different design criteria than the GBS and silo structures mentioned above; however, it is the intention of this work to relate BCG, Inc.'s experience with S-C-S sandwich construction to permanently floating structures.

BCG, Inc. has recently been engaged in several studies regarding reinforced/prestressed concrete TLP's, and is familiar with the load capacity, durability, quality control, and construction requirements associated with such floating structures. Some key requirements for permanently floating structures include:

- Water-tightness,
- Fatigue resistance,
- Column/Pontoon node design,
- Weight and draft requirements for construction, towing, and operation,
- Ability to resist hydrostatic water pressures and
- Reliability and minimized risk.

Concrete TLP's have been demonstrated to have lower costs than equivalent steel TLP's; and it is the opinion of the author of this work that S-C-S sandwich composites can be designed to have still lower costs than concrete TLP's. Some characteristics of S-C-S sandwich composites that make them particularly well-suited for permanently floating platforms include:

- Double steel membranes for water tightness.
- Use of thinner steel elements than all steel construction for better weldability.
- Superior ductility and confinement of the concrete, than for reinforced/prestressed concrete construction, thus allowing for the use of higher strength cementitious materials.
- Resistance to local indentation, such as boat impacts.
- Capacity to use the steel shell either as fixed, or floating, form work for casting the concrete core.
- Optional use of prestressing to control cyclic fatigue stresses in the plate steel.
- Use of thinner member thicknesses due to lack of concrete cover, and optional use of higher strength materials.
- Optional use of shipyard construction and use of automatic welding and automation. Possible elimination of construction of graving dock.
- Two-way action of plate steel versus one-way action of steel reinforcing bars for convention concrete.

Although past experience with C-S-C sandwich composites has been extensive, including research in Europe, North America, and East Asia still additional research is merited for S-C-S sandwich composite designs specific to permanently floating structures. Areas recommended for further research include:

- Cyclic fatigue testing, simulating wave loading conditions.
- Additional tests with the S-C-S composites loaded under multi-axial stress conditions, including membrane tensile/compression, torsion, and shear.
- Additional tests on joints and nodes between interconnecting members.
- Additional tests on larger scale cylindrical and curved members.
- Additional tests on specimens with different internal steel configurations, including internal cellular configurations as discussed below.

To elaborate on the final recommendations given above, based on the research at BCG, Inc. it is believed that cellular S-C-S sandwich composites would show particular merit for permanently floating structures. It is proposed that steel tubes would be friction welded to the inside of one of the steel plates, and that headed studs would be welded to the inside of the opposite steel plate. The tubes and the headed studs would over-lap sufficiently that the cementitious material in the core would bind the two plates together. Air voids would exist inside the tubes with cementitious material tubes, thus leading to a cellular sandwich composite similar to the high-strength, lightweight cellular composites used in such structures as jet airplanes. Some advantages that such a cellular design would have include:

- Reduced dead weight due to the air voids in the tubes.
- Reduced problems due to heat of hydration of the cementitious material.
- Optional partial infilling of the core with cementitious material.
- Tubes would help control shear stresses through the composite.
- Facilitation of the use of very high strength cementitious materials, possibly with compressive strengths as high as 30,000 to 40,000 psi.

2:15
High-Strength Cement Composites for Marine Applications
Professor Oral Buyukozturk, MIT

During the past 50 years considerable experience has been gained in the use of concrete composites for marine applications. Concrete gravity structures had their first offshore applications in the development of structures for petroleum exploration in the North Sea in early 1970's. This experience has proven some important advantages of using concrete composites in offshore structures such as structural durability and low maintenance cost. Furthermore, introduction of high-strength concrete with silica fume provides potential solutions for critical design problems of slender elements such as shafts, and of resistance of concrete against abrasion and freeze-thaw cycles, permeability, and rebar corrosion.

One of the critical problems in designing concrete structures for marine environments, and especially for ice waters, is local loadings with high-stress intensities. This is especially important for plate and shell elements subjected to critical, shear conditions. Such elements should be designed for ductile failures and the concrete composite used for these elements should possess improved strength and ductility properties. Furthermore, in designing such shear-critical elements, problems related to structural constructibility may arise due to the intensity of this required shear reinforcement to be placed in critical regions.

This presentation will discuss MIT research in the development of a concrete composite material consisting of high-strength concrete with silica fume and polypropylene or steel fibers. The objective of this research was to investigate the strength and ductility of fiber reinforced, high-strength concrete under direct shear forces. Both experimental and modeling studies have been performed and the results of these studies will be presented.

In the experimental study, push-off, fiber-reinforced, high-strength concrete specimens were tested. Two types of fibers were used: polypropylene and steel fibers. Another experimental variable was introduced by including conventional stirrups in some specimens. Load and shear deformation characteristics as well as failure modes of the specimens were studied and a comparative evaluation of the results made. The experimental program also included specimens made with fiber-reinforced normal strength concrete for comparison of the results with those from the high-strength concrete. An existing model was further developed for use in the analytical prediction of the shear-stress/shear-strain relations for these specimens. The model includes directional compression and tension softening phenomena for concrete under a biaxial, stress state.

In general, fibers proved to be more effective in high-strength concrete than in normal strength concrete, increasing both ultimate load as well as overall ductility. This is attributed to the improved bond characteristics associated with high-strength concrete. For the case with steel fibers, significant increases in ultimate load and ductility were observed. In the case with polypropylene fibers, a lower increase in ultimate load was obtained when compared to the increase due to steel fibers; while the overall ductility was greater than that with steel fibers. In the tests involving the combination of fibers and conventional stirrups, slight increases in ultimate load were observed while major improvements in overall ductility compared to plain concrete with stirrups were obtained.

In conclusion, the results obtained indicate potential application areas for the use of fiber-reinforced, high-strength concrete in marine applications where shear-critical design of the structural elements are required.

3:05
Minimum Weight Design of Foam Core Sandwich Panels
Professor Lorna J. Gibson

Structural components made up of two stiff, strong faces separated by a lightweight core are known as sandwich panels. Typical face materials include fiber composites, aluminum and plywood. Core materials include honeycombs, usually made of either aluminum or resin-coated paper, and polymer foams; honeycomb cores are preferred in aerospace applications where the weight of panel is critical while foam cores are preferred in building applications where both the weight and the thermal resistance of the panel are important. The separation of the faces by the core increases the moment of inertial of the panel with little increase in weight, making them efficient for resisting bending and buckling loads.

Here at MIT we have been studying two aspects of sandwich panels: the minimum weight design of structural sandwich panels with foam cores and the development of new core materials with improved properties. The analysis of the minimum weight design of a panel has been improved by allowing the density of the foam core to be a design variable in the optimization. The analysis has been performed for both stiffness and strength constraints for sandwich beams and sandwich panels. A software package has been developed to automate the design procedure. The results of the analysis have been compared with experiments on sandwich beams with aluminum faces and rigid polyurethane foam cores; the analysis gives a good description of the minimum weight design of the panel.

Polymer foam cores are widely used for sandwich panels in building applications. Polymers have several limitations, however: they creep over time, are combustible, and have a high cost. As an alternative to polymer foams, we have been considering the possibility of using cementitious foam cores for sandwich panels. We expect cement foams to creep less than polymeric ones, to be incombustible and to be less costly. But they are brittle: the focus on our work has been on the development of composite cement foams with improved tensile properties for use in structural sandwich panels.

3:35
Design of Fiber Reinforced Brittle and Quasi-Brittle Matrix Composites for Marine Applications
Dr. Christopher K. Y. Leung, MIT

When brittle and quasi-brittle materials such as concrete, ceramics and polymers (at low temperatures, e.g., in the Arctic) are used in marine applications, material toughness and ductility become important concerns. The introduction of fibers in such materials can lead to a significant increase in toughness, reflected in the improved impact resistance and material reliability (i.e., lower variability in material strength), and gives rise to pseudo-ductile behavior that provides ample warning before ultimate failure occurs. With proper material design to optimize performance/cost, brittle or quasi-brittle matrix composites can be competitive candidates for many applications in the marine environment.

Design of fiber composites has traditionally followed a 'trial and error' approach. Recent research work at MIT focuses on the development of micromechanical models that relate the macroscopic behavior of composites (such as strength and toughness) to the micro-properties (i.e., properties of fiber, matrix and fiber/matrix interface). Such models, together with techniques to control micro-properties (e.g. fiber coating to control interfacial behavior), allows the optimal design of composites for given performance requirements.

After a brief presentation of the theoretical framework of micromechanical modeling, two examples of the applications of such modelling techniques are described. The first example is the prediction of crack bridging force in composites arising from brittle fibers including at an angle to the crack plane. Such a problem is of relevance to random fiber composites as well as composite laminates with lamina oriented at different angles. Theoretical prediction of bridging force from independently measured micro-properties are found to be in excellent agreement with experimental results.

The other example involves the prediction of first-cracking strength, reliability and stress-deformation relations of flexible, short-fiber, reinforced, brittle, matrix composites. From the analysis, a guideline to 'engineer' micro-properties to design short, random fiber composites with the desirable features of continuous fiber composites (e.g. high reliability and pseudo-ductility) can be derived.

4:05
Future Research Needs in Advanced Composites
Open discussion by all participants

October 31

8:30
Offshore Applications and Requirements for Use of Advanced Composites
Dr. Mamdouh M. Salama, Conoco, Inc.

Over the last two decades, technology employed by the offshore petroleum industry has seen dramatic changes to allow exploration and production in environments that were considered prohibitive twenty years ago. This technology development, which has revolutionized offshore petroleum activities, is a result of the conscious effort by the oil industry to replace depleted oil and gas reserves. The exponential increase in water depth for exploration and production activities was a major motive for the development of new structural concepts such as Tension Leg Platforms (TLPs). The combination of structural optimization, weight reduction and increased water depth made it necessary to consider the application of advanced composites.

Advanced composites provide very attractive properties for mooring systems, drilling and production risers, production tubing, flowlines, and top side facilities. Composites offer the advantage of light weight, corrosion resistance and the ability to tailor their properties to achieve different stiffness, strengths, Poisson's ratios and coefficients of thermal expansion. These advantages can be used to optimize the system and, therefore, result in lower system cost even though the cost of components may be higher than those made of conventional material. The use of composites for deepwater applications and system design considerations will be presented. Current research efforts to qualify composite components in offshore structures will be discussed.

9:15
Polymer Composites in Structures
Professor Thanasis C. Triantafillou, MIT

Fiber reinforced plastic (FRP) composites offer unique advantages for solving many structural engineering problems in areas where conventional materials do not perform well. Such areas include, but are not limited to, corrosive environments, structural elements required to have a high strength/weight ratio, and applications requiring materials with neutral conductive/magnetic properties.

Potential applications of FRP in structural engineering include: (a) development of high-strength lightweight cables in cable-supported bridges, tendons in prestressed elements, and ropes for mooring offshore platforms; (b) replacement of steel used as reinforcement in concrete structures by composite rebars, offering corrosion resistance and providing non-conductive/magnetic fields; (c) development of lightweight structural components such as framing and bridges; and (d) strengthening of existing structural members or reinforcing new ones with epoxy-bonded fiber composite laminates (non-prestressed or prestressed). The presentation will be in the form of an overview of the use of composites in structural design as well as the work currently in progress at M.I.T. in this area.

9:45
Non-Conventional Profiles of Composites for Structural Applications
Mr. Andrew Green, Composite Technology, Inc.

Performance of composite materials is available but knowledge of their material characteristics and manufacturing processes is necessary to take advantage of the unique opportunities that are available with structural composite shapes. For example, elastic properties of composites can vary by a factor of four and mechanical performance by even greater factors.

The aerospace industry has been using structural composites for several years. By capitalizing on the engineering expertise that has been developed within the aerospace industry and applying it to civil structures it is possible to design non-conventional composite profile shapes that are competitive with conventional materials in the competitive construction market.

Several examples will be given that demonstrate how non-conventional composite profiles were made competitive with conventional materials by tailoring the geometry to overcome stiffness limitations, erection costs, engineering limitations and life cycle costs.

10:30
Composite in Construction Require a Structural Design System
Mr. Richard E. Chambers, Simpson, Grumpertz and Heger, Inc.

The use of composites for significant structural applications in construction was explored in some detail in the era 1955-1965. Since then, use of composites in such applications has been limited; the track record has been mixed, frequently due to a lack of understanding of the structural characteristics of these materials. The recent plethora of research by civil engineers signals a significant renewed interest in the use of composites in construction. This is perhaps driven, in part, by the realization that conventional materials have not proven durable in many significant construction applications.

The purpose of design, and hence the goal and responsibility of the designer is to provide reasonable probabilities that the structure being designed is safe and fit for its intended service life. Accordingly, a structural design system (SDS) is required to support the successful application of existing composites in construction and the implementation of innovations stemming from current research.

An SDS is a combination of rules and protocols governing design, materials, manufacture, fabrication, construction and testing that together satisfy requirements for performance and serviceability, safety, and reliability (durability). While and SDS is available for fiberglass products in recent ASME boiler and tanks codes, no similar protocol exists for construction applications. In contrast, structural design systems are in place for all types of structures and structural components normally designed and specified by the civil engineer. For example, longstanding and ever evolving design protocols and codes form the SDS for steel, aluminum, concrete and wood. These codes and rules (frequently imposed on the construction process by law in the interest of public safety) are intended to provide reasonable confidence that a viable, reliable structure will result. These existing structural design systems, while viewed by some as being overly delimiting to new products in the construction market, in fact offer the designer enormous flexibility in putting together unique products and structures.

For composites, performance standards and tests are used frequently as a basis for product acceptance. This is feasible for OEM applications such as automotive parts, or where high and sophisticated levels of engineering evaluation are available and justified e.g. aerospace structures. However, the needs are different in construction applications where, for example a single type of structural member frequently serves multiple functions (e.g. beam, column, or truss member); this type of multipurpose member cannot be characterized by performance tests and standards. More generally, the structural designer is unaccustomed, unprepared, and not compensated for the research necessary to develop or evaluate a structural design based on performance standards without an SDS.

In sum, a structural design system is needed to guide the engineer in the structural design and evaluation and specification of composites with the reliability expected for significant structures.

The approaches to design already in place and accepted for conventional materials are available as guidance for the development of an SDS for structural composites. Furthermore, the ASCE Structural Plastics Design Manual provides a perspective and detailed examples illustrating protocols and concepts appropriate for an SDS. In addition, the recent ASME codes that represent a significant leap in design-oriented standards for reinforced plastics used in corrosion-resistant tanks and pressure vessels provide a very useful frame of reference, as do new standards for structural chimney liners under development with ASTM.

11:00
Economic Evaluation of Composites for Offshore Use
Dr. Frank R. Field, III, MIT

Evaluation of material alternatives for engineering applications is neither a simple nor a trivial exercise. Each material offers a unique set of engineering, processing, and economic characteristics, many of which are intimately interrelated, and none of which can be routinely eliminated from consideration.

Research at the Materials Systems Laboratory (MSL) focuses upon the development of accessible, robust decision support tools that can be effectively used to treat the complex questions that underlie materials selection and substitution. Pre-eminent among these are technical cost modeling and decision analysis. The latter techniques are used to assess how performance and economics are balanced against each other, and are used to establish overall competitive position. The former, which has a wide range of uses, will be the subject of my talk.

Technical cost modeling is an extension of engineering process modeling. Essentially, this is a modeling process wherein, through the systematic application of engineering knowledge, economic principles, and processing conditions, the costs of manufacturing a wide range of products can be estimated. Further, this process results in the development of a process- specific tool for analysis that can be used to establish not only current operating costs, but also the economic implications of changes in processing conditions, manufacturing technology, or product design. As such, these tools can be used not only to estimate the costs of manufacturing products composed of competing materials and/or processes, but also to evaluate engineering design decisions at the so-called "zero-stage."

While the bulk of MSL studies have focused upon automotive applications, the tools described have been applied to other markets. To illustrate the utility of the tools and the types of analyses that can be performed, a simple case study examining a potential composite offshore structure will be presented. Some conclusions, focusing upon composites processing, will also be provided.

11:30
Where do we go from here?
Open Discussion by all Participants

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Allred,R.E. & Roylance, D.K., **Transverse Moisture Sensitivity of Aramid/Epoxy Composites**, *Journal of Materials Science*, Vol. 18, 1983, pp. 652-656.

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Arnold, S., Hendrichs, N., Field, III, F.R. & Clark, J.P., **Competition Between Polymetric Materials and Steel in Car Body Applications**, *Materials and Society*, Vol. 13, No. 3.

Benatar, A. & Gutowski, T.G., **Ultrasonic Welding of PEEK Graphite APC-2 Composites**, *Polymer Engineering and Science*, Vol. 29, No. 23, December 1989, pp. 1705-1721.

Berner, D.E., **Steel/Concrete/Steel Sandwich Composites in the Containment of Cryogenic Liquids Offshore**, Proceedings of Offshore Technology Conference, Houston, TX, May 1988.

Steel/concrete/steel sandwich composite design allows the hull of a storage vessel for cryogenic liquids, such as liquified natural gas, LNG, to serve as a double integrity containment barrier against leaks, and to absorb high intensity impact, safely. This offers advantages over either all steel or other prestressed concrete vessels with regards to safety, serviceability, strength, economy and simplicity of construction.

Berner, D.E., Gerwick, B.C. & Hoff, G.C., **T-Headed Stirrup Bars**, *Concrete-International*, May 1991, pp. 49-53.

Blout, J.S., Roylance, D.K., & Roylance, M.E., **Environment/Fatigue Interactions in Kevlar/Epoxy Laminate**, Technical Note AMMRC TN78-4, Army Materials and Mechanics Research Center, Watertown, MA, May 1978.

Brewer, J.C. & Lagace, P.A., **Failure of Graphite/Epoxy Induced by Delamination**, 22nd International SAMPE Technical Conference, Boston, MA, November 1990.

Busch, J.V. & Field, III, F.R., **Properties, Costs, and Applications of Polymeric Composites**, A Report to the U.S. Office of Technology Assessment November 1985.

Buyukozturk, O., & Tseng, T., **Concrete in Biaxial Cyclic Compression**, *Journal of Structural Engineering*, Vol. 110, No. 3, March, 1984.

An experimental program was conducted to study the behavior of concrete under low-cycle high amplitude biaxial cyclic compression. Biaxial loading was achieved by subjecting square concrete plates to in-plane loading where compressive stress was applied in one direction while confining the deformation of the specimen in the orthogonal direction. Three main types of tests were performed: monotonic loading to failure; cycling of compressive stresses to a limiting envelope; and cycling of compressive stresses to prescribed values. In each catagory, tests were performed on specimens under different levels of strain confinement, and for comparison, on unconfined specimens. Complete stress-strain histories were recorded and analyzed to assess the effect of confinement on concrete behavior under different nonproportional load conditions. A simple predictive model for constitutive behavior of concrete in biaxial cyclic compression is proposed. Predicted behavior from the model, which does not require any a priori information from experiments, is found to be in good agreement with the measured response.

Cai, Z., Gutowski, T.G. & Allen, S., **Winding and Consolidation Analysis for Cylindrical Composite Structures**, submitted to the *Journal of Composite Materials*, November 1990.

Cairns, D.S. & Lagace, P.A., **Residual Tensile Strength of Graphite/Epoxy and Kevlar/Epoxy Laminates with Impact Damage**, Composite Materials: Testing and Design (Ninth Volume), ASTM STP 1059, ASTM, 1990, pp. 48-63.

Cairns, D.S. & Lagace, P.A., **A Consistent Engineering Methodology for the Treatment of Impact in Composite Materials**, Proceedings of the ASC 5th Technical Conference, East Lansing, MI, June 1990, pp. 589-599.

Chambers, R.E., **Proposal on the Design and Testing of Structural Plastics for Stiffness and Strength**, presented to ASTM Committee D20 Task Group on Engineering Design Criteria, Providence, RI, October 1981.

Chen, E., & Buyukozturk, O., **Constitutive Model for Concrete in Cyclic Compression**, *Journal of Engineering Mechanics*, Vol. 111, No. 6, June, 1985.

A rate-independent constitutive model is proposed for the behavior of concrete in multiaxial cyclic compression. The material composite is assumed to experience a continuous damage process under load histories. The model adopts a damage-dependent bounding surface in stress space to predict the strength and deformation characteristics of the gross material under general loading paths. Reduction in size of the bounding surface as damage accumulates, and the adopted functional dependence of the material moduli on stress and damage permit a realistic modeling of the concrete behavior. Satisfactory prediction is obtained of the generally nonlinear stress-strain response, degradation in stiffness during load cycles, shear compaction-dilatancy phenomena, and post-failure strain softening behavior. Satisfactory prediction is obtained of the generally nonlinear stress-strain response, degradation in stiffness during load cycles, shear compaction-dilatancy phenomena, and post-failure strain softening behavior. Finite element implementation of the proposed model is feasible and computationally efficient.

Cilley, E.C., Roylance, D.K. & Schneider, N.S., **Determination of Fiber and Void Content in Composite Materials**, Composite Materials: Testing and Design, ASTM STP 546, American Society for Testing and Materials, 1974, pp. 237-249.

Demsetz, L.A. & Gibson, L.J., **Minimum Weight Design for Stiffness in Sandwich Plates with Rigid Foam Cores**, *Materials Science and Engineering*, 85, 1987, pp. 33-42.

A new relationship between the shear modulus and density of foams has been used to identify the core density as well as the core and face thicknesses which minimize the weight of a sandwich plate for a given bending stiffness. The results of bending tests on simply supported circular sandwich plates with aluminimum skins and polyurethane foam cores confirm the results of the analysis. The work should be useful in improving the design of sandwich panels in many engineering applications. It also has relevance to the understanding of the design of natural sandwich structures, such as those found in the human skull and in the iris leaf.

Field, III, F.R. & Clark, J.P., **Economics and Systems Integration**, The Competitive Edge; Research Priorities for US Manufacturing, NRC, 1991

Field, III, F.R., **An Improved Materials Selection Technique for Engineering Applications**, Second ASM/ESD Advanced Composites Conference, Dearborn, MI, November 1986.

Field, III, F.R., **Application of Multi-Attribute Utility Analysis to Problems in Materials Selection**, Ph.D. Dissertation in Materials Systems Analysis, Massachusetts Institute of Technology, 1985.

Gerwick, B.C. & Berner, D.E., **Thermal and Durability Considerations for Composite Steel/Concrete Sandwich Structures**, Proceedings of the 2nd International Conference on Performance of Concrete in the Marine Environment, Canada, August 1988.

Gerwick, B.C. & Berner, D.E., **Sandwich Composite Design - An Emerging Field**, Proceedings of 9th International Conference on Port and Ocean Engineering Under Arctic Conditions, Fairbanks, AK, August 1987.

Composite steel/concrete sandwich elements are being given intensive research and development efforts because of their excellent structural performance under intense concentrated loads such as those imposed by sea ice or icebergs. Since the initial applications are expected to be in Arctic and sub-Arctic environments, consideration must be given to thermal phenomena and to ensuring long-term durability.

Green, A. & Bisarnsin, T., **Building Construction Materials**, Advanced Thermoset Composites, Industrial and Commercial Applications, Chapter 8, Margolis, J.M. ed., Van Nostrand Reinhold Company, New York, N.Y.

The main intention of this chapter is to inform people in the construction industry, end users, engineers, and architects of what advanced composites are and to describe some advanced composite products available to overcome the effects of corrosion on metallic structures or conductive and magnetic materials for load-bearing or structural applications. Architects and engineers who understand the characteristics and unique properties that advanced composites can provide will significantly increase their range of material selection and greatly expand their design parameters.

Green, A., **Glass Fiber Reinforced Composites in Building Construction**, presented at Transportation Research Board, National Research Council, January 1987.

Glass-fiber, reinforced plastic composites have had limited use as structural components in building construction. To realize the full potential of these materials and increase their use, we must take advantage of their outstanding features. In developing composite components, it is essential to combine expertise in the disciplines of plastic and reinforcing materials, structural design and also fabrication techniques. This allows one to utilize the composite on its own merits. Efficiently designed composite components and a case history are presented to demonstrate typical practical applications.

Green, A. & Bisarnsin, T., **Predicting the Performance of Composites Experimentally**, Proceedings of Managing Corrosion of Plastics, NACE, San Antonio, TX, November 1989.

Composites offer challenging opportunities for building materials in hostile environments. Up until a few years ago, there were only a few "show case" projects that used any significant amount of composites in building construction. This is in large part because of the lack of hard data for structural design purposes. This paper presents some of the problems encountered with composites and their experimental solutions. Accumulation of this type data can increase the use of these materials for structural applications and provide a service to the industry.

Gutowski, T.G., Engineering Analysis of Composites Manufacturing Processes, Butterworth-Heinemann, in press.

Gutowski, T.G. & Sentovich, M.F., **Manufacturing Issues for Composite Materials in Marine Structures**, Automation in the Design and Manufacture of Large Marine Systems, Proceedings of the MIT Sea Grant Seminar Series, October 1988.

Gutowski, T., Henderson, R. & C. Shipp, **Manufacturing Costs for Advanced Composites Aerospace Parts**, *SAMPE Journal*, Vol. 27, No. 3 May/June 1990.

In spite of many early claims that advanced composite structures could bring down weight and reduce cost, we now know that in fact they are very often more expensive than aluminum structures they are replacing. This high cost is attributed to many things. High materials costs, high labor content, poor or non-optimum "black aluminum" designs, poor yields, and lack of automation are most frequently cited. In a recent paper, it was shown that one advanced composite part cost 190% of the aluminum part it replaced.

One well known strategy for reducing manufacturing costs is to integrate parts. Composite structures which are cost effective, or at least claim to be effective often compete by eliminating the large assembly cost required by their competitor. Is this a viable strategy, and can advanced composites be made cost effectively? In this paper, we use the results of a recent study to build a model that allows us to quantitatively evaluate these questions. We show under what conditions the use of advanced composites may be cost effective. We also show that this result is quite sensitive to a number of critical parameters, for example, small changes in the weight savings, or in the design, or in the labor content of a part.

Heger, F.J. & Chambers, R.E., **Design with Structural Plastics**, Building Structural Design Handbook, Chapter 30, White R.N. & Salmon, C.G., eds., John Wiley & Sons, May 1987.

Heger, F.J. & Chambers, R.E., **ASCE Structural Plastics Design Manual: A New Aid for the Designer of Plastics Structural Components**, Proceedings of the 41st Annual Conference of the Composites Institute of the Society of the Plastics Industry, Atlanta, GA, January 1986.

Heger, F.J., Chambers, R.E. & Dietz, A.G.H., Structural Plastics Design Manual, ASCE Manual of Engineering Practice, No. 63, American Society of Civil Engineers, New York, NY, 1984.

Huang, J.S. & Gibson, L.J., **Creep of Sandwich Beams with Polymer Foam Cores**, *Journal of Materials in Civil Engineering*, Vol. 2, No. 3, August, 1990.

Polymer foam-core sandwich panels are increasingly being considered for load-bearing components in buildings. In addition to offering a high stiffness per unit weight, such panels give excellent thermal insulation and may be easily mass-produced. But polymers creep at room temperature, limiting their use in structural applications. In this paper we model the creep of sandwich beams with linear viscoelastic polymer foam cores. A previous study indicated that the creep of polymer foam can be described knowing the creep response of the solid from which it is made and the relative density of the foam. In this study, we combine the model for foam creep with the standard analysis of deflection of a sandwich beam to develop an expression for the creep of a sandwich beam with a polymer foam core. The results are compared with data from a series of tests on sandwich beams with aluminum faces and rigid polyurethane foam cores.

Krolewski, S. & Gutowski, T.G., **Economic Comparison of Advanced Composite Fabrication Technologies**, 34 SAMPE Symposium, Reno NV, May 1989.

Lagace, P.A. & Sultana, J.A., **Effects of Residual Manufacturing Stresses on the Fracture of Graphite/Epoxy Laminates**, 22nd International SAMPE Technical Conference, Boston, MA, November 1990.

Lagace, P.A., **On Delamination Failures in Composite Laminates**, Indo-U.S. Workshop on Composites for Aerospace Applications, Bangalore, India, July 1990.

Lagace, P.A., & Saeger, K.J., **Methodology for Prediction of Delamination Initiation at Holes in Composite Laminates**, AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, AIAA Paper No. 90-1019, April 1990, pp. 1183-1190.

Lagace, P.A., **The Potential for Composite Materials in Marine Structures**, Automation in the Design and Manufacture of Large Marine Systems, MIT Sea Grant College Program Lecture and Seminar Series, 1990, pp. 259-273.

Lagace, P.A. & Brewer, J.C., **Studies of Delamination Growth and Final Failure Under Tensile Loading**, Sixth International Conference on Composite Materials, London, England, July 1987.

Lagace, P.A. & Nolet, S.C., **The Effect of Ply Thickness on Longitudinal Splitting and Delamination in Graphite/Epoxy Under Compressive Cyclic Load**, Composite Materials: Fatigue and Fracture, ASTM STP 907, ASTM, 1986, pp. 335-360.

Lagace, P.A., **Notch Sensitivity of Graph,/Epoxy Fabric Laminates**, Composite Materials and Engineering, An International Symposium, Newark, DE, September, 1984, and *Composites Science and Technology*, Vol. 26, No. 2, 1986, pp. 95-117.

Leung, C.K.Y. & Li, V.C., **Determination of Fracture Toughness Parameter of Quasi-Brittle Materials with Laboratory-Size Specimens**, *Journal of Materials Science*, Vol. 24, 1989, pp. 854-862.

Leung, C.K.Y. & Li, V.C., **First-Cracking Strength of Short-Fiber Reinforced Ceramics**, Ceramics Engineering & Science Proceedings, Vol. 10, No. 9-10, 1989, pp. 1164-1178.

Leung, C.K.Y. & Li, V.C., **A New Strength-Based Theory for the Debonding of Discontinuous Fibers in an Elastic Matrix**, accepted by *Journal of Materials Science*, 1991.

Leung, C.K.Y. & Li, V.C., **Effects of Fiber Inclination of Crack Bridging Stresses in Brittle Matrix Composites**, accepted by *Journal of the Mechanics and Physics of Solids* , 1991.

Li, V.C. & Leung, C.K.Y., **Tensile Failure Modes of Random Discontinuous Fiber Reinforced Brittle Matrix Composites**, submitted to ASCE *Journal of Enginerering Mechanics*, 1991.

Maiti, S.K., Gibson L.J. & Ashby, M.F., **Deformation and Energy Absorption Diagrams for Cellular Solids**, *Acta Metals*, Vol. 32, No. 11, Pergamon Press. Ltd., 1984

The mechanical properties of 3 types of cellular solids (flexible, plastic and brittle), have been measure as a function of density. The results are compared with models for the stiffness, strength and densification: and constitutive laws are developed. Data and models for each type of cellular solid are combined to develop *mechanism-mode maps* that summarize the properties in a single diagram; this understanding, in turn allows the construction of *energy absorption diagrams* for classes of foams. Natural cellular materials fit the same pattern: maps are presented, as an example, for wood. The maps help in design and in the selection of the optimal foam for a given load-bearing or energy-absorption application.

McElroy, P.M., Medved, D. & Roylance, D.K., **Weathering of Sheet Molding Compounds,** Proceedings of the International Symposium on Environmental Degradation of Engineering Materials, presented at Virginia Polytechnic Institute, September 1981.

Mead, J., Singh, S., Roylance, D.K. & Patt, J., **Nonlinear Response and Thermomechanical Degradation of a Urethane Elastomer,** *Polymer Engineering and Science,* Vol. 27, 1987, pp. 131-140.

Odru, P. & Guichard, **Drilling Riser for Great Water Depths: Advantage of Mass Reduction by Means of Composite Materials,** Proceedings of Deep Offshore Technology Conference, Sorrente, Italy, 1985.

Odru, P. & Guichard, **High Performance Composite Tubes for Drilling or Production Systems,** Symposium on Offshore and Arctic Frontiers, New Orleans, LA, 1986.

Odru, P., Metivaud & Sparks, C.P., **Lightening Deepwater Offshore Structures by High Performance Composite Tubes,** Proceedings of Deep Offshore Technology Conference, Monte Carlo, Monaco, 1987.

Odru, P., Sparks, C.P., Metivaud & Bono, **Advanced Composite Tubular Tendons for Deepwater Tension Leg Platforms,** Proceedings of the Offshore Technology Conference, Houston, TX, 1989.

Odru, P. & Sparks, C.P., **Thick Walled Composite Tubes Calculation and Measured Behaviour,** 10th OMAE Conference, Stavanger, Norway, 1991.

Roylance, D.K. & Roylance, M.E., **Influence of Outdoor Weathering on the Dynamic Mechanical Properties of Glass/Epoxy Laminate,** Environmental Effects on Advanced Composite Materials, ASTM STP 602, American Society for Testing and Materials, 1976, pp. 85-94.

Roylance, D.K., **Reaction Kinetics for Thermoset Resins,** The Manufacturing Science Composite, Proceedings of Manufacturing International '88, American Society of Mechanical Engineers, Vol. IV, Atlanta, GA, 1988, pp. 7-11.

Roylance, D.K., **Fracture Mechanics Evaluation of Overwrapped Pressure Vessels",** Report for Martin Marietta Michoud Aerospace, New Orleans, LA, February 1987.

Roylance, D.K., **Thermal Properties and Temperature Effects,** Engineered Materials Handbook, Vol. 3: Adhesives & Sealants, ASM International, 1990, pp. 420-427.

Sacks, R. & Buyukozturk, O., **Expert Interactive Design of R/C Columns under Biaxial Bending,** *Journal of Computing in Civil Engineering,* Vol. 1, No. 2, April, 1987.

A new computer-based approach to the problem of design of reinforced concrete columns that may be subjected to biaxial bending is presented. Previous approaches to the design of concrete columns (including those with biaxial bending) using computers have been primarily based on iterative numerical analysis. The EIDOCC (Expert Interactive Design of Concrete Columns) program described in this paper using the accumulated experience and knowledge of experts in the field of concrete column design to account for the issues involved in the design to optimize the design proposal for given loadings. The approach used in the program is that of an "expert system" and the program is developed to run on a microcomputer. The developed computer program is interactive, and it incorporates an accurate analysis routine which enables the user to analyze both the sections proposed by the design routine and any other concrete column sections.

Saeger, K.J. & Lagace, P.A., **Fracture of Pressurized Composite Cylinders with a High Strain-to-Failure Matrix System,** Composite Materials: Fatigue and Fracture, Second Volume, ASTM STP 1012, ASTM, 1989, pp. 326-337.

Salama, M.M., & Tetlow, J.H., **Selection and Evaluation of High Strength Steel for Hutton TLP Tension Leg Elements**, Proceedings of Offshore Technology Conference, Houston, TX, 1983, also published in ASME Trans., *Journal of Energy Resources Technology*, Vol. 106, No. 1, 1984, pp. 32-37.

Salama, M.M., **Lightweight Materials for the Mooring Lines of Deepwater Tension Leg Platforms**, *Journal of Marine Technology*, Vol. 21, No. 3, 1984, pp 234-241.

Salama, M.M. & Ellis, N., **Hutton TLP-A Materials Challenge**, Proceedings of 4th International Offshore Mechanics and Arctic Engineering Symposium, Vol. I, 1985, pp.1-13.

Salama, M.M., Williams, J., Lee, S. & Vennett, R.M., **Materials for Lightweight Mooring System for Deepwater Compliant Structures**, ibid., Vol. 2, 1985, pp. 357-364.

Salama, M.M., **Lightweight Materials for Deepwater Offshore Structures**, Proceedings of Offshore Technology Conference, Houston, TX, 1986.

Salama, M.M., **Materials for Mooring Systems**, Materials for Marine Systems and Structures, Hassen, D.F. & Crow, C.R.,eds., Trestise on Materials Science and Technology, Vol. 28, Academic Press Inc., 1988, pp. 389-413.

Salama, M.M., **Material Considerations for TLP Applications**, Tension Leg Platform - A State of the Art Review, Demirbilek, Z., et. al., eds. ASCE, 1989, pp. 210-226.

Singh, S.N., Roylance, D.K. & Patt, J., **Deformation Behavior and Thermomechanical Failure of Carbon--Black--Filled Elastomers**, Technical Report No. 13292, U.S. Army Tank--Automotive Command, Warren, MI, September 1987.

Sparks, C.P., Odru, P., Metivaud & Bono, **Mechanical Testing of High Performance Composite Tubes for TLP Production Risers**, Proceedings of the Offshore Technology Conference, Houston, TX, 1988.

Sparks, C.P. & Odru, P., **High-Performance Composites for Deepwater Risers**, Advances in Underwater Technology, Vol. 19, Graham and Trotman, 1989.

With increasing water depth, the weight of offshore structures for drilling or production systems becomes a major problem, and analysis shows that the weight of the risers is one of the critical points. This paper presents the principal results of a research program carried out in the field of lightweight, high-performance tubes made of composite materials, to be used as risers in the offshore industry.

Stafford, W.K., & Roylance, D.K., **Engineering Properties of Graphite Fiber Reinforced Composites**, Proceedings of the 29th Annual Technical Conference, Reinforced Plastics/Composites Institute, Society of the Plastics Industry, Section 20E, Washington, D.C., February 1974.

Tam, A.S. & Gutowski, T.G., **The Kinematics for Forming Ideal Aligned Fibre Composites into Complex Shapes**, Composite Manufacturing Vol. 1, No. 4, December 1990.

In this paper, we present a framework to analyze the kinematics for forming aligned fibre composites into complex shapes. We identify the ideal process endpoint, with equal fibre spacing and uniform part thickness, as the goal for all processes. Furthermore, we show that this ideal mapping is obtainable for a large group of 'topologically equivalent' parts by using only two deformation modes: shear in-the-plane and out-of-plane bending (which leads to shear between plies for a laminate). In addition, we show how in-plane shear is related to the instrinsic attributes of the part geometry. Example solutions are derived for a variety of shapes. Then it is shown how the kinematic analysis can be used for the development of forming limit diagrams for composites. One example of this approach is given for a vacuum forming process.

Triantafillou, T.C., Kim, P. & Meier, U., **Optimization of Hybrid Aluminum/CFRP Box Beams,** *International Journal of Mechanical Sciences,* in press, 1991.

Triantafillou, T.C. & Gibson, L.J., **Failure Mode Maps for Core Sandwich Beams,** *Journal of Materials Science and Engineering,* 1987, pp. 37-53.

Sandwich panels can fail in several ways. The faces and core can yield plastically or fracture depending on the nature of the materials from which they are made; the compressive face can buckle locally or 'wrinkle' and the bond between the faces and core can fracture, causing delamination. The critical failure mode, which occurs at the lowest load , depends in part on the properties of the face and core materials and, in part, on the design of the beam. Here, we develop equations describing the load at which failure occurs for each possible failure mode for a sandwich beam with face and core materials that yield plastically. We then develop a failure mode map, with axes of core relative density and the ratio of face thickness to span length which, for a given loading configuration and set of face and unfoamed solid core materials, shows the dominant failure mode for every possible beam design.

Triantafillou, T.C. & Gibson, L.J., **Minimum Weight Design of Foam Core Sandwich Panels for a Given Strength,** *Journal of Materials Science and Engineering,* 95, 1987, pp. 55-62.

In a sandwich beam made of materials that yield plastically, the main modes of failure are yielding and wrinkling of the face and yielding of the core in shear. The minimum weight design of a beam is such that the face and core fail simultaneously, otherwise, one component is overdesigned. In this paper, we find the minimum weight design of a foam core sandwich beam or plate of a given strength by constraining the face and core to fail simultaneously using the failure equations developed in the companion paper. We also make use of property-density relationships for foam cores to include the density of the core as one of the beam design parameters to be found in the optimization analysis. The results give the face and core thicknesses and the core density which minimize the weight of a foam core sandwich beam or plate of a given strength.

Triantafillou, T.C. & Plevris, N., **Strengthening of R/C Beams with Epoxy-Bonded Fiber-Composite Materials,** *Materials & Structures,* in press, 1991.

Strengthening of concrete beams with externally bonded fiber-reinforced plastic (FRP) materials appears to be a feasible way of increasing the load carrying capacity and stiffness characteristics of existing structures. FRP-strengthened concrete beams can fail in several ways when loaded in bending. The following collapse mechanics are identified and analyzed in this study: steel yield-FRP rupture, steel yield-concrete crushing, compressive failure and debonding. Here we obtain equations describing each failure mechanism using the strain compatibility method, concepts of fracture mechanics and a simple model for the FRP peeling-off debonding mechanism due to the development of shear cracks. We then produce diagrams showing the beam designs for which each failure mechanism is dominant, examine the effect of FRP sheets on the ductility and stiffness of strengthened components and give results of four-point bending tests confirming our analysis. The analytical results obtained can be used in establishing a FRP selection procedure for external strengthening of reinforced concrete members with lightweight and durable materials.

Triantafillou, T.C.,& Deskovic, N., **Innovative Prestressing with FRP Sheets: Mechanics of Short-Term Behavior,** *Journal of Engineering Mechanics,*
Vol. 117, No. 7, July 1991, pp.1652-1672.

The short-term mechanical behavior of a novel prestressing technique is described. The technique involves external bonding of pretensioned fiber-reinforced plastic (FRP) composite sheets on the tension zones of structural elements. Analytical models are developed describing the maximum achievable prestress level so that the FRP-prestressed system does not fail near the anchorage zones. Both adhesive layer and beam material failures are considered. It is found that the method's efficiency is improved by increasing the thickness of the adhesive layer and/or increasing the area fraction of the composite material, efficiency being defined as the level of prestress at the bottom fiber of the member. Moderate to high prestress levels are achieved depending on whether failure of the system is controlled by the shear strength of the beam material or that of the adhesive layer. The technique is applicable to the rehabilitation/strengthening of existing structures as well as the construction of new ones.

Vizzini, A.J. & Lagace, P.A., **The Role of Ply Buckling in the Compressive Failure of Graphite/Epoxy Tubes,** Proceedings of the AIAA/ASME/ASCE/AHS 25th Structures, Dynamics and Materials Conference, Palm Springs, CA, May 1984, pp. 342-350 and *AIAA Journal,* Vol. 23, November, 1985, pp. 1791-1797.

Wang, E. & Gutowski, T.G., **Cost Comparison Between Thermoplastic and Thermoset Composites,** *SAMPE Journal,* Vol. 26, No. 6, Nov/Dec. 1990.

Wang, S.S. & Roylance, D.K., **Dynamic Fracture of Nonlinear Polymeric Fabric Panels,** Proceedings of the International Symposium on Numerical Methods in Fracture Mechanics, Swansea, England, January 1978.

Wium, D.J.W., & Buyukozturk, O., **Variability in Long-Term Concrete Deformations,** *Journal of Structural Engineering,* Vol. 111, No. 8, August, 1985.

The deformation properties of concrete significantly influence the behavior of complex concrete structures. These properties are subject to large variabilities and it is therefore not possible to accurately predict the structural response. The sources of these variabilities are first examined, and an example is then presented of the long-term deformation calculations in a multiple span bridge. Finally, a procedure using the finite element method, is proposed for predicting the variability in the shortening of the bridge.

BIOGRAPHIES OF PRESENTERS

Mr. Douglas S. Barno
The Composites Institute of the Society of the Plastics Industry, Inc.

Mr. Barno presently holds a number of positions that, among them is president of GeoPlas Inc., a start-up company which will begin marketing of a multi-functional filler for thermoplastics, thermosets and elastomers. Mr. Barno is also a special consultant to the Composites Institute of the Society of the Plastic Industry, Inc., director of marketing and sales for Isorca Associates, Inc. and is president and founder of DSB Associates, an international consulting firm specializing in composites manufacturing. Mr. Barno has extensive experience in composites marketing and business development through his previous employment in a number of positions with Owens-Corning Fiberglass, Corp.

Mr. Barno received a B.A. with a major in economics, and a minor in psychology from Ohio Wesleyan University.

Dr. Dale E. Berner, P.E.
Ben L. Gerwick, Incorporated

Dr. Berner is currently a consulting engineer with the construction engineering firm, Ben C. Gerwick, Inc. His work has focussed on concrete in the marine environment with numerous studies conducted for the offshore industry including the preliminary and conceptual design for offshore gravity-based structures, field inspections and surveys of man-made Arctic islands and development of reliability and damage acceptability criteria for offshore concrete platforms. Prior to joining Ben C. Gerwick, Inc., Dr. Berner worked both as a research assistant and associate instructor in the Civil Engineering Department at the University of California, Berkeley.

Dr. Berner received his B.S., M.S. and Ph.D. in civil engineering from the University of California, Berkeley.

Professor Buyukozturk
MIT, Department of Civil Engineering

Professor Buyukozturk joined the MIT faculty in 1976. Prior to MIT, he worked within a variety of organizations including the Kadikoy College of Engineering, the Turkish Army Engineering Division, Marc Analysis Research Corporation and Brown University. Over the years, Professor Buyukozturk has provided consulting services to NASA, Exxon, Babcock & Wilcox, Westinghouse, Corp., Shimizu and Amoco. Professor Buyukozturk's current research interests are in the behavior of fiber-reinforced concrete, the behavior of fiber-reinforced, high-strength concrete in direct shear, interface fracture behavior of high-strength concrete, and material and system characterization of refractory ceramic systems.

Professor Buyukozturk received an M.S. in civil engineering from the Istanbul Technical University and an M.S. and Ph.D. from Cornell University.

Mr. Richard E. Chambers, P.E.
Simpson, Gumpertz & Heger, Incorporated

Mr. Chambers is a principal with the consulting firm Simpson, Gumpertz & Heger, Inc. and heads up their Materials Technology Division. He serves as a consultant in materials of construction and structural components with broad experience representing design, testing, research, failure analysis, repairs and development of structural materials. Mr. Chambers has worked on such projects as the development of glass fiber reinforced concrete panel design methods, the evaluation of plastic materials for construction applications and sandwich panel construction for Arctic conditions.

Mr. Chambers received his S.B. in building engineering and construction and an S.M. in materials and structures from MIT.

Dr. Frank R. Field III
MIT, Department of Materials Science and Engineering

Dr. Field is the director of MIT's Materials System Laboratory within the Department of Materials Science and Engineering. As director, Dr. Field oversees research that addresses the application of decision analysis and microeconomic principles to problems of materials selection and usage associated with product manufacture, development and design. In addition to his work at MIT, Dr. Field has also provided consulting services to a variety of organizations including E.I. du Pont, Borg-Warner, Exxon, General Motors, U.S. Bureau of Mines and U.S. Office of Technology Assessment.

Dr. Field received an S.B. in nuclear engineering, an S.M. in nuclear engineering and an S.M. in technology and policy and a Ph.D. in materials systems analysis from MIT.

Professor Lorna J. Gibson, P.E.
MIT, Department of Civil Engineering

Professor Gibson is presently an Associate Professor within MIT's Department of Civil Engineering. Her current research interests are in the mechanical behavior of cellular materials, (e.g. honeycombs, foams, cancellous bone and leaves), optimization of sandwich panel design, and engineering applications of materials science. Professor Gibson has consulted for a number of organizations including British Petroleum, Merix Corporation, Martin Marietta and the Jet Propulsion Laboratory.

Professor Gibson received her B.A.Sc. in civil engineering from the University of Toronto and her Ph.D. from the University of Cambridge.

Mr. Andrew Green, P.E.
Composite Technology, Incorporated

Mr. Green is the founder of Composite Technology, a subsidiary of W.R. Grace & Company. At Composite Technology, Inc., Mr. Green has developed structural composite designs for offshore racing sailboats, automobile chassis, bridges with clear spans greater than 90 feet and a proprietary composite structural system for industrial buildings. Previously, Mr. Green was employed with General Dynamics conducting research and development in the structural applications of reinforced plastics.

Mr. Green is currently a member of the American Society of Civil Engineers and is chairman of the A.S.C.E. Research Council for Structural Plastics. He holds both a B.S. and M.S. in civil engineering.

Professor Timothy G. Gutowski
MIT, Department of Mechanical Engineering

Professor Gutowski is an associate professor in the Department of Mechanical Engineering at MIT and is also director of the MIT Industry Composite and Polymer Processing Program. Prior to MIT, Professor Gutowski was a senior consultant at Bolt Beranek and Newman, Inc. Professor Gutowski presently serves on several editorial advisory boards for professional journals in composites and was recently appointed to be the editor for North America for *Composite Manufacturing*.

Professor Gutowski received a B.S. in mathematics from the University of Wisconsin, an M.S. in theoretical and applied mechanics from the University of Illinois and a Ph.D. in mechanical engineering from MIT.

Professor Paul Lagace
MIT, Department of Aeronautics & Astronautics

Professor Lagace is an associate professor in the Department of Aeronautics and Astronautics and is currently the director of MIT's Technology Laboratory for Advanced Composites. In addition to his teaching responsibilities, Professor Lagace conducts research in the fracture, longevity and damage tolerances of composite materials and their structures. Specific research areas addressed include, interlaminar stresses, resultant delamination and suppression methods of such, impact damage resistance and general damage tolerance of composite materials and their structures and buckling and postbuckling of composite structures. Professor Lagace is currently a member of the Materials Working Group Committee on Marine Structures of the National Research Council and is also chairman of the Scientific Advisory Board for American Composite Technology.

Professor Lagace received his S.B., S.M. and Ph.D. degrees, all in aeronautics and astronautics from MIT.

Dr. Christopher K.Y. Leung
MIT, Department of Civil Engineering

Dr. Leung is presently a postdoctoral associate within MIT's Department of Civil Engineering. His current research interests are the experimental investigation and theoretical modeling of material deformation and failure mechanisms, theoretical and experimental fracture mechanics of quasi-brittle materials, and the mechanics of composites.

Dr. Leung received his B.S. from the University of Hong Kong, his M.S. from the University of California, Berkeley and his Ph.D. from MIT.

Mr. Pierre Odru
Institut Francais du Petrole

Mr. Odru joined the Institut Francais du Petrole (IFP) in 1975 and is presently head of IFP's marine components testing facilities. Mr. Odru's primary research interests are in the characterization of new materials for flexible cylinders in deep water applications. Since 1982, Mr. Odru has worked principally on the development of advanced composite tubes and has also been involved in studies of glass reinforced plastic tubes for firewater systems on offshore structures.

Mr. Odru received his engineering degree from the Ecole Centrale de Lyon.

Professor David K. Roylance
MIT, Department of Materials Science and Engineering

Professor Roylance is currently an associate professor within the MIT Department of Materials Science and Engineering. Prior to MIT he was the group leader for the Organic Materials Laboratory at the Army Materials and Mechanics Research Center. Professor Roylance's research interests are in polymers and composites engineering with specific interest in the physics of fracture in oriented polymers, biomedical applications of polymers, environmental degradation of polymers and composites, and finite element analysis of polymers and composites.

Professor Roylance received his B.S. and Ph.D. in mechanical engineering from the University of Utah.

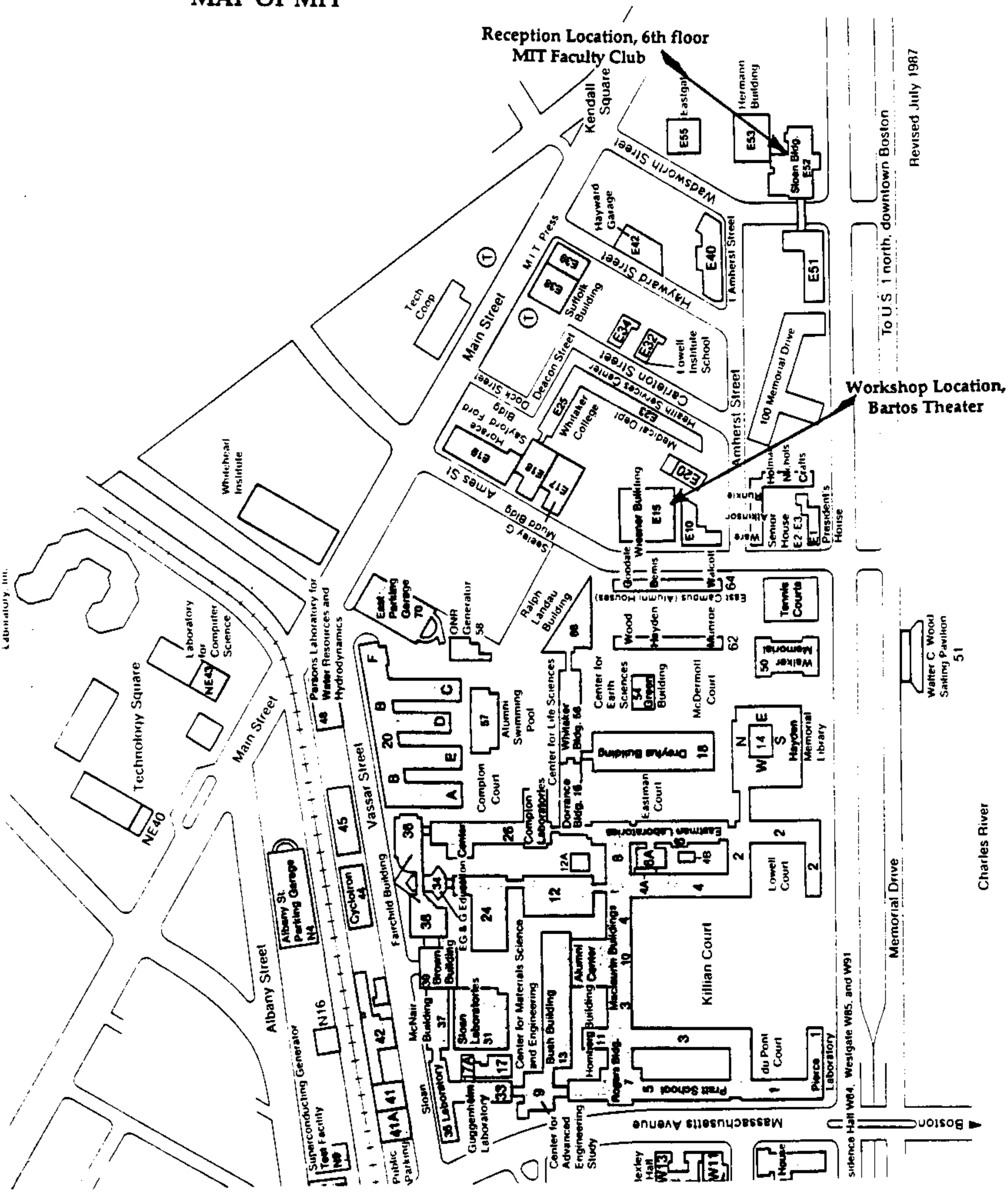
Dr. Mamdouh M. Salama
Conoco Incorporated

Dr. Mamdouh M. Salama is a Du Pont Fellow in Conoco's Production Technology. He holds B.Sc and M.Sc. degrees from Egypt, and S.M. and Sc.D. in mechanical engineering from MIT. Dr. Salama has published more than 40 papers in the areas of materials performance, integrity assessment, fabrication technology, advanced composites and structural concepts. Dr. Salama held several management positions including director of the marine and materials section and then as a director of the materials and corrosion section of Conoco's Production Research. He also served as Chairman of Conoco's marine technology steering committee and materials and corrosion technology steering committee.

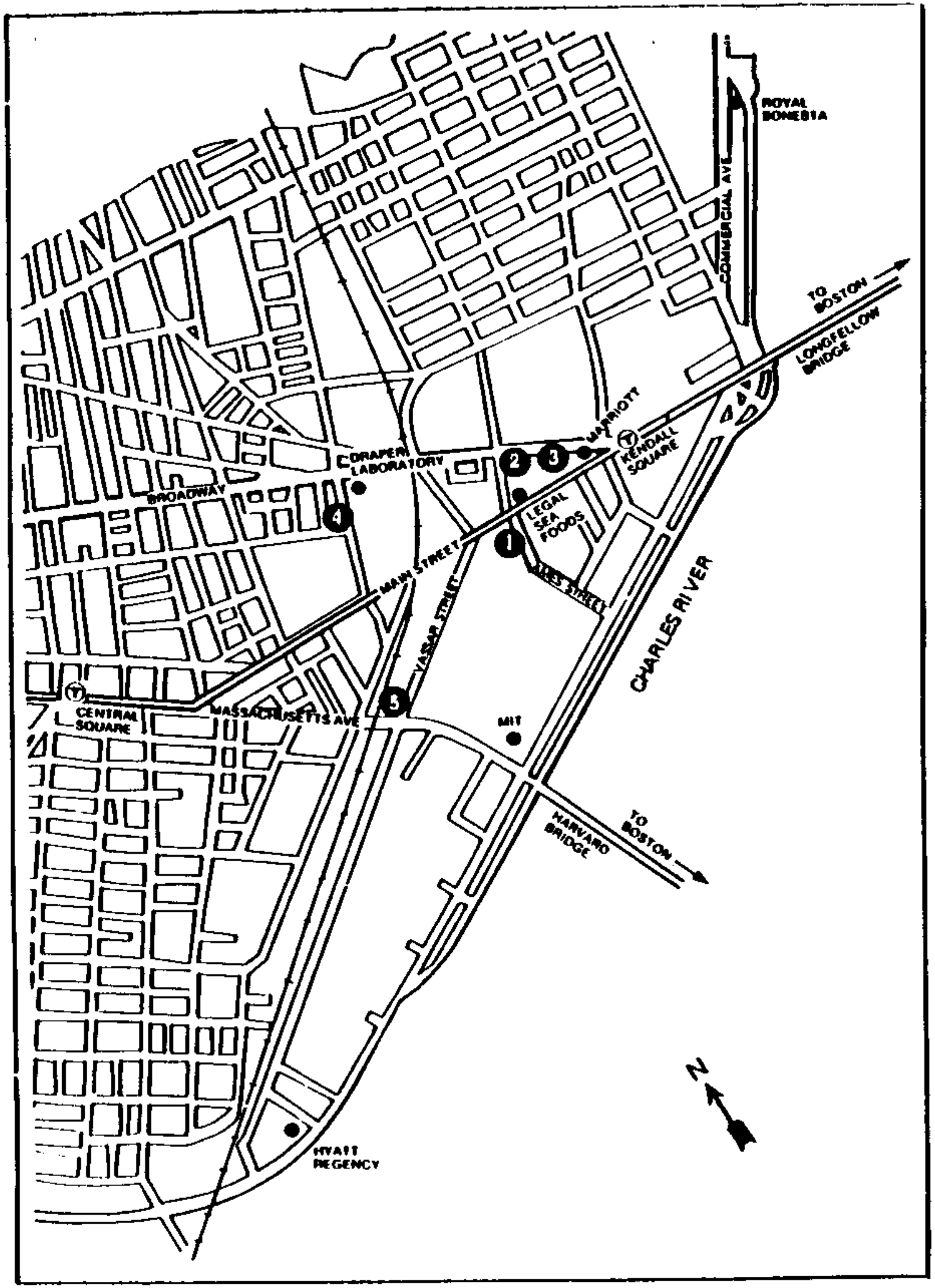
Professor Thanasis C. Triantafillou
MIT, Department of Civil Engineering

Since January 1990, Thanasis C. Triantafillou is an assistant professor of Civil Engineering at the Massachusetts Institute of Technology. In the past, Professor Triantafillou has conducted both analytical and experimental work on the optimum design of lightweight structural panels and on modeling the multiaxial behavior of cellular materials. His current primary research focus is on the development of innovative structural design concepts both for the rehabilitation of existing structures and for the construction of new ones, using advanced polymer composites in combination with more traditional construction materials (e.g. concrete, wood, steel) to maximize structural performance. Specifically, he is studying the application of fiber reinforced polymer sheets as external reinforcement of concrete and wood structures, and optimizing ways of combining pultruded composites with concrete to design better structural members. Part of his research effort is conducted in collaboration with the Swiss Federal Laboratories for Materials Testing and Research (EMPA).

MAP OF MIT



Reception Location, 6th floor
MIT Faculty Club
Workshop Location,
Bartos Theater
Kendall Square
Wadsworth Street
Hayward Street
Carleton Street
Amherst Street
Main Street
Ames St
Vassar Street
Albany Street
Memorial Drive
Massachusetts Avenue
Charles River
Technology Square
Killian Court
Sloan Bldg. E52
Hermann Building
E53
E55
E51
E40
E42
Hayward Garage
MIT Press
E38
E39
Suffolk Building
E34
E32
Lowell Institute School
Tech Coop
100 Memorial Drive
Whitaker College
E25
Health Services Center
Medical Dept
E23
E20
Horace Saylord Ford Bldg
E19
E18
E17
Mudd Bldg
Seeley G
Wiesner Building
E15
E10
Whitehead Institute
East Parking Garage
70
ONR Generator
58
Ralph Landau Building
66
Tennis Courts
Walker Memorial
50
Walter C Wood Sailing Pavilion
51
Revised July 1987
To U S 1 north, downtown Boston
Alumni Swimming Pool
57
Compton Court
McDermott Court
Center for Earth Sciences
54
Green Building
Dreyfus Building
18
Eastman Court
Hayden Memorial Library
14
Center for Life Sciences
Whitaker Bldg. 56
Dorrance Bldg. 16
Compton Laboratories
26
Eastman Laboratories
Lowell Court
du Pont Court
Pierce Laboratory
Pratt School
Laboratory for Computer Science
NE43
NE40
Parsons Laboratory for Water Resources and Hydrodynamics
48
45
Cyclotron
44
Albany St. Parking Garage
N4
N16
Superconducting Generator Test Facility
N9
Public Parking
42
41
41A
Fairchild Building
36
38
EG & G Education Center
24
12
12A
Brown Building
McNair Building
37
Sloan Laboratories
31
Center for Materials Science and Engineering
Bush Building
13
Alumni Building Center
Maclaurin Buildings
10
3
1
2
4
4A
6
8
Sloan Laboratory
Guggenheim Laboratory
35
33
9
17
Homberg Building
11
Rogers Bldg.
7
Center for Advanced Engineering Study
East Campus (Alumni Houses)
64
62
Senior House
President's House
Boston



MAP OF NEARBY PARKING AREAS

1 Ames Street Lot
Ames and Main Street
225-0847

2 Cambridge Center Garage
5 Cambridge Center
Broadway and Ames Street
(off of Main St., next to Legal Sea Foods)
492-1956

3 Cambridge Center Marriott Hotel
2 Cambridge Center (Valet parking)
494-6600

4 Polaroid Parking Garage
Adjacent to Draper Employee Parking Garage
Technology Square

5 Vassar Street Lot
Vassar St. and Massachusetts Ave.
(next to BayBank Automated Teller machine)

ACCOMMODATIONS*

Cambridge Marriott
2 Cambridge Center
Cambridge, MA 02139
1-800-228-9290
617-494-6600

Royal Sonesta Hotel
5 Cambridge Parkway
Cambridge, MA 02139
1-800-SONESTA
617-491-3600

Hyatt Regency
Memorial Drive
Cambridge, MA 02142
1-800-233-1234
617-492-1234

Howard Johnson
777 Memorial Drive
Cambridge, MA 02142
1-800-654-2000
617-492-7777

*Listed in descending order of proximity to symposium location.