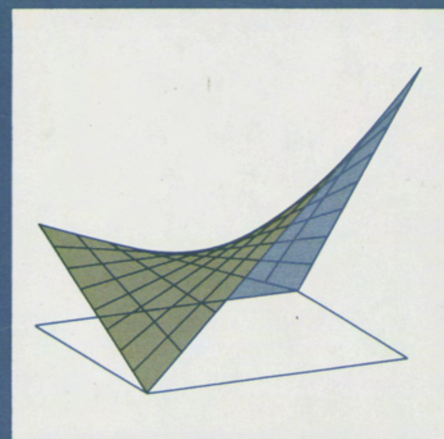
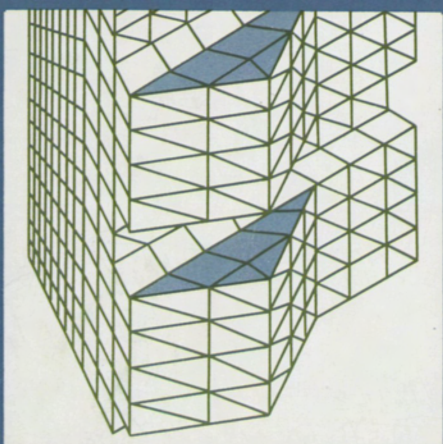
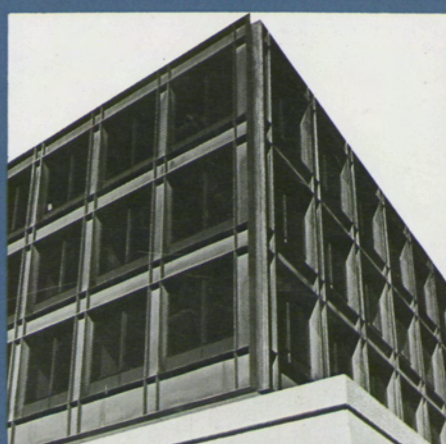
ENGINEERING

CORNELL QUARTERLY







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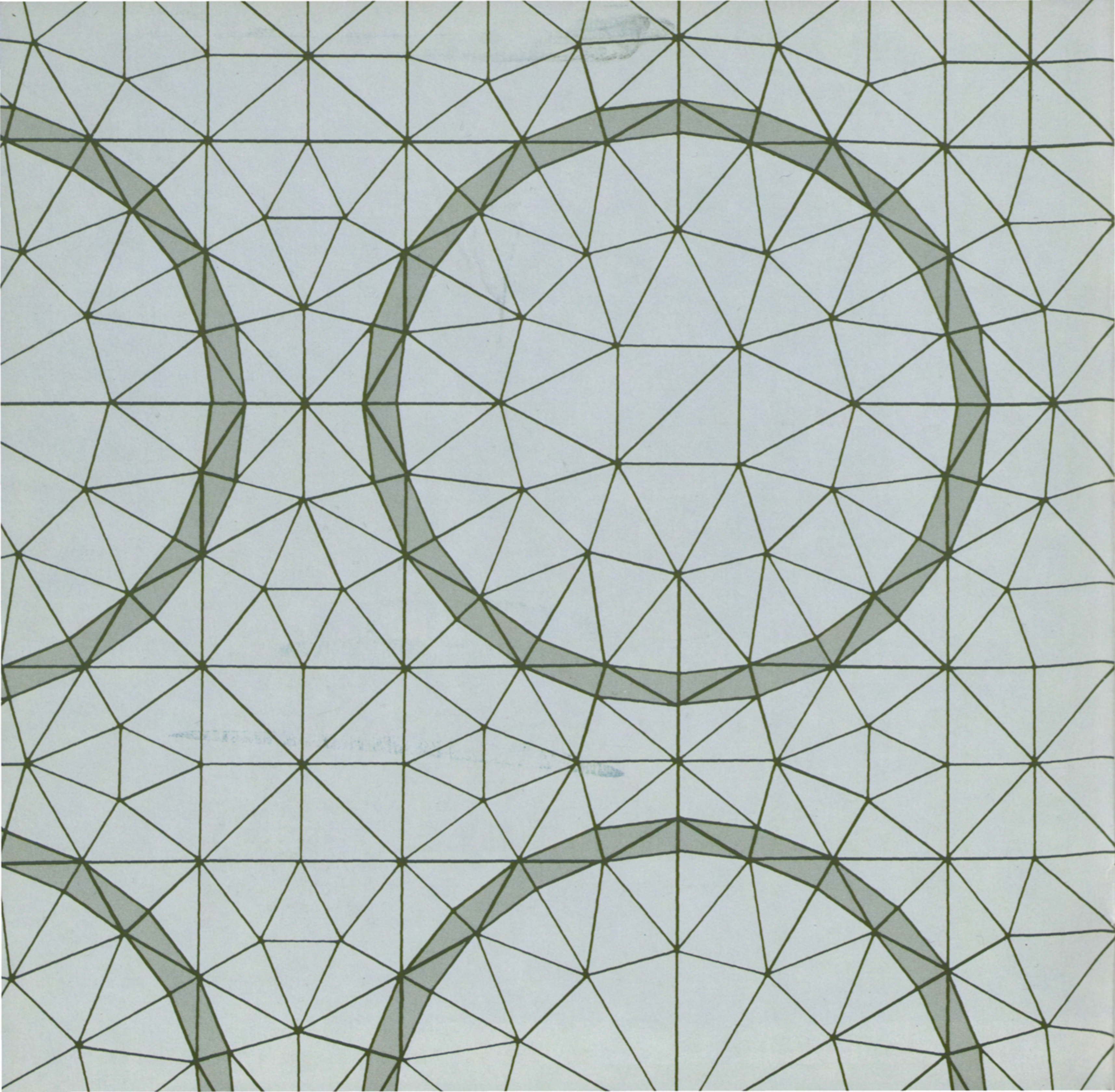
STRUCTURES FOR TODAY



IN THIS ISSUE

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Opposite: A two-dimensional representation, for finite element analysis, of an idealized cross section of plain concrete. The dark rings represent interfacial areas between stone and mortar. This interfacial region is crucial to the performance of the combined system, and special elements were devised to model it. The diagram was prepared for a study supervised by Professors Arthur H. Nilson and Floyd O. Slate of Cornell's Department of Structural Engineering.

THIN-WALLED STEEL FOR MODERN STRUCTURES

Thirty Years of Industry-Sponsored Research at Cornell

by George Winter

Modern schools, office and apartment buildings, industrial and commercial structures, and homes, here and in many other parts of the world, testify to the contributions of a large-scale research project in Cornell's Department of Structural Engineering.

These structures, made in whole or in part of cold-formed thin-walled steel components, help meet the pressing contemporary need for greater speed and economy in building construction. This is achieved by use of light, strong, versatile building components which are mass-produced and require a minimum of on-site labor.

The Cornell research program that laid the foundation for this new type of construction represents a relationship that is probably unique at the University and fairly unusual elsewhere in the United States. For thirty years it has been conducted as a cooperative project, with the American Iron and Steel Institute (AISI) as research sponsor and Cornell as the institution executing the research.

By far the largest part of engineering research in universities today is funded by governmental agencies such as the National Science Foundation, the National Aeronautics and Space Administration, and the Atomic Energy Commission. In contrast, AISI is the trade organization of the entire American steel industry and is not to be confused with bodies with similar-sounding names, such as the American Concrete Institute, which are essentially professional associations of engineers in a particular field. One main function of an industry organization like AISI is to promote new or expanded uses of its products. For this reason, the sponsoring of pertinent academic research seems an appropriate activity, and one which should benefit both the industry and the universities. Yet few trade associations do sponsor research on a large scale and over extended periods. It is this which makes AISI's sponsorship of research on cold-formed steel structures at Cornell quite unusual.

THIN-WALLED STEEL AS A BUILDING MATERIAL

The origin of this work and its motivation go back to the great depression.

Steel used in building construction is mostly in the form of familiar structural shapes, such as angles, channels, and I-sections, and heavy plates welded up into structural shapes. All these relatively thick-walled and heavy products are hot-rolled from steel billets. The other main form is sheet and strip steel, a flat product of limited thickness, say 1/8 inch down to 1/64 inch. The main use of sheet and strip is in automobile bodies, major home appliances, and the like. Now, during the great depression the market for automobiles and home appliances suffered even more than that for construction, probably because a sizable part of the national construction activity is financed by government, whereas cars and washing machines are bought, or not bought, by individual consumers. For this reason, the steel industry was searching, in the middle and late thirties, for new outlets for its largely idle sheet and strip capacity, and was looking to the construction industry to provide those markets.

The use of thin-walled steel products for buildings was not entirely unknown at that time. Corrugated sheet had been used for at least fifty years for roofs, mostly unsightly, of utility buildings. Also, in the early thirties a few companies had shown in individual pioneering efforts that thin-walled steel decks, panels, and other elements formed of sheet steel had considerable potential in building applications.

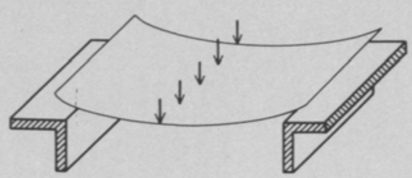

FIGURE 1a.

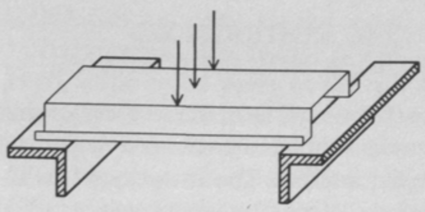

FIGURE 1b.

Why this potential exists is easily understood. If one were to use a piece of flat, thin steel to carry a load (see Figure 1a), a very small load would cause the member to fail because of excessive deflection. To make it stronger one could, of course, choose the easy but costly way and use a heavy plate instead of a thin sheet. If one made it very heavy, it would carry the load, but would require a great deal of material. However, one could also proceed in a more sophisticated manner by taking the piece of sheet steel which, when flat, was too weak, and bending it into a shape such as shown in Figure 1b. It is evident without elaborate proof that in such a configuration the same piece of steel will carry loads larger by orders of magnitude than it will in its flat form.

SHAPING STEEL FOR STRENGTH AND UTILITY

This principle of gaining higher strength and rigidity through shape rather than through mass was, of course, not new. It had been used to a limited extent in conventional steel construction and in more sophisticated ways in aircraft design, where weight saving is of overriding importance. One advantage of using relatively thin sheet and strip steel in this manner is that it can be formed fairly easily and cheaply into an almost unlimited variety of shapes, depending on the designer's skill, knowledge, and imagination.

The variety of cold-formed steel components now used as load-carrying members in buildings and other structures is illustrated in Figure 2. The only function of the shapes shown in Figure 2a is to carry loads. Those of Figure 2b, however, combine load-carrying capability with other functions, such as constituting roof, floor, and wall surfaces, incorporating insulation in the surfaces, or carrying electrical and other conduits, and even hot or cold air for heating or air conditioning, in the cells of panels. Incidentally, such cellular panels constitute the floors of Cornell's new social sciences building, as they do for perhaps the majority of high-rise office buildings constructed today.

In the late thirties, however, the large-scale use of building components of this type was severely restricted by two factors, one substantive and one legal. Substantively, gaining strength through complex configurations requires much more refined methods of design and analysis than gaining it by the simple addition of material. At that time, adequate knowledge in this field was not available, or it was available only in bits and pieces.

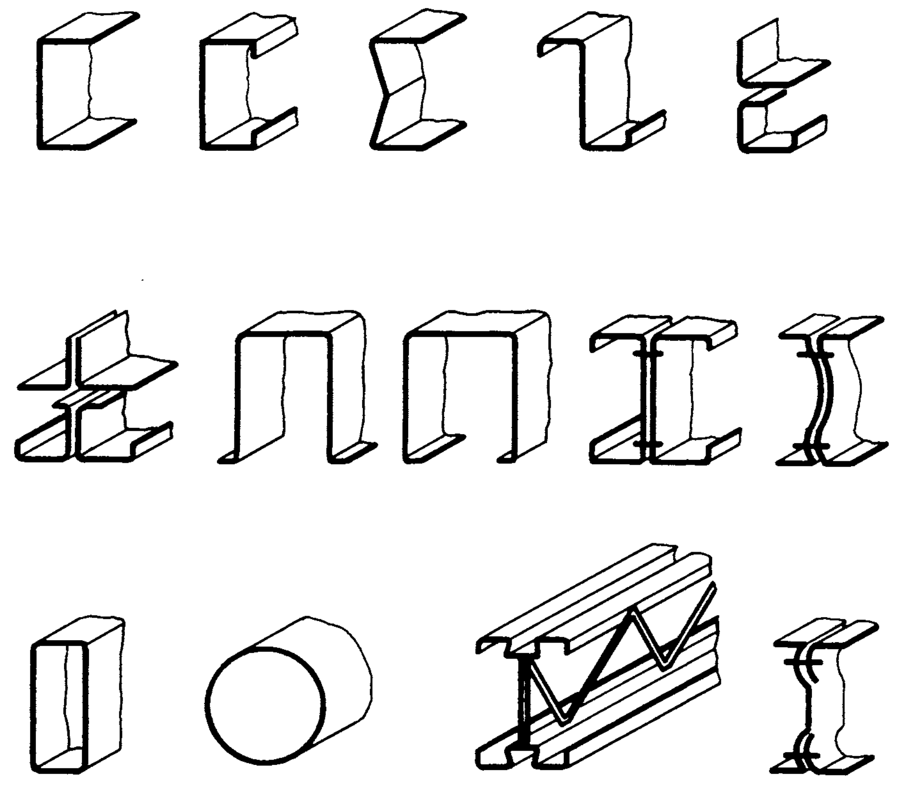

FIGURE 2a.

LEGAL RESTRICTIONS ON NEW BUILDING MODES

As to the legal side, the restrictions that were encountered concerned matters of public interest. The integrity of buildings and other structures involves public safety and, often, public property. For this reason, what can be built and what cannot, as far as safety against collapse is concerned, is a matter of public concern which is not left to the owner but, since time immemorial, has been governed by law—that is, by building codes promulgated by government.

"Since time immemorial" is literally true, for the first known building code was decreed by the Babylonian king Hammurabi some four thousand years ago as part of his great code of law. Hammurabi's building code did two things. For one, it set construction prices, and so was probably the earliest example of price control (an historical Phase I). For another, it stipulated—on an eye-for-eye basis—very severe punishment for a builder whose structure collapsed.

In contrast, modern building codes take a more positive approach. They specify design and construction methods which will assure acceptable margins of safety. New structural methods for which provision is not made in building codes can be used only under individual, case-by-case waivers. This limits widespread use until such time as the new departures are recognized and incorporated into the codes. Cold-formed steel construction was in precisely that situation. It was clear that the method could be recognized in building codes only after sound design procedures, based on proof of performance through research, had been developed. It was because of this situation that AISI decided to sponsor academic research that would fill these needs.

THE CHOICE OF CORNELL AS THE RESEARCH CENTER

How did Cornell get into the act? The University was not known at that time as a center of research in structural engineering, and, in fact, very little such research had been done here. However, Solomon Cady Hollister, who had just become dean, was determined to put the Cornell College of Engineering on the map not only in undergraduate teaching where it had always counted, but also in research and graduate work. He learned that the man at the head of the AISI division that dealt with matters of building codes happened to be a Cornell civil engineering alumnus. How he convinced that official to locate this work here when other schools with established reputations in structural research were available, I don't know. But here it was, and it came my way by the mere accident of my being on the scene.

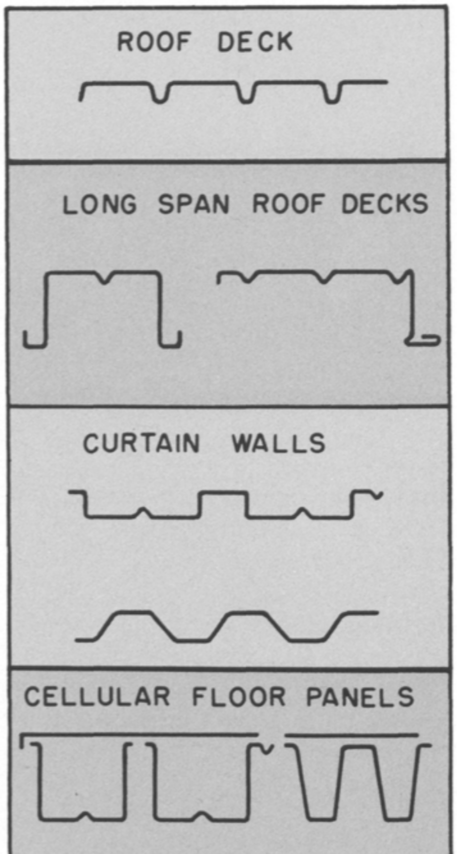

FIGURE 2b.

To complete this history briefly: in 1946, after seven years of Cornell research, AISI published the first *Specification for the Design of Cold-Formed Steel Structural Members*. The recommendations in this document, which was the first on this subject published anywhere, were soon incorporated into most American building codes, and the way was opened for large-scale use of this type of construction. Continued research and on-site experience led to four successively enlarged and improved editions of the *Specification* and supporting documents. This publication had not only national but worldwide impact. It was translated into at least six languages—German, French, Spanish, Italian, Czech, and Polish—and the design methods set forth in the documents have now been adopted in whole or in part in most of the countries where these languages are spoken. Hundreds of thousands, if not millions, of tons of steel are used annually in thin-walled steel construction.

The academic aspect of this continuing project has also been gratifying. Some thirty doctoral degrees and a fair number of master's degrees have been awarded to students who contributed to the research. Many of these men are still active in the field—a dozen of them were among the approximately one hundred engineers from all over the world who participated in last summer's First Specialty Conference on Cold-Formed Steel Structures, sponsored by the National Science Foundation (NSF), the American Association

"... industry-sponsored research is ... challenging because it must prove itself in the real world, and in some ways it is more satisfying to one who is basically an engineer rather than a scientist."

of Mechanical Engineers, and AISI. Others have gone into contiguous fields —aerospace structures, for example— or are active in various academic pursuits, in consulting engineering, or in industrial research and development. Since research output is generally, and often unfortunately, measured in terms of the number of publications, it may be mentioned that some sixty or more publications have resulted from the work on this long-range project.

WHY THIS PROJECT IS DIFFERENT

So what? Is there anything remarkable or different about this work as compared to the government-sponsored research that is more usual in engineering? Well, probably there is. For one thing, a governmental agency such as NSF rarely, if ever, funds research in one specific field at one particular institution for thirty-odd years (or even for twenty-five years, the foundation's approximate age).

But there is a more substantive difference. Except for classified research, which Cornell has never accepted, most government-sponsored academic research is of a fairly general nature, aimed at increasing the general store of knowledge or the development of general methods of research or analysis. Application is a secondary consideration, if it figures at all. To take an example in structural engineering, Professor Floyd O. Slate and I obtained successive NSF grants for some eight years for a fairly basic investigation of microcracking, inelasticity, and fracture of concrete. The results have enhanced our understanding of how concrete behaves as a structural material, and the work is widely recognized and quoted here and abroad, but it was not aimed at any direct engineering application and none has developed. A new phase of this work, now directed by Professors Slate and Arthur H. Nilson, is again of this fairly general nature. This is as it should be. There are many areas of engineering and applied science that call for research simply because there is a need for basic understanding and knowledge, quite apart from practical application. Also, the education of advanced students in research methods and thinking is a primary objective of academic research.

Yet engineering is not only knowing; engineering is also doing. Most non-academic research in industry and government is, to use a fashionable term, mission-oriented, aimed at developing new or improved technology, and finding ways of doing new things, or improving ways of doing old things. Such research has one crucial touchstone: its results must work in the real world. Now, the Cornell investigations in the field of cold-formed steel structures were and are precisely of this nature; the results must work. Structures designed by methods developed in such research must be safe against collapse or other distress, and they must also be economical, with no material or effort wasted on excess strength or rigidity. Only in this manner will a new method of construction ensure safety and also be economically competitive.

PRACTICAL RESEARCH AS SCIENCE AND ART

The fact that mission-oriented research has this additional challenge does not

Large-scale testing is done in the Thurston Hall Test Bay, viewed here through a fish-eye lens.

mean that it necessarily contributes less to the general store of scientific knowledge than research motivated in other ways. It does mean, though, that there exists an entirely different relationship between the researcher and the funding organization.

Two specific cases serve as examples. Classical stability theory predicts that when a thin plate—often used in cold-formed construction—is compressed in its own plane, it will buckle at a calculable stress. However, the Cornell researchers knew in a general way, from early work by others, that the actual usable strength of such plates exceeds, often by large amounts, the calculated buckling stress. Not to utilize this available excess strength would be wasteful and would hamper practical use. On the other hand, certain weaknesses in thin-walled shapes had to be taken into account. It was known that when compression struts or columns in ordinary steel, concrete, or timber construction are overloaded, they fail by bending out sideways, again at stresses fairly easily calculated by classical methods. Yet when the open, thin-walled shapes typical of cold-formed construction are used as compression members, they can fail by a combination of bending and twisting at loads lower than those calculated for pure bending failure. Not to account for this lower strength could lead to collapse of wrongly designed structures. Research intended to provide working standards and procedures must encompass practical aspects such as these.

In order to introduce these new features into routine structural design, it is necessary first to develop new theory or supplement existing theory and to verify or modify theoretical predictions by extensive testing. But the work does not stop there. It is also necessary to make sure that the knowledge that has been developed covers the entire range of practical needs in a particular problem. And finally, it is necessary to formulate these findings in terms sufficiently simple and direct for use in building design practice and in building codes which govern such practice. These steps are an art rather than a science.

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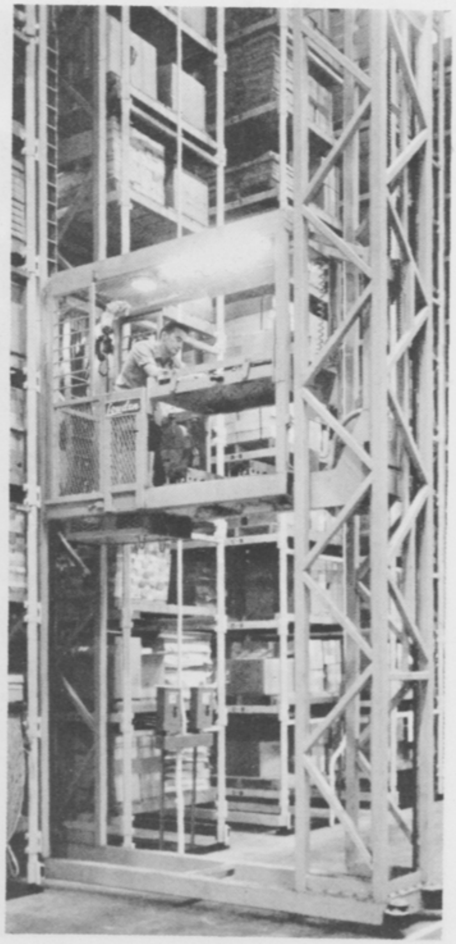


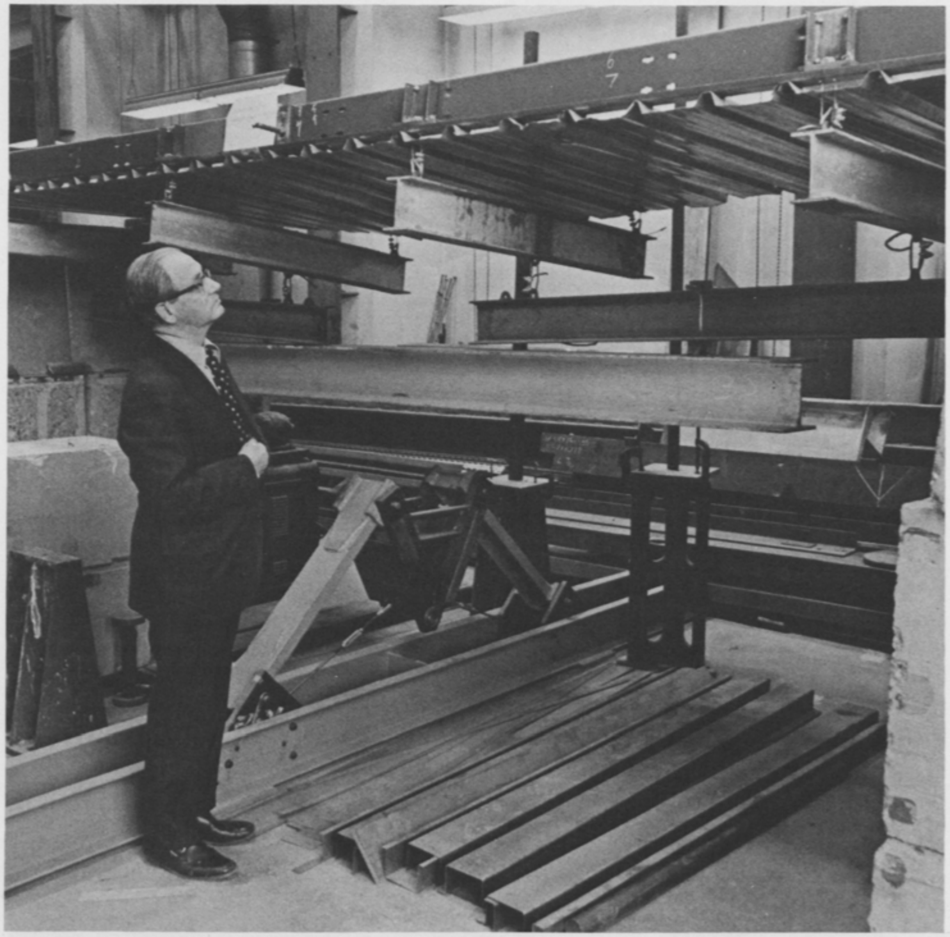
Cold-formed thin-gage steel components are used today in many kinds of structures. (1) Structural members of cold-formed steel are used in space-saving industrial storage racks. A worker can be seen operating a cab which can move vertically or horizontally. (2) Low-cost houses built of mass-produced steel components are a result of federally subsidized development. In this house, designed to enhance privacy in high-density neighborhoods, all windows and glass doors face away from the street. (3) Mass-produced components can be used in custom-designed school buildings. (4) Multi-purpose floor panels in high-rise office buildings not only support loads, but accommodate utility conduits. Cells in these panels serve as electrical raceways and as ducts for hot and cold air. (Photo courtesy H. H. Robertson Co.)

4

3

2

Maximum use of the strength of steel is achieved with an imaginative use of roof trusses in the Superbay Maintenance Facility at the San Francisco International Airport. The building is shown under construction and after completion. This structure, which is duplicated at the Los Angeles International Airport, was selected as a prize winner in the 1971 Architectural Awards of Excellence competition sponsored by AISI. The design was cited for both structural and architectural excellence. The hyperbolic paraboloid roof surfaces, which consist of cold–formed steel panels, project freely 250 feet from either side of the central core of the hangar. The absence of outside supports permits the entire front of the building to be opened for free access of the large airplanes. (Photo courtesy of Modern Steel Construction.*)*



The complex of demands of the "real world" requires continuous co-operation between the researchers and those in industry and practice who will utilize the results. In most cases, this means that the industry committee which oversees the general research undertaking appoints a special task force to work with the research group on each specific problem. Researchers and task forces meet about twice a year to assess findings, to agree on the next steps to be taken and the general direction of the investigation, to review papers and reports that present the research findings, and, finally, to co-operate in formulating the results in terms that are useful and acceptable to the engineering practitioner.

In one sense, research so organized is more tedious and occasionally more frustrating than research funded by "few-strings-attached" government or foundation grants. On the other hand, industry-sponsored research is more challenging because it must prove itself in the real world, and in some ways it is more satisfying to one who is basically an engineer rather than a scientist. In fact, it is a considerable satisfaction to the Cornell researchers to know that not only in the United States but, to varying degrees, in most other industrialized countries, construction with cold-formed steel has developed because of the Cornell project, and utilizes methods developed here.

COLD-FORMED STEEL IN SYSTEMS BUILDINGS

The chief applications of this method of construction are in what is coming to

Left: Professor George Winter inspects the results of large-scale testing of a thin-gage steel diaphragm.
Right: A test of the corrugation of a light-gage steel section is carried out by graduate student Amir Simaan. Looking on is Professor Teoman Peköz, manager of structural research in the Thurston Hall laboratory.
Below: Publications based on Cornell research are standard references in many parts of the world.

be known as systems buildings. These are designed so as to integrate structural functions, and consist of mass-produced components. A fairly elementary example of structural members with additional functions are floor panels such as those used in the new social sciences building on the Cornell campus, and in many high-rise office buildings. These panels, in addition to carrying the floor loads, also accommodate a great variety of conduits in their cells and serve as ducts for hot and cold air.

Many recent school buildings consist of mass-produced cold-formed steel components which are designed so that a limited number suffice for the construction of buildings of many different plans and sizes. "Preengineered" metal utility buildings in many shapes and sizes can be ordered from catalogs and erected on the site by very simple procedures.

In a highly industrialized society the problems of production are often more than matched by those of distribution. This is why industrial storage racks, with automated loading and unloading devices, are becoming increasingly important. They, too, are preponderantly made of cold-formed steel.

Residential construction in this country is hampered, in volume and in price, by antiquated custom-building methods. This is why the federal Department of Housing and Urban Development is promoting industrialized residential construction through a program called Operation Breakthrough. One result of this project is an all-steel house consisting of mass-produced components which include factory-installed service facilities for plumbing, heating, air conditioning, and electrical supply.

The largest applications, in terms of sheer physical size, are probably the jumbo jet hangars just completed in San Francisco and Los Angeles. These were designed by the firm of a Cornell Ph.D. holder who served as a research assistant on the cold-formed steel research project.

With this small sampling ends the tale of what is probably the longest continuous research activity in the College.

George Winter, the Class of 1912 Professor of Engineering, has served on the Cornell faculty for thirty-two years, including twenty-two as chairman of the Department of Structural Engineering, a position he resigned in 1970. Next year he will continue beyond the normal retirement age in part-time teaching and research.

Winter was born in Vienna, Austria, and received his first engineering degree, the Dipl. Ing., from Technical University in Munich in 1930. After eight years of practice and consulting in engineering design in Europe, he came to Cornell in 1938 and studied for a Ph.D., awarded in 1940. His work with the American Iron and Steel Institute (AISI) on cold-formed steel structures, discussed in this article, was begun in 1939. He has also conducted many other research projects in the areas of concrete and steel structures.

Winter has received many honors during his years at Cornell. One of the most recent was the 1971 Henry C. Turner Medal, awarded in March of this year by the American Concrete Institute (ACI) for his contributions to concrete construction technology, research, and education. He was honored by election to the National Academy of Engineering, and he has been a Guggenheim Fellow. He has received the Leon S. Moiseiff Award and the J. J. Croes Medal of the American Society of Civil Engineering (ASCE), the Technical Meeting Award of the AISI, and the Wason Research Medal of the ACI. In 1969 he was awarded an honorary doctoral degree from his undergraduate university, Technical University of Munich.

In addition to directing the research for various editions of Specification for the Design of Cold-Formed Steel Structural Members *(see page 5), he has published many papers in American and foreign periodicals and has contributed articles to special publications such as the* Encyclopedia Britannica *and the* Structural Engineering Handbook. *He is an author, with his Cornell colleague Arthur H. Nilson and others, of* Design of Concrete Structures, *which is now in its seventh edition and has just been published in Spanish.*

Winter has served as a consultant to various industries and as a visiting professor at the California Institute of Technology, Cambridge University, the University of Liege, Belgium, the University of California at Berkeley, and other institutions. He is vice chairman of the Column Research Council, a council member of the International Association of Bridge and Structural Engineers, and a member of AISI, ACI, and ASCE.

STRUCTURAL MODELING IN RESEARCH, DESIGN, AND EDUCATION

by Richard N. White

The structural engineer is responsible for devising and evolving improved structures to house and support the diverse activities of man. Progress toward more efficient structures is dependent upon strengthening our knowledge of how structures actually behave as they are subjected to loads.

We can pose any number of questions that are answerable only if we understand structural behavior. How will a given skyscraper or bridge perform when loaded with a severe earthquake? How does the wind action on a multi-story building get transferred to the foundation piles driven into the earth? How can we best guarantee that the internals of a nuclear power plant will be adequately contained in case of an accident? How can a giant antenna structure be made stiff, yet light, so as to remain within a preset tolerance of a certain shape? While computer-aided analyses are indispensable in helping to answer these questions, we must also utilize physical testing to fully understand structural behavior and to form a basis for further theoretical developments.

Full-scale experiments are confined mainly to components of structures, such as beams, columns, panels, and connections, because it is extremely difficult and prohibitively expensive to build and test full-scale structural assemblages. The experimental study of structural behavior, therefore, is conducted most often on structures of reduced size called *models,* which have an important role in contemporary research, design, and education. At Cornell, research and instruction in this field is facilitated by the Structural Models Laboratory, one of the best equipped centers of its kind in the United States.

MODELING IN STRUCTURAL RESEARCH

Models and reduced-scale structures have always played a key role in structural research, particularly for reinforced and prestressed concrete structures. Much of the empirical data used in evolving and substantiating the design expressions for concrete structures has been determined with tests on reduced-size specimens about half the size of typical prototype (full-scale) specimens. These reduced-size elements are really not models and are usually fairly large; the experimental work is carried out in regular structural laboratories such as Cornell's Thurston Hall Test Bay (see page 7).

Small-scale models have been indispensable in recent research on shell roof structure; behavior ranging from elastic stress distributions to elastic buckling and ultimate strength have been studied. Models have been used extensively and will continue to be used for substantiation of proposed theories for many types of structural forms, including pressure vessels, shells, slabs, and undersea structures. Models testing has also been used to verify the predicted behavior of various systems; an example is construction based on the tubular structure concept now being employed in high-rise buildings such as the Sears Tower in Chicago (see page 29) and the world's highest concrete building in Houston, Texas.

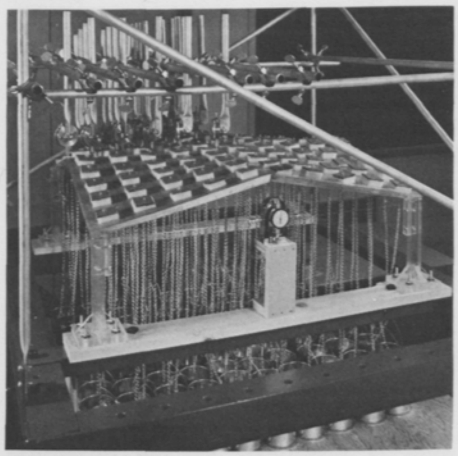
The primary role of research models is to provide information on behavior, from which appropriate theories can be developed and substantiated. Once an acceptable mathematical model has been evolved for a particular form, relatively little additional experimental work is required for that form.

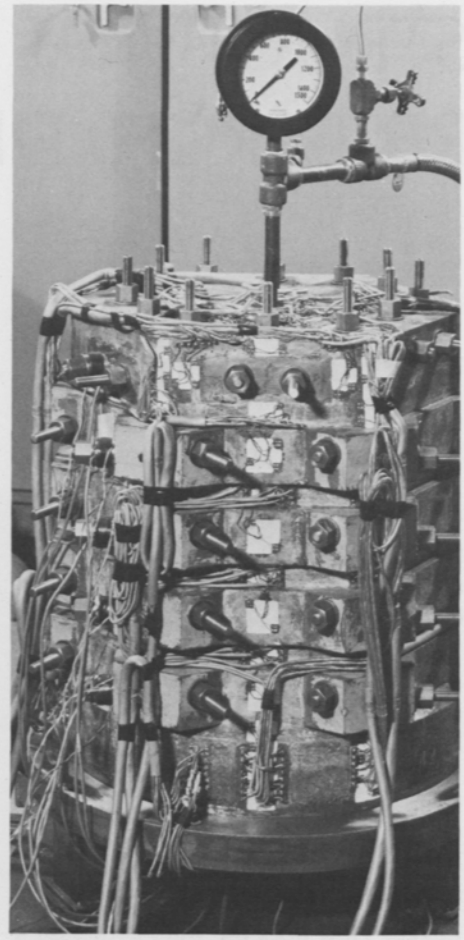
RECENT PROJECTS IN THE CORNELL LABORATORY

Recent sponsored research in the Cornell Structural Models Laboratory has been concentrated in three main areas: reinforced concrete shell structures used to roof large buildings, reinforced concrete frames subjected to repeated and reversing overloads, and prestressed concrete pressure vessels for housing nuclear reactors.

A model of a shell roof structure in the form of a hyperbolic paraboloid is shown in the accompanying figure. A number of shells of this configuration and of a cylindrical shape have been studied to assess the effect of varying geometries and internal reinforcing configurations on the ultimate load capacity and hence the safety of the shell roofs. The complex behavior of the hyperbolic paraboloid shell has been clarified and considerable information has been gathered for use in comparing various theories with real results.

Below: A model of a "hypar" shell roof is tested under loading applied vertically to the square load pads visible on the surface. This model is about 30 inches wide.
Right: A model of a prestressed concrete pressure vessel for a nuclear reactor plant.





The research on small-scale frames is aimed at a better understanding of how reinforced concrete framed buildings, such as Hollister Hall on the Cornell Engineering Quadrangle, would perform when subjected to either repeated heavy gravity loads or reversing horizontal loads such as those produced by earthquake accelerations. Extensive preliminary work has been conducted to ensure the validity of the modeling approach, and experiments on multistory frames are now in progress. The frames are designed in accordance with the latest provisions for earthquake-resistant buildings. The experiments should provide substantial information concerning the critical problem of improved design for earthquake loadings. As with the shell model study, parallel analytical development is under way.

Several model studies of prestressed concrete pressure vessels were carried out in conjunction with the Oak Ridge National Laboratory as part of a development program to improve the tech-

"There is simply no substitute for an understanding of how a structure really behaves under the full range of loading, and the best way to acquire such understanding is through a judicious mixture of theory and experimental work."

nology for primary containment of gas-cooled nuclear reactor power plants. The first of these programs involved failure tests of internally pressurized small vessels that were representative of very large prototype vessels. Extensive comparisons were made of results obtained with models of different sizes. Results of model testing were also compared with analytical predictions based on the finite-element method of analysis. The mathematical analysis proved to be adequate for most sections of the vessel at lower levels of internal pressure but inadequate for predicting how the vessel would behave at pressures approaching the ultimate capacity. Subsequent theoretical developments by a number of investigators have at least partially bridged the analytical deficiencies.

A second models study of concrete pressure vessels, conducted under the supervision of Professor Peter Gergely, was aimed at predicting localized stresses and behavior at the anchorage zones of the highly stressed steel tendons which enable the concrete vessels to withstand internal pressures on the order of 1,500 psi.

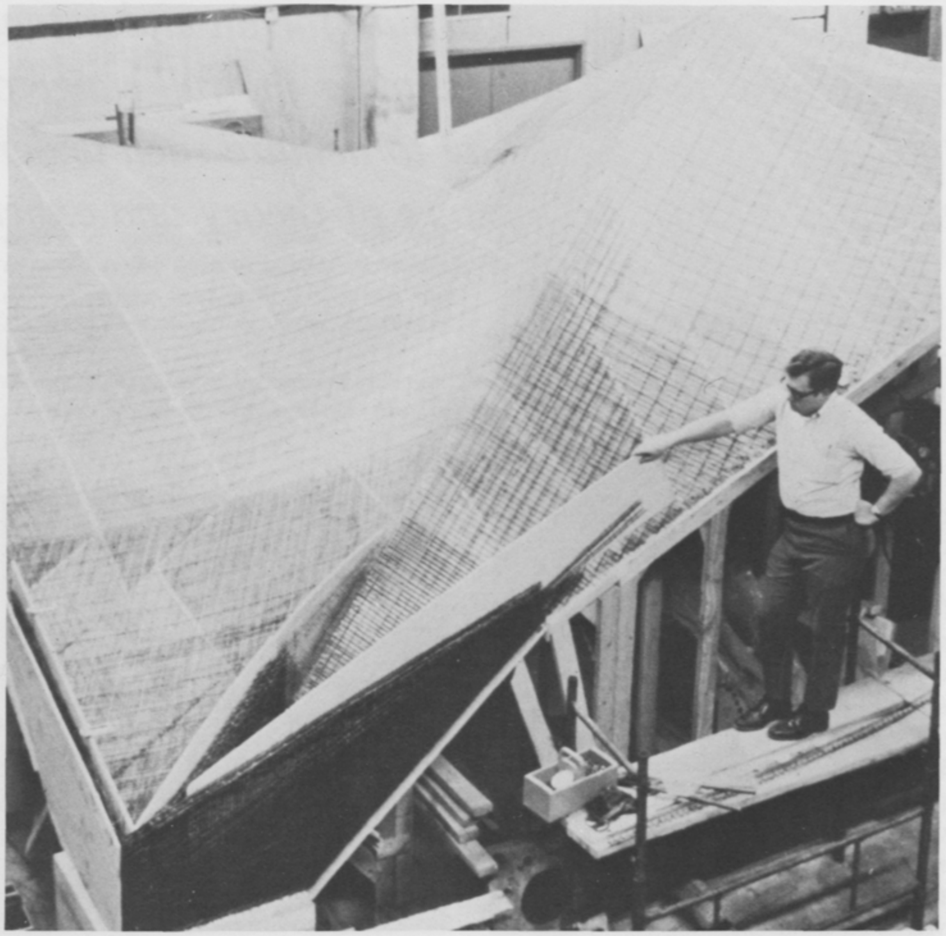
Investigators at other structural models laboratories are studying a wide range of building systems and structural forms, including new types of concrete bridges, unusual slab structures, stayed-cable steel bridges, and shell roofs. Another important area of investigation is the response of high-rise buildings to wind pressures.

MODELING AS PART OF THE DESIGN PROCESS

Structural design is a multistep process that begins with formulation of proposed structural systems suitable for a given situation. The alternate systems are then quickly analyzed by approximate methods to estimate the required sizes of main members, and finally more accurate analysis and proportioning is done on one or more of the alternates. Analysis for forces, stresses, and displacements is usually carried out by setting up and solving a mathematical model of the structure. If this approach is judged to give sufficiently reliable results, it is ordinarily not practical to attempt to supplant the mathematical model with a physical design model because the latter is nearly always more expensive and time-consuming to employ.

It may be found, however, that the mathematical model is simply inadequate to predict the behavior of a complex structural form. In this case, a structural model is an extremely important part of the design process. Physical models are also useful in substantiating supposedly adequate mathematical models to be used in the design of structures whose failure would cause grave consequences to the public.

One of the most publicized recent design models is a 1/10 scale model of the proposed Three Sisters Bridge over the Potomac River. The bridge is to be a large prestressed concrete cellular box structure with a central span of 750 feet; it is substantially larger than any previous construction of this type in the United States. Several questions had been raised about the design; one involved possible instability modes in the thin, curved web elements of the bridge. It was decided to construct and test a model of half



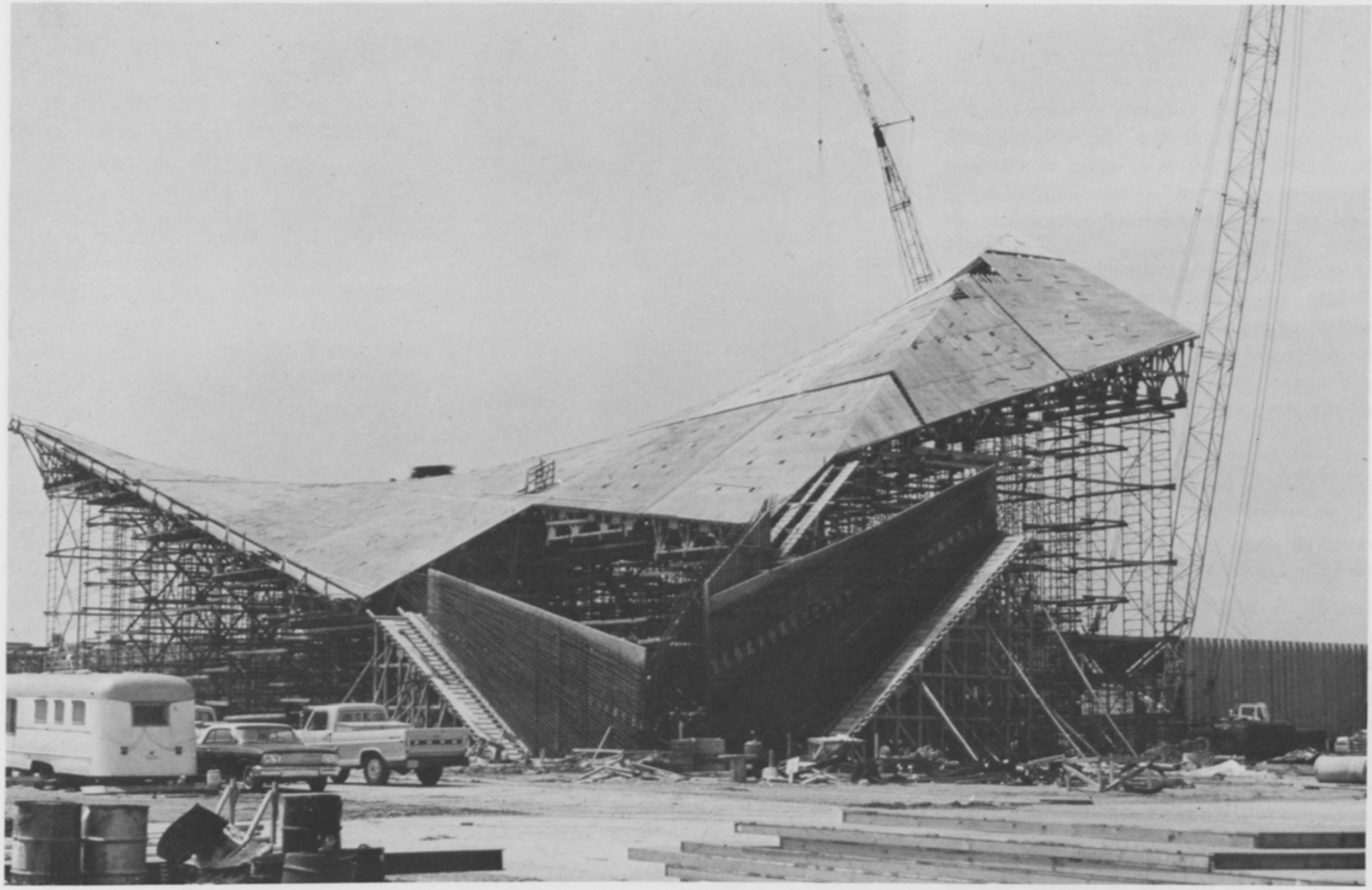
The design of a reinforced concrete jumbo jet hangar in Kansas City involved the building and testing of four models. A 1/10-scale model is shown at right. Opposite page: The prototype "hypar" hangar, shown under construction, is the largest and tallest thin-shell concrete structure of its kind. The building is supported on two corners only. (Photos courtesy of Wiss, Janney, Elstner and Associates.)

of the bridge in the Portland Cement Association Laboratories in Skokie, Illinois. The model was subjected to a large number of different loading conditions and finally loaded to failure with a scaled load representing many times the maximum to which the full-size structure could possibly be subjected. Although the final report on the model has not yet been released, the structural model appears to have performed extremely well and has removed any doubts about the adequacy of the design.

TESTING THE BEHAVIOR OF JUMBO JET HANGARS

The introduction of jumbo jets necessitated the planning and construction of a number of hangar buildings of unprecedented size. An example of one of these important airport facilities is the TWA Overhaul Complex in Kansas City. In addition to many conventional buildings, the complex includes four thin-shelled concrete structures in the form of hyperbolic paraboloids, each of which has a span of 330 feet. The design called for thicknesses of only three inches over much of the shell area, and an intricate system of reinforcing and prestressing in the concrete.

A series of four models was used in arriving at the final design. A 1/500 scale wooden shape model of the complex and a 1/100 scale wooden shape model of one hyperbolic paraboloid hangar building were tested in a wind tunnel to determine wind pressure distribution over the surface. Then a 1/50 scale elastic model of one shell structure was used to determine re-



sponse under dead, snow, and wind loadings. Finally, a 1/10 scale reinforced concrete model of the shell was tested to give additional information on response to wind and snow loadings, as well as to permit determination of the failure capacity and mode.

These models were an integral part of the design process. They produced information on wind pressures that was later used in analytical studies of the shell behavior, and the final large-scale model yielded results that led to changes in the design of portions of the shell.

HOW WILL THE WIND AFFECT THE BUILDING?

The wind-effects model has come into prominence rather recently and is being used in the design of many large exposed structures. Rather strange effects can occur from wind pressures and suctions on buildings and bridges: perceptible building motion in high winds, the falling of glass panels from high-rise buildings, and severe oscillations of bridges have all occurred. In studies of such effects, two types of wind models are utilized—a shape model as described above to establish the character and velocity of the wind flow around the structures, and an aeroelastic model in which the dynamic characteristics of the structure are modeled in order to determine the actual response to winds of prescribed velocity and direction. The shape of the Sears Tower in Chicago, soon to be the world's tallest building, was partially determined by wind tunnel tests.

Structural models are widely used in designing prestressed concrete pres-

A model of the proposed Three Sisters Bridge over the Potomac River was tested under simulated highway loading to verify the adequacy of the design. See discussion on page 15. (Photo courtesy of the Portland Cement Association.)

sure vessels for gas-cooled nuclear reactor power plants. In fact, the British code of practice requires that a model be built and tested for each new vessel design. A 1/4 scale model was used in designing the vessel used in the first United States gas-cooled reactor, now nearing completion in Fort Saint Vrain, Colorado; and a 1/20 scale model was instrumental in perfecting the design concept for the larger 1,100-megawatt-capacity gas-cooled reactors to be built soon in this country.

The use of models in foreign design practice is widespread. Most of the world's major arch dams are modeled in laboratories such as the National Civil Engineering Laboratory in Portugal. In an automated models laboratory recently constructed in Basel, Switzerland, the application of loads and the acquisition and reduction of data are controlled completely by computer. Incidentally, a Cornell graduate student in electrical engineering played a major role in building this system and implementing its operation.

Civil engineering curricula at many universities have evolved into programs containing a great many science and humanities courses. The curricula have become more flexible, with fewer required engineering courses. These developments place rather severe demands on the teaching of upperclass engineers, and the challenge must be met by providing the best possible instruction.

EDUCATIONAL USES OF STRUCTURAL MODELS

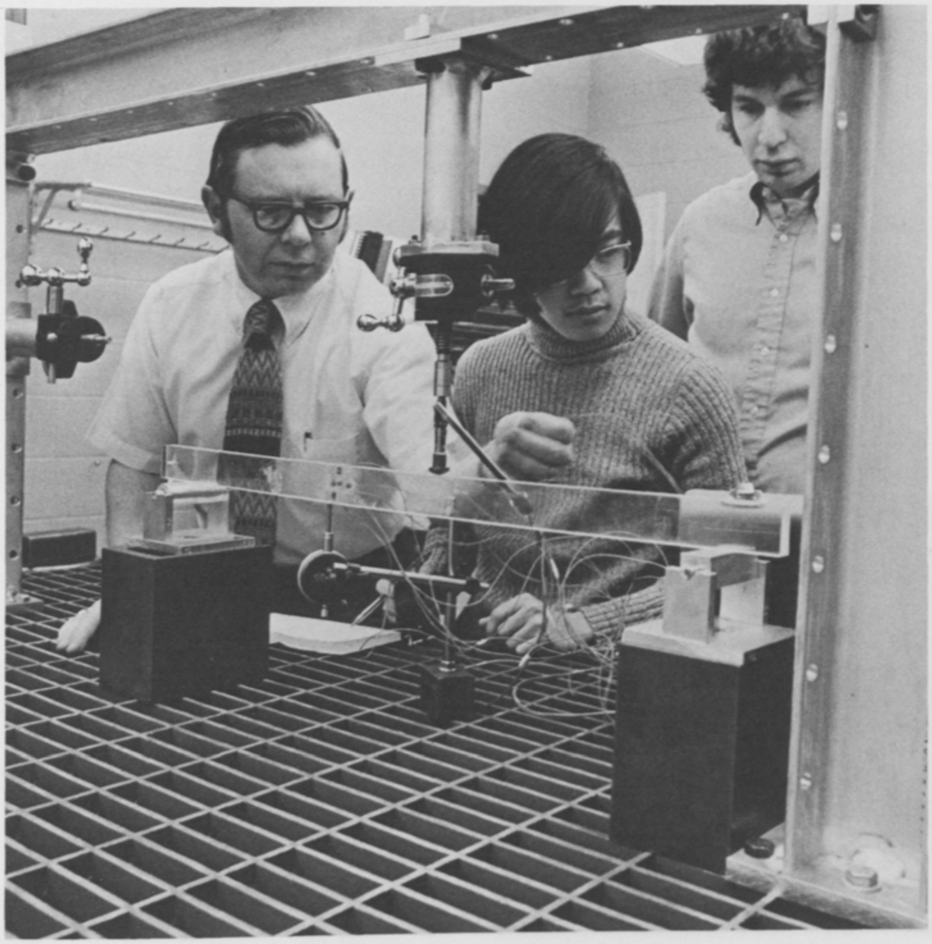
The mathematical sophistication achieved by today's engineering student must be complemented by a sound understanding of the basic physical phenomena involved in his particular field of study. He must appreciate how true physical behavior affects the solution to engineering problems. He must be able to evaluate total performance, including behavior under possible heavy overloads.

Because of the inherent nonlinearities and complexities of the many interacting components in a structure, the analytical approach to structural response is not adequate by itself. There is simply no substitute for an understanding of how a structure really behaves under the full range of loading, and the best way to acquire such understanding is through a judicious mixture of theory and experimental work.

A recently completed addition to the Structural Models Laboratory at Cornell is used exclusively for educating undergraduate and graduate students.

The laboratory experiments are focused on nonlinear and inelastic structural behavior as well as on some of the basic concepts of linear elastic performance. The equipment was designed to accommodate nearly any kind of models experiment and to avoid the type of laboratory environment in which the same experiments must be conducted, year after year, on a rigid basis. A portable version of the laboratory's testing tables is available for classroom demonstration: typical usage is the testing of a reinforced concrete beam or a continuous steel beam during a lecture on the pertinent basic theory.

The first major usage of the laboratory was in the fall term of 1971, when a new undergraduate course called Structural Behavior Laboratory was introduced to complement regular structural engineering courses taken concurrently. In the laboratory course, teams of two students each perform four experiments during the term, selecting one from each of four categories: linear elastic behavior, geometrically nonlinear behavior, inelastic behavior due to nonlinear material response, and structural systems. Small-scale structures are utilized in all experiments. The model structures are relatively easy to fabricate and handle, and place minimal demands on the capacity of loading devices. The validity of using small-scale models for deter-



Undergraduate students are supervised by Professor Richard N. White in performing a creep test in the Structural Models Laboratory. The development of this laboratory was financed by the National Science Foundation and the Olin Equipment Fund of the School of Civil and Environmental Engineering. Available are eight testing tables and associated equipment, most of which was constructed in the civil engineering shop.

mining the complex behavior of reinforced concrete and other types of structures was established in earlier research conducted in the laboratory.

A typical team might begin the term with a study of some basic law of linear structural behavior, such as Maxwell's reciprocal theorem relating displacements and forces at different points on a structure. This would be followed by a study of stability of simple frameworks, with which the effects of different support and restraint conditions can be illustrated so clearly that the underlying concepts are quickly grasped and appreciated. The third experiment might be a series of tests on very small reinforced concrete elements, about one square inch in cross section, in which the ratio of bending action to axial compressive load is varied to produce the complete range of possible failure modes. Finally, the team might select a small project, such as the assemblage of elements, a slab structure, a simple folded plate or shell, or some other structure that they are interested in, and plan and conduct a testing experiment. Each team operates independently and has at its disposal a full complement of loading and measuring devices, including ten channels of strain gage instrumentation.

The same laboratory is used in a senior and graduate course in structural modeling. It can also be used for a limited number of experiments by students enrolled in regular undergraduate structures courses, for independent project work, in freshman minicourses on structural engineering concepts, and in helping to solve design problems met in the upperclass and master-of-engineering design projects.

It is appropriate that modeling should have an important role in education for structural engineering, for it is an intrinsic part of current development and practice. Models are not only highly effective in helping to transmit concepts of structural behavior to students. They also play an important role in extending knowledge of structural action and in the crucial task of improving analytical capabilities. And finally, they are utilized in the design process for a wide variety of structural forms.

Richard N. White, associate professor of structural engineering, has been teaching and conducting research at the College of Engineering since 1961.

His primary research interest is in the use of small-scale structural models for studying the behavior of reinforced concrete structures, and during his years at Cornell he has developed the Structural Models Laboratory and supervised a variety of research projects involving modeling techniques. Special areas of investigation include nuclear reactor containment vessels, shell roof structures, and building frames under overloads and severe loads such as earthquakes and extreme winds.

White holds three degrees in structural engineering, all awarded by the University of Wisconsin: the B.S. in 1956, the M.S. in 1957, and the Ph.D. in 1961. While at Wisconsin, he served as an instructor at the university and as a structural designer for John A. Strand in Madison. He has also had experience in the development of soil-cutting equipment for the Bell Telephone Laboratories, and in research and development of prestressed concrete reactor vessels for Gulf General Atomic, Inc. He has served as a consultant to several organizations, including the Oak Ridge National Laboratories and the Stone and Webster Engineering Corporation. He is registered as a professional engineer in New York State.

Among honors White has received is the 1967 Collingwood Prize, awarded by the American Society of Civil Engineers (ASCE) in recognition of his research on connections for tubular steel structures. His effectiveness as an educator was recognized by the Cornell Society of Engineers, an alumni group, and the honorary society Tau Beta Pi, which awarded him the annual Excellence in Teaching Prize in 1965. He serves as faculty adviser to the Cornell Engineer, *a student publication, and has been active on committees and in a number of special educational activities of the College.*

White, together with College of Engineering professors Peter Gergely and Robert G. Sexsmith, is collaborating on a series of four texts on structural engineering for undergraduate students. The first two volumes of the series, which is being published by John Wiley and Sons, Inc., appeared in early 1972. White has also published extensively in technical journals.

He is a member of ASCE, the American Concrete Institute (ACI), the American Society for Engineering Education, and the Society for Experimental Stress Analysis. He has served in all the offices of the Ithaca section of ASCE and on a number of national technical committees of ASCE and ACI.

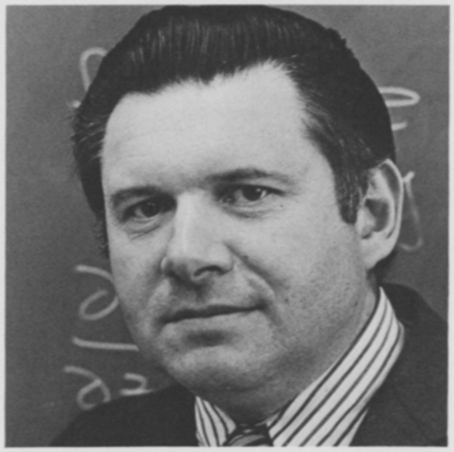
CONSULTING THE COMPUTER

A New Resource for Structural Engineers

By Richard H. Gallagher

Structural engineering design is practiced by thousands of independent organizations across the United States. Certain other disciplines, in contrast, are practiced in a relatively small number of offices by very large staffs; aerospace engineering is one example. Because of the availability of large capital resources in such offices, the computer revolution arrived there quite early, more than ten years ago, but this reorientation of practice is only now reaching fruition in the overall field of civil engineering structural design. The significance of the computer is, however, much greater in structural engineering than in the specialized areas where it made its first impact, simply because of the huge aggregate scale of structural projects.

How has the computer already affected the practice of structural engineering? What are the ways in which it is or could be used, and what are the strengths and weaknesses of computerized techniques? What are the implications for structural engineering education? These are questions of importance to engineers, educators, students—indeed, to everyone, because we all use and perhaps live in structures which required professional engineering analysis before being constructed.



In order to explore these issues, a clear distinction must be made between *structural analysis* and *design*. Analysis is comprised of (1) the calculation of the internal forces and displacements produced by designated loads acting on a structure of tentative proportions, and (2) the comparison of these results with specified allowable values in order to verify the adequacy of the proportions. Design refers to the total process of devising a structure to meet specified functions and goals of performance. Design evolves through iterative application of analysis.

ONE HUNDRED YEARS OF STRUCTURAL ANALYSIS

Procedures used by designers to calculate the strength of proposed structures crystallized by the late nineteenth century and enjoyed a steady but unspectacular development until about 1950. The basis of these methods was the visualization of the structure as a *truss* or *framework* consisting of a grid of one-dimensional members, as shown in Figures 1b and 2a. A difficulty, however, was that the complexity of real structures, especially monumental ones such as bridges of inventive form and arena roofs, outstripped the ability of these procedures to produce analytical models which corresponded directly with the real structure. In consequence, structural design depended upon astute engineering judgment and experience for the formation of relatively simple models of behavior, and this was

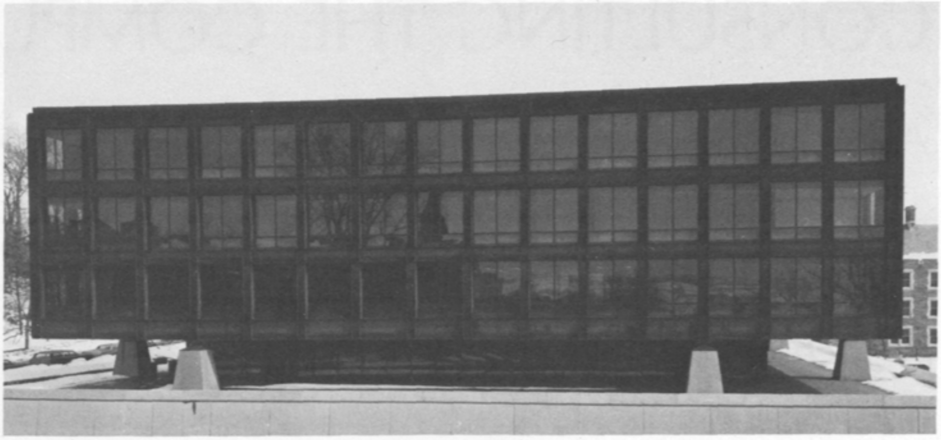
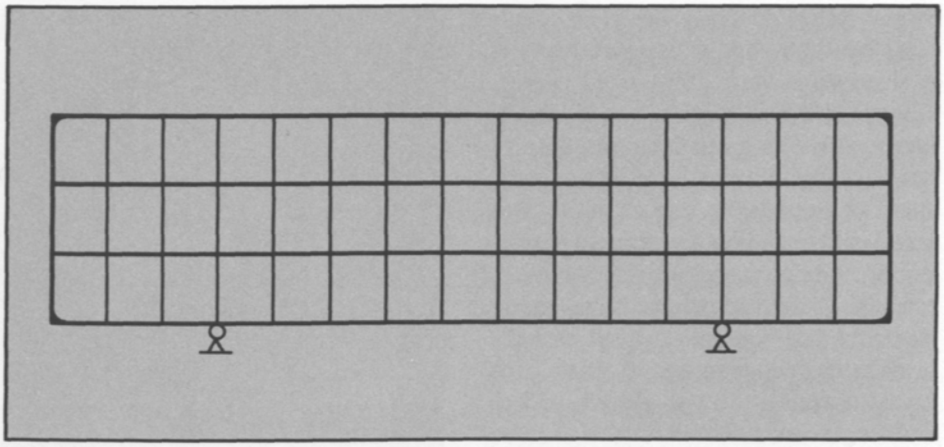


Figure 1a. The new social sciences building on the Cornell campus has exterior structural framing of a type called a Vierendeel truss. Figure 1b (below): This kind of truss is represented for purposes of analysis as a grid of one-dimensional structural members.



coupled with large expenditures of design man-hours.

The workability of this approach has been demonstrated in countless structures which have stirred the public imagination. Here and there, however, the simple models proved inadequate to predict the response of the structure to the actual environment; the Tacoma Narrows Bridge disaster is one prominent example. Also, there are many existing structures that were analyzed in a crude manner and continue to stand only because they were overdesigned. A less obvious deficiency of this approach is the constraint it imposes on the emergence of novel and perhaps more economical or esthetically pleasing structural forms whose behavior defies highly idealized analysis.

IMMEDIATE BENEFITS OF COMPUTER ANALYSIS

A characteristic of these traditional structural analysis procedures is that they involve, as a central requirement, the formulation of simple simultaneous algebraic equations and the solution of these equations for the internal forces and displacements of the structure. When the electronic digital computer was introduced to practitioners some fifteen years ago, it was advertised as a device especially useful for solving algebraic equations, and the equations of structural analysis were fed to it for solution. It was soon found, though, that the computer could also be coded to construct the equations as well as solve them, as long as the basic data pertaining to the design problem were given. As a result, capabilities in the analysis of framework structures expanded almost without limit within a short period of time and virtually without the introduction of any new theoretical concepts.

The structural design of Cornell's new social sciences building demonstrates these expanded analysis capabilities. The exterior surface of the building consists of weathering (or "self-painting") steel members; these serve as an integrated structural grid in which each plane is a type of frame called a *Vierendeel truss* (Figure 1b).

If the design analyst chooses to adopt the most straightforward approach to an analysis of such a structure—an analysis in which each member joining the intersection points of the grid is treated as an entity—the solution of approximately 180 algebraic equations is required. Other ways of setting up the analysis of the frame might result in fewer equations but would require perhaps more effort in their establishment. In the past, therefore, some approximation would have been used in the analysis, for by hand computation the average person would not have sufficient patience to work through more than five equations, and any attempt to solve as many as one hundred would surely fail. With digital computation, however, the truss analysis is completed in a few seconds. Furthermore, it takes account of such previously neglected effects as the stress caused by constrained thermal expansion.

THE FINITE ELEMENT METHOD

Certain dramatic structural forms—shell roofs, folded plates, cellular structures, three-dimensional solids—cannot be analyzed satisfactorily as equivalent frameworks. Similarly, there is a wide range of difficult analysis problems which arise in conjunction with small but structurally important components. Such problems occur, for example, when light-gage steel members (discussed by George Winter elsewhere in this issue) must be designed to account for cutouts or when they are studied in detail for special forms of buckling and inelastic behavior.

Fortunately, the use of such structural forms and members was facilitated by a new analytical technique. A small but enormously significant step easily extended the ideas of framework analysis to "continuum structures," which previously had required the direct solution of partial differential equations for their analysis. This step took the form of the *finite element method*.

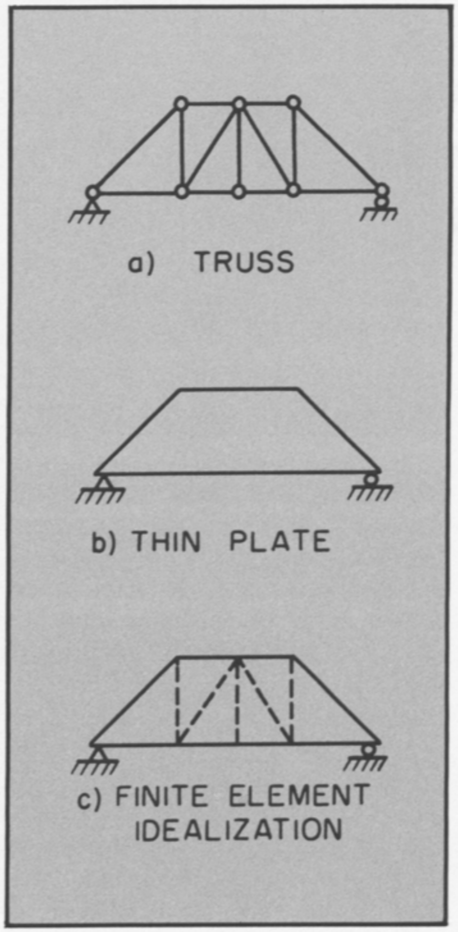


Figure 2. The basis of the finite element method of structural analysis. Traditional framework concepts can be used to analyze a simple truss (a), but are not adequate if the region is covered by a thin plate (b). By the finite-element method, the structural element would be treated as an assembly of finite elements such as the triangles shown in (c). The analysis would be accomplished by computer solution of equations similar in form to those used in conventional framework analysis.

How does this method work? The structures shown in Figure 2 illustrate the concept. Analysis of a truss structure (Figure 2a) is easily accomplished in terms of the traditional framework concepts. But suppose that the region is covered, instead, by a thin plate (Figure 2b): a simple framework is no longer an adequate model. However, if elements in the form of triangles (Figure 2c), instead of bars, were available, the framework analysis concepts—and computer programs as well—could be applied to the plate analysis. This idea is the basis of the finite element method.

In its rudimentary form, then, the finite element method seeks to establish, for various simple shapes and types of structural behavior, relationships that have the same format as the equations used in analysis by the conventional framework concept. The analytical model of the complete structure is an assembly of finite elements put together rather like a Tinkertoy model, except that one deals with input data to a computer instead of with actual little parts of various shapes and functions. The data consist of information about loads, geometry, the properties of the construction material, and the characteristics of the finite element gridwork. As in framework analysis, the computer transforms this information into a system of algebraic equa-

"Computer-aided design can encompass the construction of an analytical model, the display of results, and even the preparation of engineering drawings by computer-driven drafting machines."

tions, proceeds to a solution of the equations, and produces a printout of the predicted displacements and internal forces. Much sophistication has been introduced into the method in the fifteen years since its inception, but the simple view that has been described remains valid for most applications.

COMPUTER PROGRAMS FOR FINITE ELEMENT ANALYSIS

A great advantage of the finite element method is that it lends itself to the development of large-scale general-purpose programs that can be used at any computer facility and can be applied to the analysis of a very wide range of problems. Several such programs have been developed at costs in the range of one to five million dollars. Two of the best known are NASTRAN (*NA*SA *Str*uctural *An*alysis) and STRUDL-II (*Stru*ctural *D*esign *L*anguage).

NASTRAN, developed over the past six years, has virtually unlimited capacity and is perhaps the most versatile engineering analysis computer program in existence. In a recent NASTRAN application, an analysis was performed of the upgraded reflector of the huge Arecibo radar-radio facility operated by Cornell for the National Science Foundation. More than 29,000 equations had to be solved in order to determine the distribution of forms in this cable-suspended structure.

More widely used in civil engineering design practice is the STRUDL-II program, actually a component of the larger ICES (*I*ntegrated *C*ivil *E*ngineering *S*ystem), which was developed originally at MIT. More than four hundred organizations have banded together in a users' group to ensure distribution and upkeep.

BUT ARE THE ANSWERS CORRECT?

Once it is realized that the finite element method permits the solution of problems so complex that no alternative analysis procedures are even remotely applicable, a disquieting question arises. How can one be sure that these results, emerging from a vastly complex computational process, are reliable? Outlandish numerical results can be rejected out of hand and there are simple checks, of course, to detect gross errors. But how does one establish the validity of ostensibly reasonable answers?

Conceptually, a simple way of resolving this dilemma is to perform two finite element analyses of the same structure, in terms of gridworks that have been refined to different degrees. If the results are sufficiently close, the analyst is reassured by this duplication of his answers in independent analyses and can assume that changes which will occur through further grid refinement have no design significance. The difficulty is that a structural engineering form of the so-called "Parkinson's Law" often prevails: the simplest gridwork is already so refined that no resources are available to perform a second, more refined, analysis.

Another approach, which is more promising although even farther from the possibility of practical application, stems from the fact that it is theoretically possible to formulate the finite element approximation in two different, complementary ways. Each of these methods is guaranteed to produce

The NASTRAN computer program for finite-element structural analysis was used in a current project to upgrade the antenna surface of the radar-radio facility at the Cornell-operated National Astronomy and Ionosphere Center in Arecibo, Puerto Rico. Contributing to the complexity of the analysis was the fact that the 18.5-acre reflector surface is slightly irregular because of the cable suspension system (top photo). The wire mesh surface shown is being replaced a section at a time by perforated aluminum panels. The photo below gives an idea of the size and contour of the reflector.

certain solution parameters that are either greater than or less than those of an exact solution. If analyses are performed by both of these alternative methods for a single level of analytical refinement, the results "bracket" the correct solution parameters. The difficulty with this approach is that the solution parameters formulated in this way do not always have design significance: the parameters obtained may not be structurally important ones such as displacement and internal stress. Also, the theory has not been implemented to the extent necessary if it is to be capable of application to any situation. Nevertheless, this avenue toward the validation of computed solutions is one of the most promising and active approaches in finite element research, and applied mathematicians, including a group at Cornell, are working at it intensively.

Since purely analytical procedures for solution validation are not often feasible, at least at the present time, it is logical that experimental verification has assumed new importance. Structural model testing, for example,

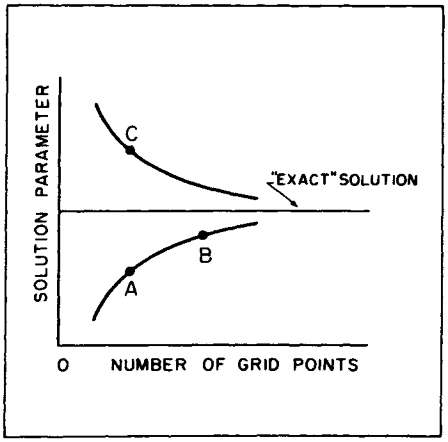


Figure 3. Possible methods of verifying finite element solutions. Points A and B are compared in a method based on two analyses of successively refined gridworks. In an alternate method, points A and C, which "bracket" the theoretical solution, are compared.

is experiencing a renaissance. The laboratory of Cornell's Department of Structural Engineering has in no small measure contributed to this development; Richard N. White reviews this work in this issue of the *Quarterly*. Among the models he discusses is one of a prestressed nuclear reactor structure (see page 14). This type of structure, which presents unprecedented design problems, provides an example of how two very different, but often complementary, approaches can be applied at this point in the development of structural engineering analysis. The stress in this structure is fully three-dimensional (no simplifying assumptions are possible) and finite elements in the form of tetrahedra or hexahedra (Figure 4) are appropriate to the problem. Even with the recognition of certain symmetries which permit treatment of only an octant, more than five thousand unknowns are represented. The analysis encompasses response to such factors as applied pressure loads, prestressing, and thermal strains. Analyses of this type are performed routinely, on a daily basis, at dozens of large design offices.

It is important to note that the success of these analyses depends partly on the use of automatic "mesh generation" programs, into which the analyst feeds only the barest data. The computer then defines and identifies individual finite elements and their connection points. The implications of further automation are indeed significant, because as computerized structural analysis has grown more efficient, its share of the total costs of design analysis has contracted. A recent study at a large industrial design organization disclosed that computer operations accounted for only 10 percent of the total design analysis expense. The major portion was divided among the functions of input data preparations and the interpretation of output. The greatest potential for economy in design analysis lies in the increased computerization of these functions.

FROM ANALYSIS TO DESIGN

An important engineering goal, from an economic as well as a technical standpoint, is optimality in design, and analysis is a factor in the achievement of optimal design, especially when the increased speed and lower cost of computerized analysis permit rapid successive analyses of continually improved designs. A problem is that in most cases the latitude given by increased efficiency in computerized structural analysis has nearly always been taken up by an increase in the sophistication and refinement of a single analysis. There are now signs, however, that a plateau is being reached in the degree of refinement sought, and the resources made available through efficiencies in analysis are more likely to be directed to the design process.

The meaning of "optimality," as applied to structural design, requires clarification. Minimal cost is generally of paramount concern, although for certain structures, notably aerospace vehicles, the highest premium is placed on minimal weight. Reliability of performance may also be a primary objective. For the most part, practicing structural designers adopt the view that an optimum design is one in which each structural component sustains its full allowable load under at least one of the anticipated loading conditions, an approach known either as the "fully stressed" or the "one-hoss-shay" * design philosophy. The structural proportions arrived at on this basis cannot be the same as those associated with minimum cost or weight and at the same time be those associated with maximum

* *A terminology drawn from the paragon of structural excellence described by Oliver Wendell Holmes in his poem, "Have you heard of the wonderful one-hoss shay, / That was built in such a logical way / It ran a hundred years to the day, / and then, of a sudden . . . it went to pieces all at once. . ."*

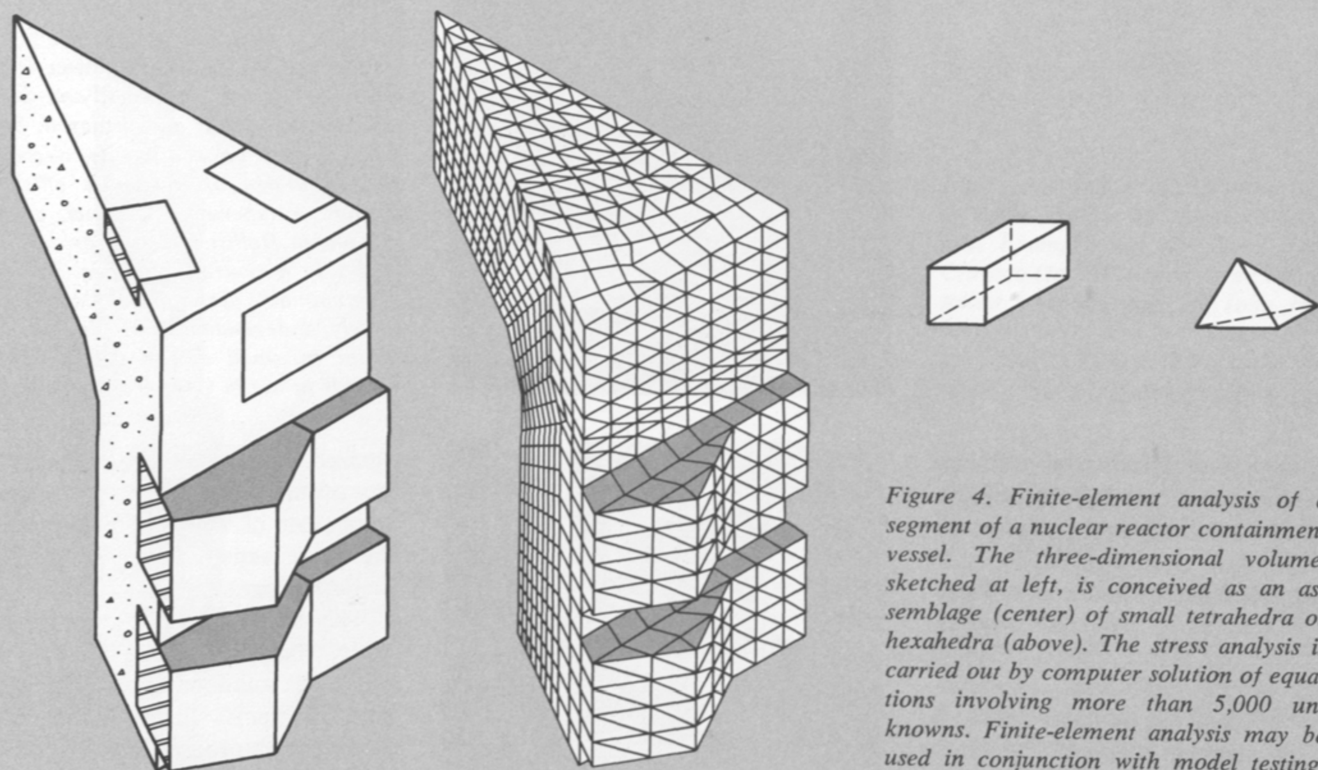


Figure 4. Finite-element analysis of a segment of a nuclear reactor containment vessel. The three-dimensional volume, sketched at left, is conceived as an assemblage (center) of small tetrahedra or hexahedra (above). The stress analysis is carried out by computer solution of equations involving more than 5,000 unknowns. Finite-element analysis may be used in conjunction with model testing; a photograph of a model of this same vessel is shown on page 14.

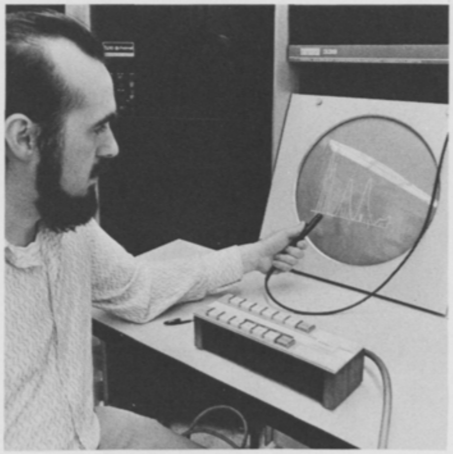
reliability; generally they do not correspond to any of these criteria. Fortunately, the difference between fully-stressed design and that which meets a specified goal of optimality is often small.

Two computer-related technologies have emerged during the past decade to meet the challenge of optimality in structural design. One is *computer-aided design,* and the other is the use of theoretical procedures founded in the concepts of *mathematical programming*. Each has moved along a path of independent development and, since neither has as yet made widespread impact in practical structural design, their confluence to form an integrated tool is still a long way off.

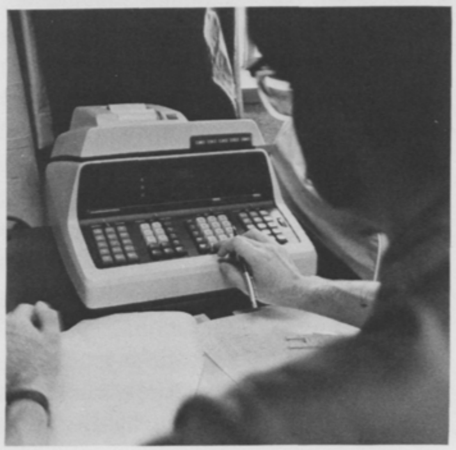
TALKING TO THE COMPUTER

The techniques of computer-aided design place at the disposal of the designer a mode of communication with the ongoing computational process. With the use of a cathode-ray tube device or oscilloscope, for example, a designer can obtain a visually displayed analysis of his design in a very short period of time. He can manipulate his design on the basis of this knowledge—perhaps change the proportions of one or more members of the structure—and have it reanalyzed almost instantly. With the use of this technique, the design process converges rapidly.

The typewriter terminal, a more mundane and considerably less expensive device, is directly competitive with the cathode-ray tube device in certain design situations. This type of terminal, connected directly to a central com-



Three ways of "talking to the computer" are illustrated at left. Above: When the light pen is touched to the face of the oscilloscope, an analysis sequence is activated within the computer, and almost instantly the results are displayed. Specifications can be continually altered to yield a design of maximum efficiency. Center: A typewriter terminal, such as this one in Hollister Hall, provides direct access to a central computer. Below: A programmable desk-top calculator, a completely independent unit, is especially useful in small design offices. One of these is in use in Cornell's Thurston Hall.



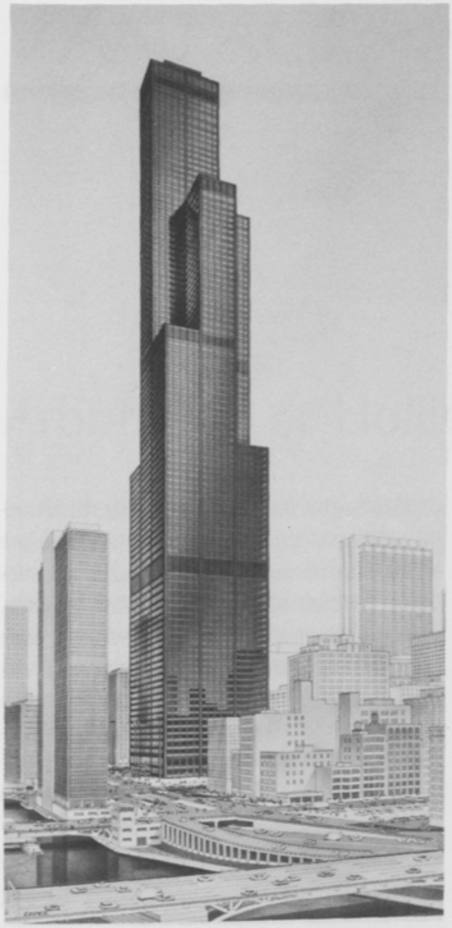
puter, is preferred for large problems with small input-output data requirements and relatively few design variables.

A device at the lowest level of hardware in interactive electronic computation, but one whose impact in small design offices has been enormous within the past two or three years, is the programmable desk-top calculator. This completely independent device, driven by electricity from a wall socket, costs in the range of $1,200 to $5,000. Besides being easily programmable, it is capable of storing a program sufficient to analyze a design whose elements approach the complexity of a Vierendeel truss.

The potential of computer-aided design extends, however, far beyond the purely imput function. Computer-aided design can encompass the construction of an analytical model, the display of results, and even the preparation of engineering drawings by computer-driven drafting machines.

The emergence of new industries as a consequence of the evolution of the electronic digital computer is well recognized. A parallel phenomenon that has occurred in technology is the development of new disciplines, one of the most active of which is mathematical programming.

This methodology, couched in algebraic, computer-oriented terms, seeks optimum solutions to engineering design problems. In its most familiar form, linear programming, it provides a routine tool for economic as well as technological decision-making processes, when all relationships can be expressed as linear functions of the quantities to be decided upon. For structural design problems, however, it is generally necessary to express the relationships as nonlinear functions of pertinent quantities, and the vastly more complex techniques of nonlinear programming are required. Also, mathematical programming methods are not yet capable of dealing with all the pertinent variables at once. There has been some success in limited problems such as the determination of member sizes in the minimum-weight design of small-scale structures with fixed overall configuration and preselected material.



Innovative design of high-rise buildings is made possible by computerized methods. Examples are the Sears Tower in Chicago (far left), soon to be the world's tallest building, and the John Hancock building (left), also in Chicago. An exciting feature of this building is the visibility of its basic structural elements.

A major difficulty in the effective utilization of mathematical programming in structural design for minimum cost or weight is the plethora of available procedures. It is difficult for a practitioner to determine the most appropriate approach to his particular problem. A disorganized sorting-out of alternatives, based on results obtained by many individual researchers, is in progress, however. It is entirely possible that experience will show that procedures less complicated than mathematical programming are often valid.

WILL THE STRUCTURAL DESIGNER'S CREATIVITY BE LOST?

Despite the remarkable progress that has been made in computerized structural analysis, the technique is far from reaching the limits of its applicability. One might question whether the anticipated extension of automation in design will lead to a loss in creativity. The answer is no, primarily because the elimination of routine calculation can free engineers to devote more time and talent to such concerns as esthetics, function, economics, and serviceability.

The evolution of new forms of tall-building design illustrates this point. Fazlur Khan, who was selected by *Engineering News-Record* as the 1972 Construction's Man of the Year, has investigated many new types of structural systems for high-rise buildings during the past decade. These studies produced the cross-braced tubular concept used in the design of the John Hancock building in Chicago, and more recently the multitubular concept used for the new Sears Tower in the same city. These striking and original structures depended on the comparison of many design alternatives, a process that would have been impossible with noncomputerized methods.

IMPLICATIONS FOR EDUCATIONAL PROGRAMS

Concomitant with the expansion in the scope of creativity is an expansion of the responsibilities of the structural designer. First, he must be able to recognize when to use the more expensive computational procedures and when to rely on more economical and often quite adequate traditional methods. Second, he must have an understanding of a broader range of subject matter than was required in the past. For example, in order to take advantage of the versatility of finite element analysis, the practitioner must have some comprehension of relevant fundamental concepts such as the theory of elasticity, numerical analysis and computer programming, the characteristics of new structural materials, and such special phenomena as buckling, plasticity, and dynamic response. Finally, the structural designer must supplement his understanding of this subject matter with an ability to interpret properly the results of an analysis.

At Cornell today, these challenges are being met in an integrated undergraduate and graduate program. Undergraduates are provided with instruction in the behavior of structures, design of steel and concrete structures, and the theory of structural analysis. Computer analyses reinforce their understanding of the basics. Graduate students generally avail themselves of course work in finite element analysis early in their program of study, and the theory of optimum structural design attracts students approaching the completion of their graduate work. The scope of instruction in the decision-making aspects of design analysis has been widened; but here, inevitably, substantive capability emerges only from application in engineering practice. For instruction is only part of the process of developing good design analysts. Even—or especially—in a computer era, there is no substitute for experience.

Richard H. Gallagher, professor of structural engineering, has been chairman of the department for the past two years and a member of the Cornell faculty since 1967.

Gallagher has not only an academic background, but the experience of seventeen years in structural engineering practice as well. Before coming to the University, he spent twelve years with the Bell Aerosystems Company.

His first professional experience was a two-year period of service as a civil engineer with the Civil Aeronautics Administration, following his graduation in 1950 from New York University with the degree of Bachelor of Civil Engineering. From 1952 to 1955, while studying for his master's degree, also at NYU, he worked as a structural designer for Texaco, Inc., in New York City. He studied for a Ph.D. in structural engineering at the State University of New York at Buffalo during the years he was employed by Bell, and was awarded the degree in 1966.

Of major research interest to Gallagher at the present time is finite element analysis, and he is interested in the overall application of computer techniques in structural engineering and has written a number of papers on that subject. Early this year he served as program coordinator for the International Symposium on Computers in Optimisation of Structural Design, held at the University of Wales. Several years ago he organized and was the United States chairman of a U.S.A.–Japan Seminar on Matrix Methods of Structural Analysis and Design.

Gallagher is the author of Correlation Study of Matrix Structural Analysis *(Pergamon Press, 1964), and of numerous technical papers. He is co-editor of the* International Journal for Numerical Methods in Engineering.

He has served as a consultant to several industrial firms and is a licensed engineer in New York State. He is a member of the American Society of Civil Engineers, the American Institute of Aeronautics and Astronautics, the Society for Experimental Stress Analysis, the International Association for Bridge and Structural Engineering, and the American Concrete Institute.

VANTAGE

Arbor Day at Hollister Hall

Hollister Hall has a new sugar maple on its front lawn—a living example of conservation practice provided, appropriately, by the environmental engineering people at the College.

"Save a Tree," a paper-salvage project, was started last spring by environmental engineering graduate students under the leadership of Chip Lawrence, and by Arbor Day this year had yielded enough capital to finance the purchase of the tree. Members of the graduate student group decided to make their tree-planting ceremony a part of the University Arbor Day festivities which initiated a campaign for campus beautification.

The project involves Hollister Hall students, faculty, and staff members, who save the paper, collect it, and deliver it to a local salvage company. According to graduate student Joel Brainard, who is now heading the campaign, nobody seems to mind the extra effort because "it is the right thing to be doing."

Profits from the venture, about four or five dollars a month, have not been exactly overwhelming. Brainard feels, however, that such an operation on a larger scale, such as on a university-wide basis, could at least pay its own way through more efficient operations and improved business arrangements.

The Hollister Hall environmentalists hope that their project will help call attention to the overall need for conservation of resources, even if it is not immediately financially advantageous. Practices such as paper recycling must become widespread eventually, Brainard said, but they may develop very slowly unless "the structure of our economy is given a push." He feels that comprehensive planning, encompassing such factors as the optimal location of paper companies for reprocessing as well as for tree cutting, could result in workable conservation procedures.

So far the local project has saved an estimated fifty-five trees. This may be a small contribution to anti-pollution and forest conservation efforts, but it is a push in the right direction.

Hollister Hall secretaries throw the first shovelfuls of dirt while Walter R. Lynn, director of the School of Civil and Environmental Engineering, stands by.

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1. The "Save a Tree" project begins with the collection of scrap paper in special containers placed in offices and near the mail boxes. A preliminary feasibility study conducted by the student sponsors indicated that white paper would be the most suitable for collection under local conditions. 2. Clyde S. Stevens, head custodian, collects the saved paper on his regular rounds. Others on the Hollister Hall custodial staff who have helped in the project are Edith E. Hurd, Reed E. Knettles, and James A. Courtney. 3. Administrative secretary Genevieve Smith contributes to the collection box in the office of the School director. 4. Graduate student Joel Brainard loads containers of salvaged paper for delivery to the processing plant. 5. The paper is weighed in at Ithaca Scrap Processors. 6. The sugar maple purchased with project proceeds arrives in front of Hollister Hall for its Arbor Day planting. The tree in the background is probably doomed by the Dutch elm disease. 7. Coordinated effort is required to lower the maple into place. Indeed, according to project sponsors, cooperation characterizes a project of this kind at every step and is the most necessary factor for success.

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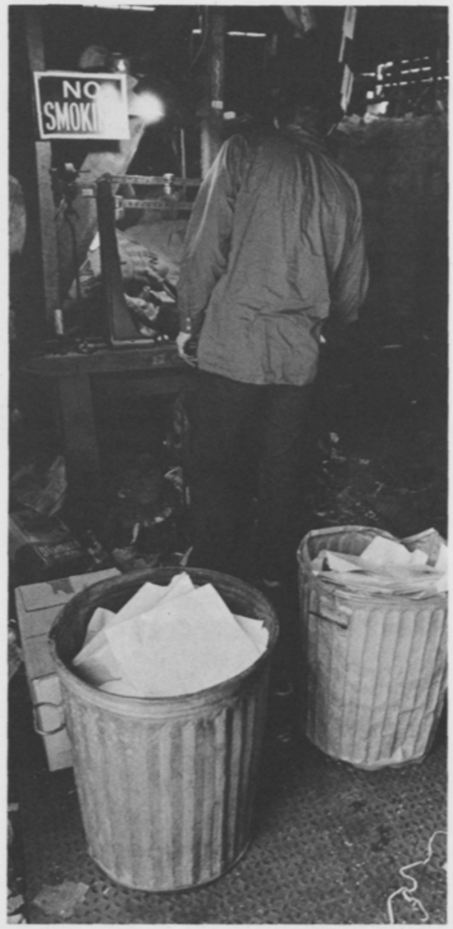

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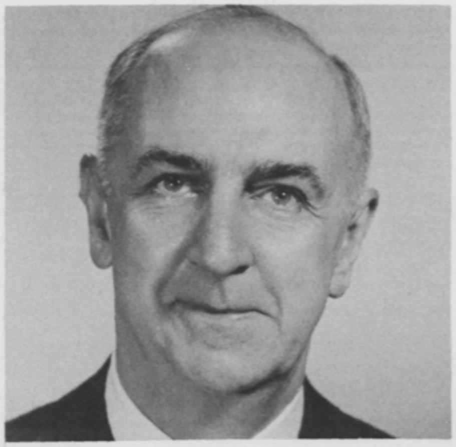
REGISTER

Two members of the College of Engineering faculty who began their Cornell teaching careers at almost the same time more than forty years ago will become professors, emeritus, when they retire at the conclusion of the current academic year. The Quarterly *presents brief biographical sketches of Howard N. Fairchild and Trevor R. Cuykendall in recognition of their long and distinguished service to the College.*

■ It was in 1930 that *Howard N. Fairchild* joined the Cornell faculty as an instructor in heat power engineering. The University was not new to him, however; he had just graduated from Cornell as an Electrical Engineer and had completed work for the Cornell degree of Mechanical Engineer in 1929. Except for a two-year period early in his career, when he was an instructor in the Department of Mechanical Engineering at Pennsylvania State College, he has taught thermal engineering at Cornell continuously since his initial appointment.

Fairchild progressed from his post as instructor to become a full professor.



His title of professor of mechanical engineering, emeritus, effective in July, was awarded by the University's Board of Trustees.

Fairchild is regarded at the Sibley School of Mechanical Engineering as the authority in the Department of Thermal Engineering in the area of thermal technology. He offers senior and graduate-level courses in such subjects as refrigeration, air conditioning, and combustion engines. He has been particularly effective in developing the program leading to the professional degree of Master of Engineering (Mechanical).

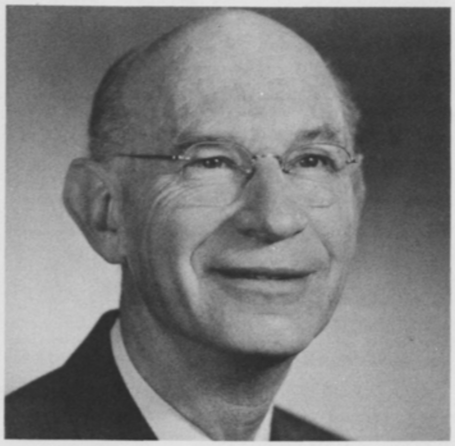
During the years of World War II, Fairchild was assigned to the Naval Training School that was established at Cornell, and took charge of classroom and laboratory instruction in Diesel engines. During his Cornell tenure, he also served the United States government as a consultant or visiting professor in two national laboratories. These appointments were in the Department of Reactor Science and Engineering of Brookhaven National Laboratory, and in the Experimental Reactor Division of Oak Ridge National Laboratory.

His industrial experience includes work during several successive summers with the Babcock and Wilcox Company as principal investigator in a project on heat transfer and flow. He spent an academic leave and two summers with the Westinghouse Electric Corporation, developing test facilities for heat pumps, heat exchangers, and air conditioning systems. He is a licensed professional engineer in New York State.

■ *Trevor R. Cuykendall,* the Spencer T. Olin Professor of Engineering, first came to Cornell in 1929 as an instructor in physics, and has continued his association with the University throughout his career. He is especially noted for his contributions to the development of the undergraduate program in engineering physics and the graduate program in nuclear science and engineering.

Cuykendall, a native of Colorado, came to Cornell from the University of Denver, where he earned a B.S. degree in electrical engineering and an M.S. in physics. (In 1962 he was awarded that university's Distinguished Alumnus Award.) He completed work for a Cornell Ph.D. in physics and mathematics in 1935, served as a research associate in engineering, and then was appointed an assistant professor of engineering in 1939.

His early research activities—such as in the development of thin-gage steel as a structural element, the study of stresses in earth dams by photoelastic methods, and the measurement of soil moisture and density by radiation scattering—formed a link between physics and engineering.



During World War II he was associated with the Naval Ordnance Laboratory and the Los Alamos Scientific Laboratory, and after returning to Cornell in 1946 he continued his activities in the area of nuclear science and engineering. He helped introduce the curriculum in engineering physics and initiated the University's first course in nuclear engineering. He served successively as director of the Department of Engineering Physics, as associate director of the Department of Engineering Physics and Materials Science, and as Director of the School of Engineering Physics, which was consolidated in 1971 into the present School of Applied and Engineering Physics.

He was appointed to full professorship in 1949, and in 1966 was named the Spencer T. Olin Professor of Engineering, a title he will retain in his emeritus status.

Cuykendall has been a consultant to the Division of Education of the Atomic Energy Commission (AEC), and has been active on a number of committees of the American Society for Engineering Education (ASEE) concerned with nuclear science and engineering. He has directed several summer faculty institutes sponsored by ASEE and AEC. He is a fellow of the American Physical Society and a member of the American Nuclear Society, the American Association of University Professors, ASEE, and the honorary societies Tau Beta Pi and Sigma Xi. He has published a number of papers in the fields of applied physics and engineering.

■ A 1972 recipient of the College's Engineering Award is *Thomas J. Kelly,* vice president of the Grumman Aerospace Corporation and deputy director of Grumman's Space Shuttle Program, and a 1951 Cornell graduate in mechanical engineering.

Kelly's award, "in recognition of achievement lending distinction to the College," is represented by a silver medal presented at the spring meeting of the Engineering College Council on May 5 in Ithaca.

The award to Kelly is the first of a number the College expects to grant to distinguished alumni, according to Dean Andrew Schultz, Jr. The Engineering Award was established last fall as part of the College's centennial-year observations. The initial group of fifteen recipients were recognized for support of the College and for contributions to its development.

Kelly, who became known as "Mr. LM" during his work with the National Aeronautics and Space Administration on the Grumman lunar module, had responsibility for all spacecraft engineering work on the vehicle. He participated in the Apollo Spacecraft program at Grumman from the time of its inception in 1960.

Before beginning his work with the Apollo program, Kelly was a propulsion engineer for Grumman missile and aircraft programs, and he worked with Lockheed in space propulsion system development. He served as a first lieutenant in the United States Air Force from 1956 to 1960, working in the capacity of performance engineer.

After completing his undergraduate studies at Cornell, Kelly earned the Master of Science degree in mechanical engineering at Columbia University in 1956. He took additional graduate work at Ohio State University and the Polytechnic Institute of Brooklyn, and in 1970 earned a master's degree in industrial management as a Sloan Fellow at MIT. He is a member of the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, and several honorary societies. In 1971 he was elected a fellow of the American Astronautical Society.

FACULTY PUBLICATIONS

The following publications and conference papers by faculty members and graduate students of the Cornell College of Engineering were published or presented during August, September, and October 1971. The names of Cornell personnel are in italics.

■ AEROSPACE ENGINEERING

George, A. R., and *Seebass, A. R.*, 1971. Sonic boom minimization including both front and rear shocks. *AIAA Journal* 9(19): 2091–3.

Koch, W., *Ludford, G. S. S.*, and *Seebass, A. R.*, 1971. Diffusion in shear flow past a semi-infinite flat plate. Part II: Viscous effects. *Acta Mechanica* 12: 99–120.

■ AGRICULTURAL ENGINEERING

Heald, W. R., and *Loehr, R. C.* 1971. Utilizing agricultural wastes. In *1971 yearbook of agriculture*, pp. 299–304. Washington: United States Department of Agriculture.

Loehr, R. C. 1971. Liquid waste treatment: I. Fundamentals. II. Oxidation ponds and aerated lagoons. III. Oxidation ditch. In *Proceedings of the Cornell Agricultural Waste Management Conference*, pp. 54–79. Ithaca: Cornell University.

———. 1971. Poultry Waste Management. Paper read at National Symposium on Animal Waste Management, September 1971, at Warrenton, Virginia.

———, Anderson, D. F., and *Anthonisen, A. C.* 1971. An oxidation ditch for the handling and treatment of poultry waste. In *Livestock Waste Management and Pollution Abatement*, ASAE publication PROC-271, pp. 73–6. St. Joseph, Michigan: American Society of Agricultural Engineers.

Stensel, H. D., *Loehr, R. C.*, and *Lawrence, A. W.* 1971. Biological Kinetics of the Suspended Growth Denitrification Process. Paper read at 44th Annual Conference of the Water Pollution Control Federation, 5 October 1971, in San Francisco.

■ APPLIED AND ENGINEERING PHYSICS

Abermann, R. J., and *Yoshikami, D.* (associates of *B. M. Siegel*). 1971. Binding of Transfer RNA to Carbon Films for Electron Microscopy: A Quantitative Approach. Paper read at 29th Annual Meeting of the Electron Microscopy Society of America, 9–13 August 1971, in Boston.

Ast, D. G. 1971. Optical simulation of the origin of contrast in the electron microscope. *American Journal of Physics* 39: 1164–8.

Cady, K. B., and Shani, G. 1971. Neutron waves in a reflected reactor. In *Transactions of the American Nuclear Society 1971 winter meeting*, p. 866. Hinsdale, Illinois: American Nuclear Society.

Chaudhari, P., Herd, S., *Ast, D. G.*, Brodsky, M., and Gutfeld, R. V. 1971. The structure of laser written lines in a $Te_{81}Ge_{15}As_4$ glass. IBM research report RC 3543 (no. 16015). Yorktown Hts., New York: International Business Machines Corporation.

Demuth, J. E., *Tong, S. Y.*, and *Rhodin, T. N.* 1971. Absolute Intensity-Energy LEED Spectra for Clean Ni(001) Surfaces. Paper read at 1971 International Conference on Solid Surfaces, 11–15 October 1971, in Boston.

Hartman, P., *Loh, E.*, and *Trudeau, J.* 1971. Another method for the determination of "c". *American Journal of Physics* 39(8): 877.

Ignatjevs, A., *Rhodin, T. N.*, *Tong, S. Y.*, Lundqvist, B. I., and Pendry, J. B. 1971. LEED spectra study of temperature effects in crystalline xenon surfaces. *Solid State Communications* 9: 1851–5.

Riddle, G. H. N., and *Siegel, B. M.* 1971. Thin Phrolytic Graphite Films for Electron Microscope Substrates. Paper read at 29th Annual Meeting of the Electron Microscopy Society of America, 9–13 August 1971, in Boston.

Webb, W. W. 1971. Magnetometers and Interference Devices. Paper read at Georgetown Summer Conference on Superconductivity, 24–27 August 1971, at Georgetown University, Washington, D.C.

———, *Strait, S. F.*, and *Buhrman, R. A.* 1971. Stable superconducting point contact weak links. *Journal of Applied Physics* 42: 4527–8.

Yoshidami, D., and *Abermann, R. J.* (associates of *B. M. Siegel*). 1971. Qualitative and Quantitative Analysis of tRNA with the Electron Microscope. Paper read at 29th Annual Meeting of the Electron Microscopy Society of America, 9–13 August 1971, in Boston.

■ CHEMICAL ENGINEERING

Dabes, J. N., *Finn, R. K.*, and Wilke, C. R. 1971. Equations of Substrate-Limited Growth: The Case for Blackman Kinetics. Paper read at 21st Canadian Chemical Engineering Conference of the Canadian Society for Chemical Engineering, 12–15 October 1971, in Montreal.

Edwards, V. H. 1971. How to invent for fun and profit or the genesis of some novel separation techniques, part 2. *Chemical Technology* 1: 425–31.

Harriott, P. 1971. Kinetics of vinyl acetate emulsion polymerization. *Journal of Polymer Science* A-1 9: 1153.

———. 1971. Surface reactions with non-equilibrium adsorption. *Journal of Catalysis* 22: 266.

Klugherz, P. D., and *Harriott, P.* 1971. Kinetics of ethylene oxidation on a supported silver catalyst. *AIChE Journal* 17: 896.

Michot, G., and *Wiegandt, H. F.* 1971. Countercurrent liquid-liquid extraction in a rotating multiple helix. *I and EC Process Design and Development* 10(4): 586–92.

Morgan, M. S., and *Edwards, V. H.* 1971. Simulation of the effects of temperature on microbial cell propagators. In *Advances in bioengineering,* ed. R. G. Buckles, *Chemical Engineering progress symposium series,* vol. 67, no. 114, pp. 51–8. New York: American Institute of Chemical Engineers.

■ CIVIL AND ENVIRONMENTAL ENGINEERING

Bereano, P. L. 1971. One Approach to Technology Assessment in Universities—the Cornell Program. Paper read at Conference on Technology Assessment: Management, Manpower and Methodologies, sponsored by the Engineering Foundation, 30 August–3 September 1971, in Andover, New Hampshire.

Bisogni, J. J., and *Lawrence, A. W.* 1971. Relationships between biological solids retention time and settling characteristics of activated sludge. *Water Research* 5(9): 753–64.

Buyukozturk, O., *Nilson, A. H.*, and *Slate, F. O.* 1971. Stress-strain response and fracture of a concrete model in biaxial loading. *ACI Journal* 68(8): 590–9.

Gallagher, R. H. 1971. Survey and evaluation of the finite element method in fracture mechanics analysis. In *Proceedings of the international conference on structural mechanics in reactor technology,* ed. T. Jaeger. Luxembourg: Commission of the European Communities.

———. 1971. Trends and Directions in the Applications of Numerical Analysis. Paper read at the ONR Symposium on Numerical and Computer Methods in Structural Mechanics, 8–10 September 1971, at the University of Illinois, Urbana.

———, and *Dhalla, A.* 1971. Direct flexibility finite element elasto-plastic analysis. In *Proceedings of the international conference on structural mechanics in reactor technology,* ed. T. Jaeger. Luxembourg: Commission of the European Communities.

———, *Lien, S.*, and *Mau, S.* 1971. Finite element plate and shell pre- and post-buckling analysis. In *Proceedings of the third Air Force conference on matrix methods in structural mechanics.* Dayton, Ohio: U.S. Air Force.

———, and Mallett, R. 1971. Efficient solution processes for finite element analysis of transient heat conduction. *Journal of Heat Transfer* 93: 257–63.

Lawrence, A. W. 1971. Design of wastewater treatment systems to satisfy effluent quality requirements based on intended use. Technical report no. 33 of the Cornell University Water Resources and Marine Sciences Center for the Office of Water Resources Research, U.S. Department of the Interior, project A-016-NY.

———, and Milnes, T. R. 1971. Biokinetic Approach to Activated Sludge System Design. Paper read at 162nd National Meeting of the American Chemical Society, 13 September 1971, in Washington, D.C.

Milnes, T. R., and *Lawrence, A. W.* 1971. Dynamic Modeling of the Completely Mixed Activated Sludge Process: Laboratory and Mathematical Studies. Paper read at 44th Annual Conference of the Water Pollution Control Federation, 5 October 1971, in San Francisco.

Slate, F. O., and Meyers, B. L. 1971. Some physical processes involved in creep of concrete. In *Proceedings of Southampton 1969 civil engineering materials conference,* ed. M. Te'eni, pp. 769–73. London: Wiley-Interscience.

Verma, R. D., and *Brutsaert, W.* 1971. Similitude criteria for flow from unconfined aquifers. *Proceedings of the ASCE, Journal of Hydraulics Division* 97: 1493–1509.

———, and ———. 1971. Unsteady free surface ground water seepage. *Proceedings of the ASCE, Journal of Hydraulics Division* 97: 1213–29.

Wahla, M. I., *Scott, N. R.*, and *Nilson, A. H.* 1971. Direct measurement of bond-slip in reinforced concrete. *ASAE Transactions* 14(4): 762–7.

White, R. N., *Chowdhury, A.*, and *Chang, T. C.* 1971. Behavior of Reinforced Concrete Structures under Repeated and Reversing Overloads. Paper read at ASCE Environmental Engineering Conference, 18–22 October 1971, in St. Louis, Missouri.

Yeh, G. T., and *Brutsaert, W.* 1971. A numerical solution of the two-dimensional steady-state turbulent transfer equation. *Monthly Weather Review* 99: 494–500.

———, and ———. 1971. Sensitivity of the solution for heat flux or evaporation to off-diagonal turbulent diffusivities. *Water Resources Research* 7: 734–5.

———, and ———. 1971. A solution for simultaneous turbulent heat and vapor transfer between a water surface and the atmosphere. *Boundary Layer Meteorology* 2: 106–24.

■ COMPUTER SCIENCE

Bunch, J. R. 1971. Equilibration of symmetric matrices in the max-norm. *Journal of the Association for Computing Machinery* 18(4): 566–72.

Ginsburg, S., and *Hopcroft, J.* 1971. Images of AFL under certain families of homomorphism. *Mathematical Systems Theory* 5(3): 216–27.

Hopcroft, J. 1971. An n log n algorithm for minimizing states in a finite automaton. In *Theory of machines and computations,* ed. Z. Kohavi and A. Paz, pp. 189–96. New York: Academic Press.

———, and Karp, R. 1971. A $n^{5/2}$ algorithm for maximum matching in bipartite graphs. In *Proceedings of the 12th annual symposium on switching and automata theory,* pp. 122–5. New York: IEEE.

———, and *Tarjan, R.* 1971. Planarity testing in v log v steps. In *Proceedings of the IFIP Congress 1971,* vol. TA-2, pp. 18–22. Amsterdam: North Holland Publishing Company.

Horowitz, E. 1971. On decreasing the computing time for modular arithmetic. In *Proceedings of the 12th annual symposium on switching and automata theory,* pp. 126–8. New York: IEEE.

Salton, G. 1971. Experiments in automatic thesaurus construction for information retrieval. In *Proceedings of the IFIP Congress*

1971. Amsterdam: North Holland Publishing Company.

———. 1971. On the use of computers in libraries. *Library Journal* 96(18): 3277–82.

———. 1971. *The SMART retrieval system —experiments in automatic document processing*. Englewood Cliffs, New Jersey: Prentice-Hall.

■ ELECTRICAL ENGINEERING

Andrews, M. L., Davitian, H., Fleischmann, H. H., Kribel, R. E., Kusse, B. R., Nation, J. A., Lee, R., Lovelace, R. V., and *Sudan, R. N.* (1971). Application of intense relativistic electron beams to astron-type experiments. In *Proceedings of 4th conference on plasma physics and controlled nuclear fusion research*, pp. 169–80. Vienna, Austria: International Atomic Energy Agency.

Ballantyne, J. M., Baukus, J. P., and *Lavin, J. M.* 1971. Bulk GaAs Millimeter-Wave Detector with Fast Response. Paper read at IEEE International Electron Devices Meeting, 12–13 October 1971, in Washington, D.C.

Baukus, J. P. 1971. Harmonic Content in Solid State Microwave Oscillators. Paper read at IEEE International Electron Devices Meeting, 12–13 October 1971, in Washington, D.C.

Brice, N. M. 1971. Artificially Induced Substorms. Paper read at International Association of Geomagnetism and Aeronomy General Assembly, 3–11 August 1971, in Moscow.

———. 1971. Harnessing the Energy in the Radiation Belts. Paper read at IAGA General Assembly, 3–11 August 1971, in Moscow.

Carlin, H. J., and Noble, D. 1971. Circuit properties of dispersive coupled transmission lines. In *London 1971 IEEE international symposium on electrical network theory*, IEEE catalog no. 71C 53-CT, pp. 140–1. London: The City University; IEEE.

Dalman, G. C., and *Lee, C. A.* 1971. Local oscillator noise in a silicon Pt-n-p+ microwave diode source. *Electronics Letters* 1: 565–6.

———, and ———. 1971. A Low-Noise Ku-Band Silicon Pt-n-p+ Diode Oscillator. Paper read at IEEE International Electron Devices Meeting, 12–13 October 1971, in Washington, D.C.

———, ———, and Chien, C. 1971. Noise in Pulsed and CW Solid State Microwave Oscillators. Paper read at Conference on High Frequency Generation and Amplification: Devices and Applications, 17–19 August 1971, at Cornell University, Ithaca, New York.

Fine, T., 1971. Comparative Probability and its Application to Decision Making. Paper read at Colloquium of the Philadelphia Chapter of the IEEE Group on Information Theory, 20 October 1971, in Philadelphia.

———.1971. A note on the existence of quantitative probability. *Annals of Mathematical Statistics* 42: 1182–6.

———. 1971. Stochastic independence and computational complexity. In *Proceedings of IFIP Congress 1971*, vol. TA-2, pp. 1–6. Amsterdam: North Holland Publishing Company.

Frey, J. 1971. The Cornell Conference. Paper read at 2nd European Microwave Conference, 24 August 1971, in Stockholm, Sweden.

———. 1971. Ion Implated Computer Logic and Bulk Negative Conductivity Devices. Paper read at United Kingdom Atomic Energy Research Establishment, 2 September 1971, in Harwell, England.

———, and *Bowers, R.* 1971. Microwave Solid State Devices: A Preliminary Technology Assessment. Paper read at Conference on High Frequency Generation and Amplification: Devices and Applications, 17 August 1971, at Cornell University, Ithaca, New York.

———, and Bravman, J. 1971. High Performance Varactor Tuned Gunn Oscillators. Paper read at Conference on High Frequency Generation and Amplification: Devices and Applications, 17 August 1971, at Cornell University, Ithaca, New York.

McFarlane, R. A. 1971. Tunable Lasers in Molecular Spectroscopy. Paper read at Annual Meeting of the Optical Society of America, 5–8 October 1971, in Ottawa, Ontario, Canada.

Stern, C. A., and *Torng, H. C.*, 1971. NAND Cellular Arrays. In *Proceedings of the 12th annual symposium on switching and automata theory*, pp. 91–104. New York: IEEE.

Tang, C. L., and Flytzanis, C. 1971. Charge-transfer model of the nonlinear susceptibilities in polar semi-conductors. *Physical Review B* 4: 2520–4.

Wharton, C., Korn, P., and *Robertson, S.* 1971. Skin effect and anomalous resistivity accompanying turbulent heating. *Physical Review Letters* 27: 499–501.

———, ———, *Prono, D., Robertson, S., Auer P.*, and *Dum, C.* 1971. New results in turbulent heating. In *Proceedings of the 4th conference on plasma physics and controlled fusion research*, vol. 2, pp. 25–36. Vienna, Austria: International Atomic Energy Agency.

■ GEOLOGICAL SCIENCES

Oliver, J., and Murphy, L. 1971. WWNSS: Seismology's global network of observing stations. *Science* 174: 254–61.

■ MATERIALS SCIENCE AND ENGINEERING

Ast, D. G., and *Seidman, D. N.* 1971. Noble gas imaging of gold in the field ion microscope. *Surface Science* 28: 19–31.

Blakely, J. M., and Schwoebel, R. L. 1971. Capillarity and step interactions on solid surfaces. *Surface Science* 26: 321–6.

Bubeck, R. A., and *Kramer, E. J.* 1971. Effect of water content on stress aging of nylon 6–10. *Journal of Applied Physics* 42: 4631–6.

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Editor's Note: The Summer 1972 issue of ENGINEERING: Cornell Quarterly *will be concerned with efforts of the College of Engineering to facilitate the education of women and members of minority groups as engineers.*

Please address any correspondence, including notification of change of address, to ENGINEERING: Cornell Quarterly, Carpenter Hall, Ithaca, New York 14850.

Chen, Y. C., and *Seidman, D. N.* 1971. The field ionization characteristics of individual atomic planes. *Surface Science* 27: 231–55.

Good, J. A., and *Kramer, E. J.* 1971. Yield and recovery of the flux line lattice in a type II superconductor. *Philosophical Magazine* 24: 339–57.

■ MECHANICAL ENGINEERING

Eno, B. E. 1971. Stability of a plane vortex sheet between gases exchanging heat by radiation. NASA Lewis Research Center report CR-1931.

Gutman, D. P., and *McManus, H. N., Jr.* 1971. Secondary flow effects upon heat transfer in asymmetrically roughened ducts. In *Proceedings of the 12th midwestern mechanics conference,* vol. 6, *Developments in mechanics,* pp. 263–76. Notre Dame, Indiana: University of Notre Dame Press.

Hieber, C. A., and *Gebhart, B.* 1971. Stability of vertical natural convection boundary layers: Some numerical solutions. *Journal of Fluid Mechanics* 49: 625–46.

———, and ———. 1971. Stability of vertical natural convection boundary layers: Expansions at large Prandtl number. *Journal of Fluid Mechanics* 49: 577–92.

Krauter, A. I., and *Bartel, D. L.* 1971. An Automated Method for Evaluating Truck Design. Paper read at International Design Automation Conference, September 1971, in Toronto.

Markowsky, J. J., and *McManus, H. N., Jr.* 1971. The heterogeneous condensation of mercury from a high velocity carrier gas. *International Journal of Heat and Mass Transfer* 14: 1079–91.

Paul, C. K., McDonough, T. R., Schorr, A. W., Matilaine, J. L., Lamy, P. L., and *Redline, M. H.* 1971. José—A Jupiter orbiting spacecraft. National Aeronautics and Space Administration report NGR 33–010–071.

Ruhl, R. L., and *Booker, J. F.* 1971. A Finite Element Model for Distributed Parameter Turborotor Systems. Paper read at ASME Vibrations Conference, 8–10 September 1971, in Toronto.

Torrance, K. E., and *Kopecky, R. M.* 1971. Numerical study of axisymmetric vortex breakdowns. NASA Lewis Research Center report CR-1865.

■ OPERATIONS RESEARCH

Billera, L. J. 1971. Some recent results in n-person game theory. *Mathematical Programming* 1(1):58–67.

Brown, M. 1971. Some Remarks about Poisson Processes. Paper read at Conference on Stochastic Processes and Their Applications, August 1971, at the University of Rochester, Rochester, New York.

———. 1971. Some Remarks on the Cramér-Von-Mises Statistic. Paper read at Conference on Sample Distribution Functions and Their Applications, August 1971, in Buffalo, New York.

———. 1971. Statistical Analysis of Nonhomogeneous Poisson Processes. Paper read at Conference on Stochastic Point Processes: Statistical Analysis, Theory and Applications, August 1971, in Yorktown Heights, New York.

Lucas, W. F. 1971. Some recent developments in n-person game theory. *SIAM Review* 13(4):391–523.

Nemhauser, G. L., and Widhelm, W. B. 1971. A modified linear program for columnar methods in mathematical programming. *Operations Research* 19:1051–60.

Weiss, L., and Wolfowitz J. 1971. Asymptotically efficient estimation of nonparametric regression coefficients. In *Statistical decision theory and related topics,* ed. S. S. Gupta and J. Yackel, pp. 29–39. New York and London: Academic Press.

■ THEORETICAL AND APPLIED MECHANICS

Alfriend, K. T. 1971. A Nonlinear Stability Problem in the Three Dimensional Restricted Three Body Problem. Paper read at AAS-AIAA Astrodynamics Conference, 17–19 August 1971, at Fort Lauderdale, Florida.

———. 1971. Stability and motion about L_4 at three-to-one commensurability. *Celestial Mechanics* 4(1):60–77.

———. 1971. Stabilty and motion in two degree of freedom Hamiltonian systems. *International Journal of Nonlinear Mechanics* 6:563–78.

Boley, B. A. 1971. On a melting problem with temperature-dependent properties. In *Trends in elasticity and thermoelasticity,* ed. W. Nowacki, anniversary volume, pp. 22–28. Groningen, The Netherlands: Wolters-Noordhoff Publishing Company.

Rand, R. H. 1971. A higher order approximation for nonlinear normal modes in two degree of freedom systems. *International Journal of Nonlinear Mechanics* 6:545–7.