PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Offshore Structure Design and Development

J. A. Mercier

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By J. A. Mercier

Conoco (U.K.) Limited, 116 Park Street, London W1, U.K.

The kinds of technology currently being applied to the design, construction, installation and operation of offshore structures for oil and gas exploration and production are quite sophisticated and include many examples of innovative configurations and approaches. The decade of the 1990s should see further evolution, reinterpretation and improvements of concepts that are already in service or being readied for service. The importance of offshore oil and gas may be judged by the projection that over half of overall exploration investments will go to offshore prospects in future years. This paper surveys some expected evolutions, with particular emphasis on the challenging area of deep-water applications. Some features of a tension leg platform design are discussed as an example of a deep-water oil production system. An attempt is made to recognize the problems of applying advanced engineering and analytical capabilities, when many specialists must interact, to producing a thoroughly engineered design, which is also balanced and economical, for such innovative systems.

1. Introduction

About a quarter of the world's discovered oil lies beneath the sea. The importance of offshore oil and gas recovery for the future may be measured by the fact that oil companies expect to spend over half of their overall exploration investments on offshore prospects in the coming years. Many high-potential exploration tracts lie below deep oceans where winds and waves are hostile to the workings of men and machines.

Technological requirements for developments will depend on the attraction of exploration targets, success with discoveries and the economic incentives for the recovery of discovered resources. Forecasting the kinds of technology that will be used in offshore systems in the 1990s does not require a crystal ball: the techniques, equipment and structures that will be used in those years are either similar to those currently in use or they are already being designed and tested.

The set of available structures and equipment is, indeed, quite broad, encompassing steel-piled space frames, concrete or steel gravity-based structures, floating systems, articulated systems, completely submerged production systems, man-made islands and others. The magnitude and complexity of offshore projects is such that novel concepts must be scrutinized and researched from a multitude of viewpoints before corporate managements will consent to their application in projects. Experience of several recent major innovations shows that the time-frame for completing such thorough assessments is of the order of a decade.

The available spectrum of techniques may be reconfigured, reinterpreted and improved to satisfy specific future requirements. What advances may we expect to see in offshore development technology in the 1990s? This paper will present a brief survey of some expected evolutions, with particular emphasis on deep-water applications, for which the technological challenges are especially interesting.

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2. Background and trends

Exploration for and production of oil and gas from beneath the sea is a relatively recent endeavour. Offshore drilling in the Gulf of Mexico began in the late 1930s, and by the mid-1950s exploratory drilling was being carried out from floating drilling vessels, especially off the California shore. The arena for offshore exploration and production has now spread worldwide and the continental shelves of every continent except Antarctica are being probed and resources extracted.

Each area of operation has its particular requirements that affect design solutions, perhaps associated with adverse seabed soil quality, earthquakes, severity of winds and waves, distances for logistic support, ice floes or bergs, or other circumstances. One of the most challenging operational areas of the past decade has been the North Sea, where the oil and gas fields of the United Kingdom and Norwegian continental shelves have called for the introduction of innovative technology on a massive scale.

Whereas the targets for early offshore exploration plays were related to onshore oil and gas discoveries, and were in water depths now regarded as 'shallow', the main oil discoveries of the North Sea are less closely linked with onshore operations, and are in water between 100 and 200 m deep. Exploration prospects in deep waters that are related to successful shallow-water plays are least risky and most evidently promising.

Present-day thinking identifies 'deep' water as depths in excess of about 200 m in the North Sea. In the Gulf of Mexico, the threshold for 'deep' water is around 300 or 400 m. Drilling in deep North Sea depths, up to 1350 m, has produced some oil discoveries, but commercial viability is unconfirmed. Plans and technology for exploitation have not yet been worked out. There are, in addition, exploration targets in deep water, remote from successful plays, for which the possibility of discovering large reserves might justify a gamble.

What does it take to gamble on deep water? The expected cost of a single wildcat well in deep water is between \$20 M and \$50 M. Costs for development in deep water will depend on the technology applied, but should be competitive with the present generation of ambitious offshore projects. In a recent article, Ellers (1982) cites capital investment for four innovative designs as ranging from \$12000 to \$32000 per barrel of oil (*ca.* 0.159 m^3) per day production capability (peak rate).

The projects include: Statfjord B concrete gravity platform (North Sea); Magnus steel jacket and piling (North Sea); Hutton tension leg platform (North Sea); Block 280, Mississippi Canyon, Guyed Tower (Gulf of Mexico).

Heavy exploratory and development investments, which will characterize deep-water projects, can only be afforded for high production rates from large reserves.

Shallow-water prospecting areas, where conventional production schemes and structures can be most effective, have not yet been fully explored, let alone exhausted, so most future platforms can be expected to look like the present commonly used steel piled jackets or concrete gravity platforms, or both. Improvements can be expected in materials, fabrication processes, design and analysis techniques, installation and other areas, but the basic concepts will stay about as they are. Extensions of existing concepts to increasing water depths may continue in some offshore areas but the economics of increasingly large platforms present an eventual barrier. Ellers (1982) speculates that the 41000 t Magnus field self-floating platform, for 186 m deep water, may represent the ultimate development of steel jacket technology. Although platforms in the

Gulf of Mexico, including the three-piece Cognac jacket and two Cerveza jackets, are already standing in water depths of over 300 m and 280 m, respectively, it seems likely that still taller platforms might be installed where environmental conditions permit. The sedimentary basins of the continental slopes, where water depths exceed 200 m, cover an area greater than the continental shelves and explorers will probe these depths increasingly in the 1990s.

Economic limits will compel further development and application of deep-water structures characterized by dynamic motions in response to wave action, instead of the relative rigidity of conventional bottom-fixed structures. Most of the concepts have already been used or are currently being prepared for at least some offshore engineering service:

(i) floating structures, including column-stabilized semisubmersibles, used for exploratory drilling and, recently, for production of several oil fields; ships, used for exploratory drilling, temporary storage and oil processing and tanker loading; single column spars, used for temporary storage and tanker loading;

(ii) bottom-fixed guyed towers, to be applied for drilling and production;

(iii) bottom-fixed articulating buoyant structures, including tension leg platforms, to be applied for drilling and production; articulating columns (and single anchor leg moorings), used for tanker loading and as flare towers.

The various concepts have each been devised and developed to satisfy certain requirements and have entailed considerable innovative engineering. Perhaps the most important and most audacious advance was made several decades ago with the start of drilling operations from floating vessels moored in the open ocean.

The design of novel systems requires creative talents and attracts the energies of skilful analysts, whose ability to predict and interpret the performance of these dynamic systems is vital to operational and design confidence. Indeed, engineering capabilities for dynamic offshore systems can be said to be coming of age in time to serve the deep-water development requirements of the coming decades.

Such advanced capabilities need to be applied to development of any of the above-mentioned deep water systems and should prove valuable in improving the effectiveness of conventional 'shallow'-water projects.

The technology of a tension leg platform will be discussed in more detail in § 3, as an example of a deep-water oil production system. Some special features of designs and analyses and of the engineers who are responsible for this work will be noted.

3. Tension leg platforms

(a) *General features*

A tension leg platform, or TLP, is simply an evolutionary form of semisubmersible, connected to anchors fixed in the seabed by vertical mooring lines instead of the catenary moorings used on drilling semisubmersibles. Figure 1 illustrates the TLP for the U.K. Hutton Field, which is currently being constructed for Conoco (U.K.) Limited, who are acting as operators on behalf of a consortium of companies including British National Oil Corporation, Gulf Oil Corporation, Amoco (U.K.) Exploration Company, Gas Council (Exploration) Ltd, Mobil North Sea Inc., Amerada Petroleum Corp. of U.K., and Texas Eastern North Sea Inc. The tension legs will be kept in tension for all weather and loading conditions by the platform's buoyancy, which exceeds its mass. The excess buoyancy also provides the restoring force to keep the TLP

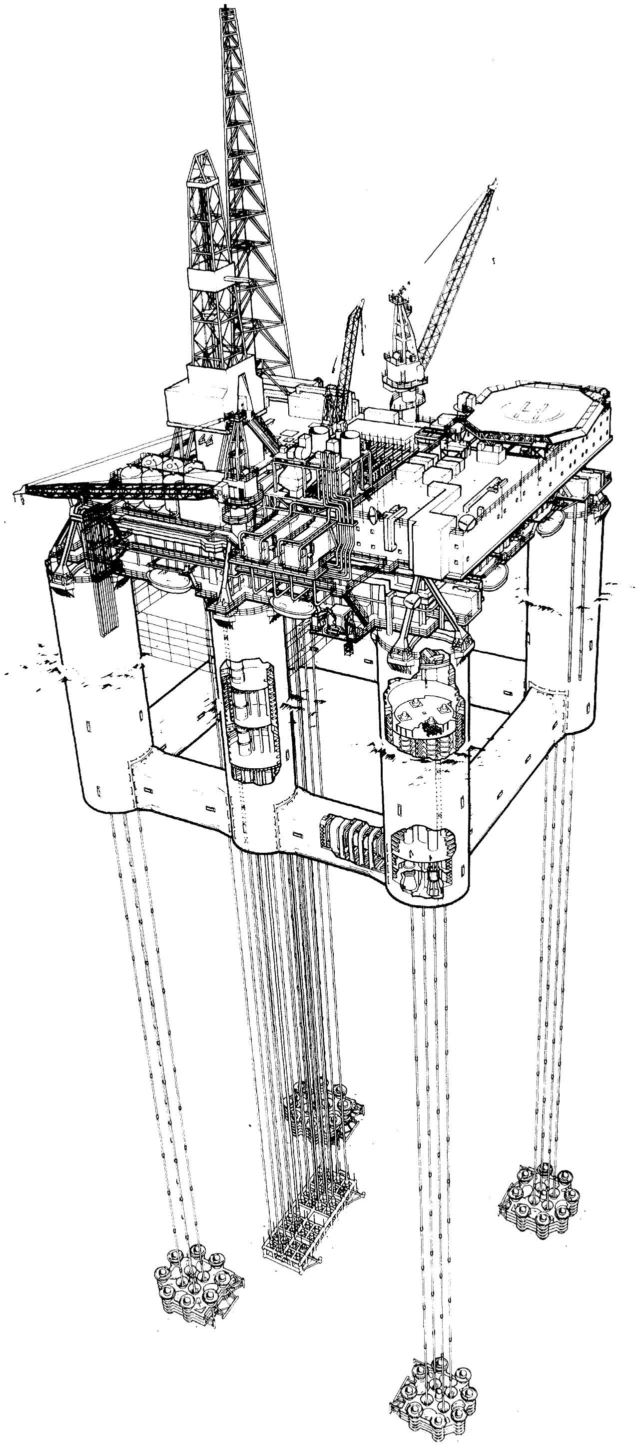

FIGURE 1. Hutton Field tension leg platform.

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permanently on station with risers connecting each well from the sea floor to the TLP. Lateral plane movements of surge, sway and yaw are compliantly restrained while vertical plane movements of heave, pitch and roll are stiffly restrained. The dynamic behaviour of a TLP is similar to an inverted multifilar pendulum, where excess buoyancy plays the role of gravity and the TLP deck is held level by the pantograph-like configuration of the tension legs. The dynamic behaviour of a TLP is similar in kind to that of the articulated columns in use in the North Sea Beryl and Statfjord fields as towers for loading crude oil into cargo tankers, as well as for other applications: articulated columns might be considered to be single-leg TLPs.

Table 1. Comparison of principal dimensions and operating conditions of Hutton TLP with semisubmersibles

	Hutton TLP	Sedco 700 (drilling rig)	Viking Piper (pipelay barge)	Balder (crane barge)
		dimensions		
upper hull (deck)				
length/m	78	70.4	152	137
breadth/m	74	60	58.5	86
depth/m	12	2.4	6.0	7.0
weather deck elevation above keel/m	69	39.6	33.2	42
lower hull				
length/m	95.7	89.9	162	118
breadth/m	8.0	15.2	13	26
depth/m	10.8	6.4	8.2	12
overall width/m	91.7	74.7	58.5	79.9
number of columns	6	8	6	6
total waterplane area/m^2	1324	355	1181	2765
		operating conditions		
draft/m	33.2 (MWL)	24.5	20	27.5
displacement/tonnes	63300	25000	53500	110000

The chief premises for the design of the Hutton TLP are: (*a*) it is to be an effectively permanent installation in that it must stay moored on station in the most severe environmental conditions for the full duration of oil production, (*b*) fabrication, outfitting and hookup of the structure and facilities will be finished before the TLP is towed from its inshore mooring to the Hutton field, (*c*) components are designed for a minimum of 20 years' service life, (*d*) key components, such as tension legs and well riser tensioners, are simple and intrinsically reliable, have backups and are replaceable for inspection and maintenance, and (*e*) the structure is configured so that all areas are accessible for inspection from inside. General descriptions of the design features for the Hutton TLP have been presented more fully in descriptive papers by Mercier & Marshall (1981), Mercier & Marr (1982), and in a group of papers presented to the 14th Offshore Technology Conference (Ellis *et al.* 1982; Tetlow & Leece 1982; Mercier *et al.* 1982).

Prospective advantages for TLPs in deep-water offshore missions include: (*a*) minimal vertical motions, thus improving accessibility and maintainability of well systems and other connections from seabed to deck, (*b*) reduction of expensive offshore work by completing before towout, (*c*) schedule improvements by separating offshore work packages and because weather-sensitive offshore work is typically brief, (*d*) costs for deeper water are not greatly increased, and (*e*) field abandonment should be simplified and less costly.

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Table 1 compares some of the principal dimensions of the Hutton TLP with those of other large column-stabilized semisubmersible drilling, pipelaying and crane barges. Distinctive features of the Hutton TLP are: (*a*) no diagonal members are used to brace the structure, which is composed of a small number (six) of non-slender vertical columns connected at the lowest elevation by horizontal pontoons, (*b*) a large proportion (over 70 %) of buoyancy is provided by the vertical columns, compared with the proportions of free-floating semisubmersibles, because the TLP's requirement is for wave-induced tension leg force attenuation rather than wave-induced heave motion attenuation, and (*c*) the overall TLP depth is exceptional because the design uses deep draught to attenuate wave forces, a range of tidal elevations must be accounted for, severe underdeck wave slam due to extremely high waves must be avoided, including consideration of the lowering of the TLP due to the pantograph action of the tension legs with platform offset, and the TLP's deck is quite deep to accommodate equipment.

The well template, shown beneath the TLP in figure 1, was the first part of the system to be

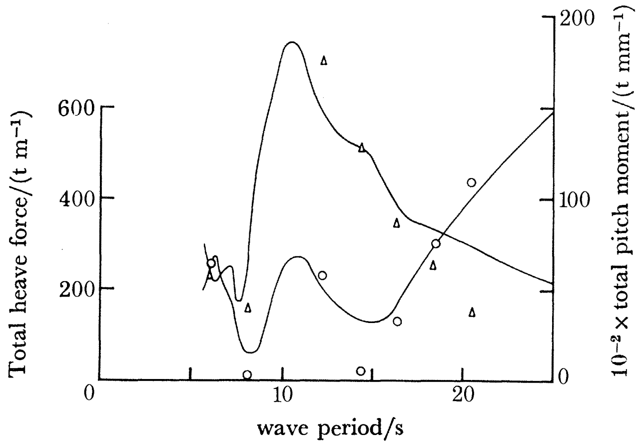

FIGURE 2. Comparison of theory (NMI WAVE) (points) and experiment (curves) for wave-induced heave force (○) and pitch moment (Δ).

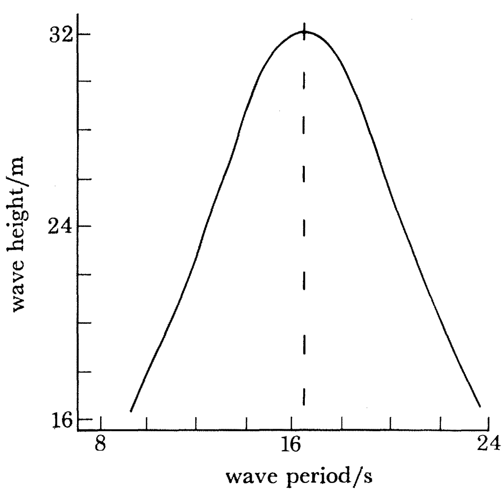

FIGURE 3. Wave-height–period boundary for extreme design (regular) waves, based on Longuet-Higgins's (1975) theory and a significant wave height of 16.6 m.

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installed at the Hutton Field, in May 1981. A number of wells are currently being drilled through this template, by a semisubmersible drilling rig, so that a high rate of oil production can be achieved shortly after the TLP is installed.

The foundation templates will be installed in the spring of 1983, by a semisubmersible heavy lift vessel. A temporary spacer frame on the seabed will be used to position foundation templates accurately with respect to the well template and each other. Large diameter stiff piles will be driven by an underwater pile driver through the eight pile sleeves on each foundation template and into sandy clay soil. Piles will subsequently be bonded to the pile sleeves by grout.

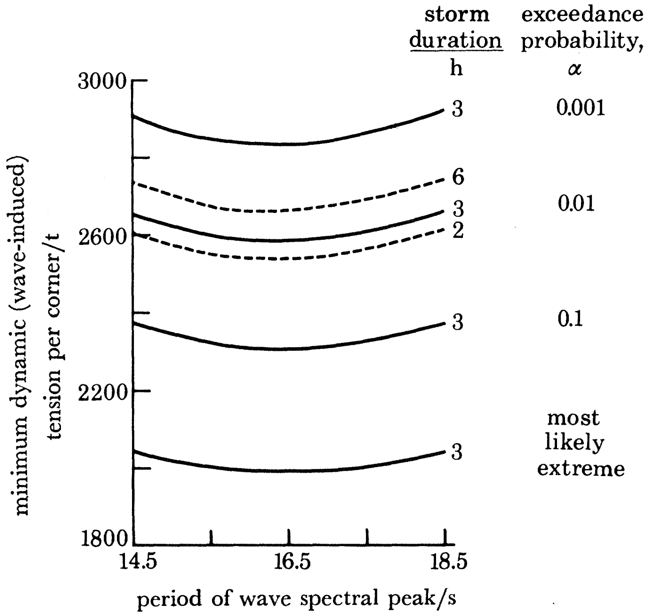

FIGURE 4. Probabilistic estimate of wave-induced load variation in lee-side tension legs (reduced tension), showing dependence on wave spectral peak period, probability of exceedance and duration of exposure to 100 year storm waves (based on Ochi's (1978) method).

(*b*) *Dynamic behaviour*

Natural periods of compliant and stiff modes of response of a TLP should be removed from the periods for which significant ocean wave energy is present. For the Hutton TLP the compliant mode natural periods are 50–60 s for surge and sway and 42–48 s for yaw, with the variation depending chiefly on excess buoyancy, which in turn depends on water level variations due to tide and surge. Stiff mode natural periods are all around 1.9 s for the TLP, but in deeper water longer tension legs with less longitudinal stiffness will lead to longer natural periods.

It is necessary to predict the behaviour of an ocean structure in response to winds, waves and currents in order to execute the design of the components. The hydrodynamic behaviour of buoyant compliant systems, including ships, semisubmersibles, articulated columns and TLPs, has been a fruitful field for experimental and analytical research in recent years. *Ad hoc* scale-model tests in wind tunnels and wave basins must be used to provide configuration-specific empirical confirmation of analyses used in designs. During the Hutton design work about 20 different series of hydrodynamic and aerodynamic model tests have been carried out to evaluate: (*a*) platform motions and loads due to waves, for several development versions of the configuration, (*b*) dynamic stresses and motions of groups of risers, (*c*) hull and riser interaction effects, (*d*) towing resistance and motion behaviour, (*e*) simulations of mating of the deck and hull in the presence of small waves, (*f*) installation simulations, and (*g*) wind force and flow field studies.

Certain kinds of wave-induced responses can be adequately predicted by advanced analyses provided that waves are not too steep and high. Figure 2 shows a comparison between experiments and theoretical estimates of total heave force and pitch moment for a tension leg, from a wave diffraction computer program (Standing 1978) that accounts for period-dependent free

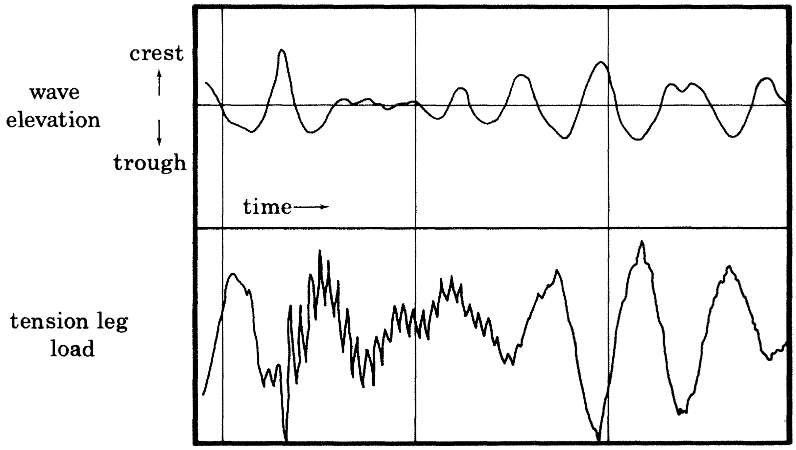

FIGURE 5. Tension leg load time history, exhibiting 'ringing' in irregular waves.

surface effects and the flow interactions induced by adjacent columns and pontoons. Such analyses entail complex arithmetic but the predictions are strictly applicable only to linear responses in inviscid fluids. Some important aspects of responses are nonlinear, however, and analytical prediction methods are less reliable for these. Scale-model tests provide the most complete data for making detailed predictions of responses such as surge motions including slow drift oscillations, fluid drag effects on tension leg loads, wave profile modifications including column run-up and nonlinear refractions, and others.

Performance predictions call for skilful combination of the lessons of experiments and calculations for prescribed environmental conditions. But the prescription of appropriate environmental conditions, which combine in a variety of ways, requires the dynamics analysts to appreciate the art and science of oceanography as well. Motions and tension leg loads, among other responses, depend on waves, currents, winds and tides in combination with each other. The chief characteristic of environmental conditions is their random variability, which obliges designers to adopt probabilistic design crieria. Joint probability of occurrence of the several inputs ought to be considered, including combinations of wave periods and heights.

Offshore structure design practice has historically favoured representing the effects of waves on structures by considering a characteristic extreme individual wave whose height and period were predicted by extrapolating sea-state data or hindcasts, or both. Techniques for identifying periods of extreme waves have not been well developed until recently. Goda (1978) has found that Longuet-Higgins's (1975) method for identifying the joint distribution of wave heights and periods is appropriate for high waves. An iso-probability wave-height–period contour used for design of the Hutton TLP is shown in figure 3. For several kinds of response (structural racking, wave run-up, riser deflexions, etc.) waves of 12–15 s period are most important and a consistent approach to relating extreme event heights and periods is required.

Nonlinear responses to high, steep waves are most easily derived from tests and analyses for regular periodic waves. The nonlinearity of wave-induced tension leg loads causing reduced tension is most important for waves of around 14–15 s period and accounts for about an extra 25 % on the linear prediction. The judicious choice of design wave height and period combinations importantly affects the amount of nonlinearity and the required excess of buoyancy over mass.

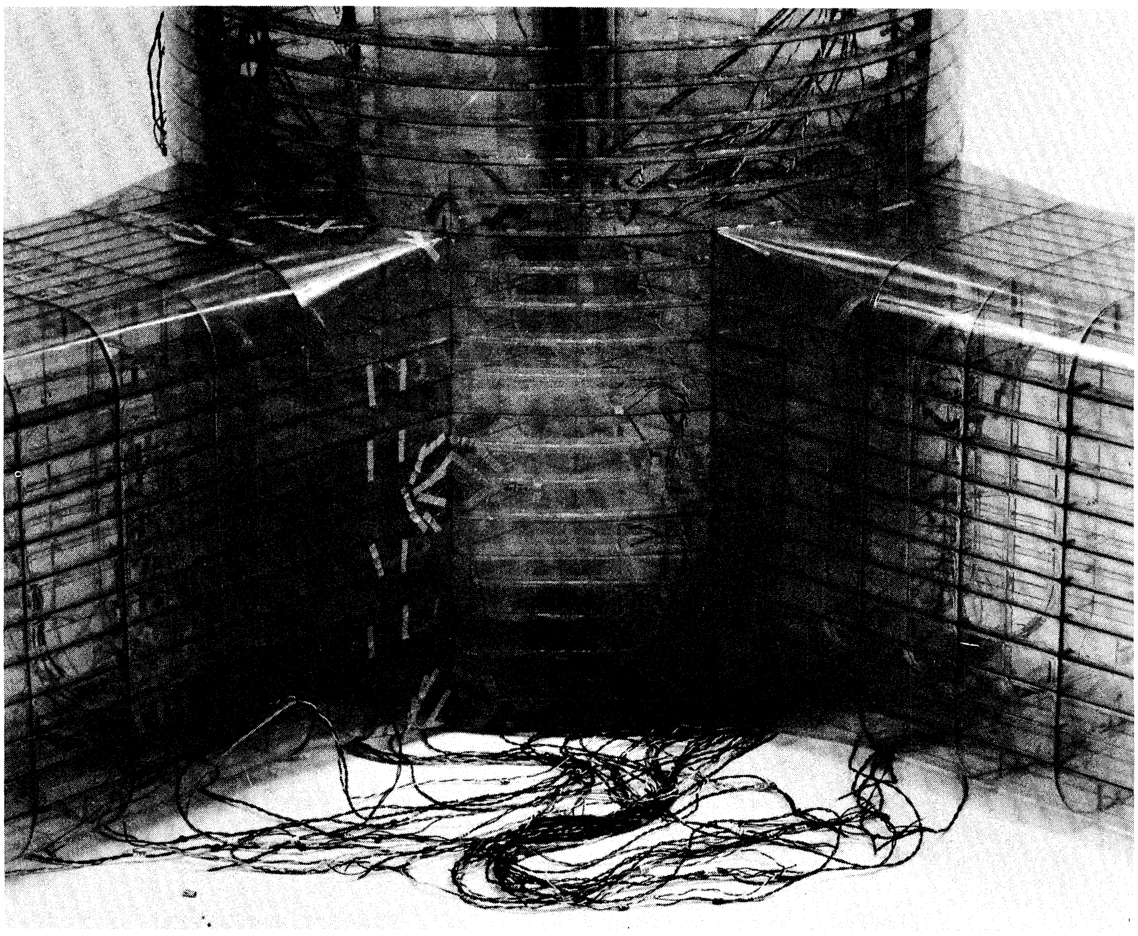

FIGURE 6. Acrylic structural model, with 400 strain gauges, which was tested to provide data to check finite element stress analysis. (Photograph courtesy of Lloyd's Register of Shipping, Research Department.)

Ship theorists have found it most useful to retain an explicit recognition of the randomness of the seaway in analysing dynamic responses to waves. One of the most coherent expressions of a probabilistic analysis method (Ochi 1978) combines linear-system response evaluations and extreme-value statistics. Predictions are made in which the probability of being exceeded in a given duration of exposure are explicitly stated. Figure 4 shows predictions for tension reduction due to a severe (short-term) sea state: for a given duration and probability, the estimated loads vary by less than 5% over the range of credible wave spectral modal periods. Tension leg load transfer functions for use in the analysis were obtained from model tests in severe irregular waves.

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The occurrence of extraordinary response events, especially strongly nonlinear responses, are not accounted for in this very instructive technique.

Some wave tests exhibited high-frequency variations in tension leg loads at the heave or pitch natural period of the platform. These occurred especially in waves that were both high and steep. The response, illustrated in figure 5, appears impulsive and decays because of system damping. Possible mechanisms for causing this 'ringing' vibration were examined, including vortex-shedding from the pontoons, and wave-breaking against the columns, to consider whether the full-size response might be more or less intense than the model test. While a specific causal mechanism could not be convincingly identified it was decided that model test ringing intensities were appropriate for design use.

A variety of other inputs and responses could be elaborated, such as the joint occurrence of extreme tides and meteorological surges, combinations with winds, including gustiness effects, wave profile modifications, and motion damping estimates. Research opportunities and design challenges should compel the attention of workers in this area throughout the 1990s. An account of the Hutton TLP environmental response evaluation programme is contained in a recent paper (Mercier *et al.* 1982).

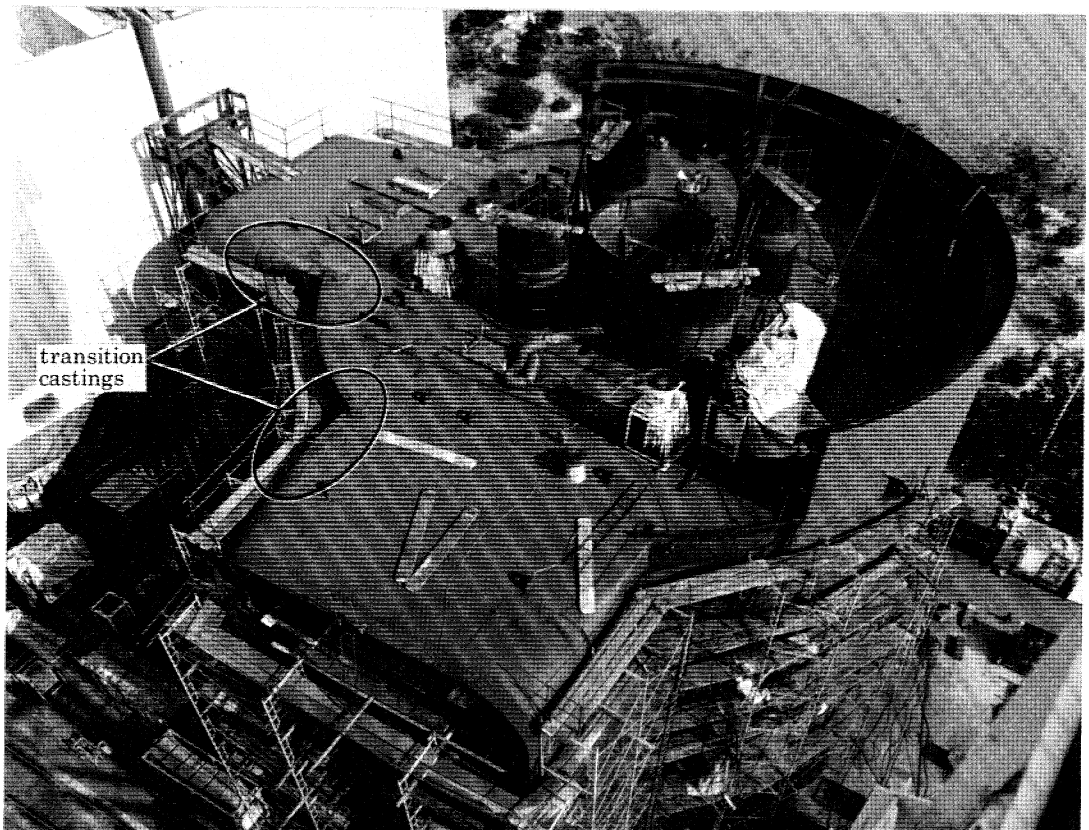

FIGURE 7. Corner column to pontoon joint subassembly. Note transition castings inserted at intersections of cylindrical column and pontoon top and side shell plating, to avoid welds at stress 'hot spot'.

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(c) *Structures and moorings*

Structural arrangements and design will account for functional loads of the operating platform, and additional environmental and other variable loads for the in-place platform for its service life and pre-operating conditions, including fabrication, deck-to-hull mating, towing and installation. The main objectives of the design are safety, reliability and minimum mass. The Hutton TLP configuration is similar to that of other column-stabilized semisubmersibles, with the special qualifications noted in § 3*a*. Ellis (1982) gives a more complete account of the structural design of the Hutton TLP, some aspects of which will be highlighted here.

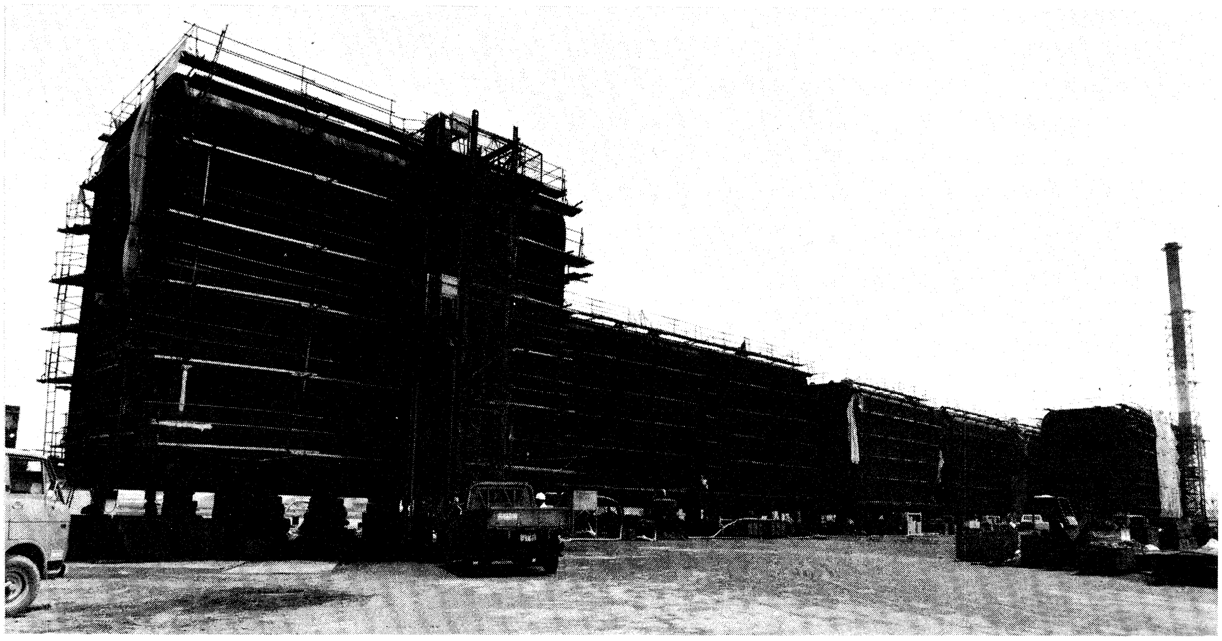

FIGURE 8. Pontoon subassemblies, ready for shipment, are similar to sections of small tankships.

The analysis of the complex stiffened-shell structure of a TLP, which must be stationed in a severe open ocean environment for the service life of the field, must scrupulously account for all recognized aspects of static, dynamic and accidental loads acting on the overall structure and on the component parts, including large subassemblies, stiffened panels and structural details. Three levels of analyses were used: (*a*) a global stick model, (*b*) a global finite element model and (*c*) local finite element models. Each level of analysis contributed to the selection and refinement of structural scantlings.

Local finite element analyses were carried out for a large number of major subassemblies and critical components of the structure, and were especially useful for designing joints between columns and deck and between pontoons and columns. The column–pontoon corner joint was modelled by using 4000 elements, and a strain-gauged acrylic model was built and tested to provide a rapid comparison with the computer analyses. Figure 6 shows the model with 400 attached strain gauges. Strains were measured for a variety of unit load types applied to the end flanges of column and pontoon stubs. Acrylic models do not provide useful results for buckling, plastic deformation or other large-displacement response features, but proved useful

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as an independent approximation for stress concentration factors as well as for generally confirming the computer analyses.

Structural design involves strength and buckling checks as well as fatigue checks for a wide range of loading cases. Limit-state design practices were applied, with partial safety factors applicable to various categories and their probabilities of occurrence. Fatigue design made extensive use of new data and interpretations of the fatigue performance of steel welded joints generated in recent years through the Department of Energy's U.K. Offshore Steels Research Project. Many areas of the TLP, especially at joints, are controlled by fatigue life requirements.

The materials chosen for the Hutton TLP structure are modified high-strength steels with special attention to weldability and freedom from defects. Smedley (1981) has described the evolution of steelmaking processes for structures to the present state, where excellent quality steels are now commonly available. Developments in welding processes and consumables are now needed to produce further benefits to the integrity of welded constructions.

The importance of fatigue and expected difficulties in producing high-quality weldments in complex and thick-walled joints have led the Hutton designers to adapt castings for a particularly complex geometrical detail, namely the transition pieces that form the junction of the column shell and the pontoon side and top (or bottom) shell plating. Webster *et al.* (1981) discuss the advantages of cast steel nodes. To my knowledge, the only previous use of castings in critical structural parts of offshore structures has been for the nodes of the legs for two large jack-up mobile drilling rigs (Laplante & Clauw 1978). Forty-eight of the transition castings have been incorporated in column–pontoon joint subassemblies, such as that shown in figure 7. Prototype castings were made first, and destructively tested to prove strength, toughness, hardness, weldability and repairability. As for steel plates and sections, the welding of the castings to other structures required considerable development of procedures. Designers of platforms of the future would do well to examine the advantages of high-quality steel castings for complex configurations.

Not all of the structural subassemblies for the TLP are innovative, although an equal level of care in design and fabrication is vital to overall reliability. Pontoon subassemblies, shown in figure 8 ready for shipment, are configured much like the cross section of a small tankship, with longitudinal stringers, transverse deep frames and watertight subdivision bulkheads.

The tension leg mooring system features are well described by Tetlow & Leece (1982), who cover design development and the comprehensive test and evaluation programmes for materials and components. Designs for tension leg systems will undoubtedly be modified and improved but certain premises should remain fixed: (*a*) key components must be highly reliable, implying careful design, defect-free materials, excellent workmanship, diligent inspection and full acceptance testing; (*b*) installation methods and apparatus will figure prominently in the design development; (*c*) tension leg loads must be measured so that operators can control on-board loads; and (*d*) weight (in water) should be minimized.

Specially tailored lightweight components, which would produce valuable advantages for deep-water structures like TLPs, should play an increasing role in future designs. The mass of risers, for conducting fluids and carrying out other operations between the structure and sea floor, become significant for design in very deep water. Composite tubes, made of glass or carbon filaments wound in an elastomeric matrix, are being studied in France (Falcimaigne *et al.* 1981) for this application. Mass savings of up to 40% and reduced stiffness are advantages in these applications. Structural integrity under the effects of internal or external pressure as well as tension, bending and elevated temperatures are vital requirements. Compatibility with hydrocarbon contents must be tailored for each product. Other applications of non-metallic materials can be expected in the 1990s as engineers and designers recognize requirements and advantages and learn to design with these relatively unfamiliar materials.

4. Other developments

Above-water floor space will play a key role in future deep-water offshore developments because of the number of air-breathing mechanical components and humans needed for offshore drilling and production activities. As water depths increase, the deck space will be provided by structures that are at least partly dependent upon buoyancy. Systems will be kept on station by conventional or novel mooring systems (catenaries, tension legs, single articulations, guyed towers, etc.) where feasible. It is rather hazardous to speculate on depth limitations for these kinds of systems, but for various reasons design complexities for these concepts may be expected to become heavily burdensome for water depths between about 800 and 1500 m. The threshold depth for fixed moorings may, of course, be advanced by increasingly clever design solutions.

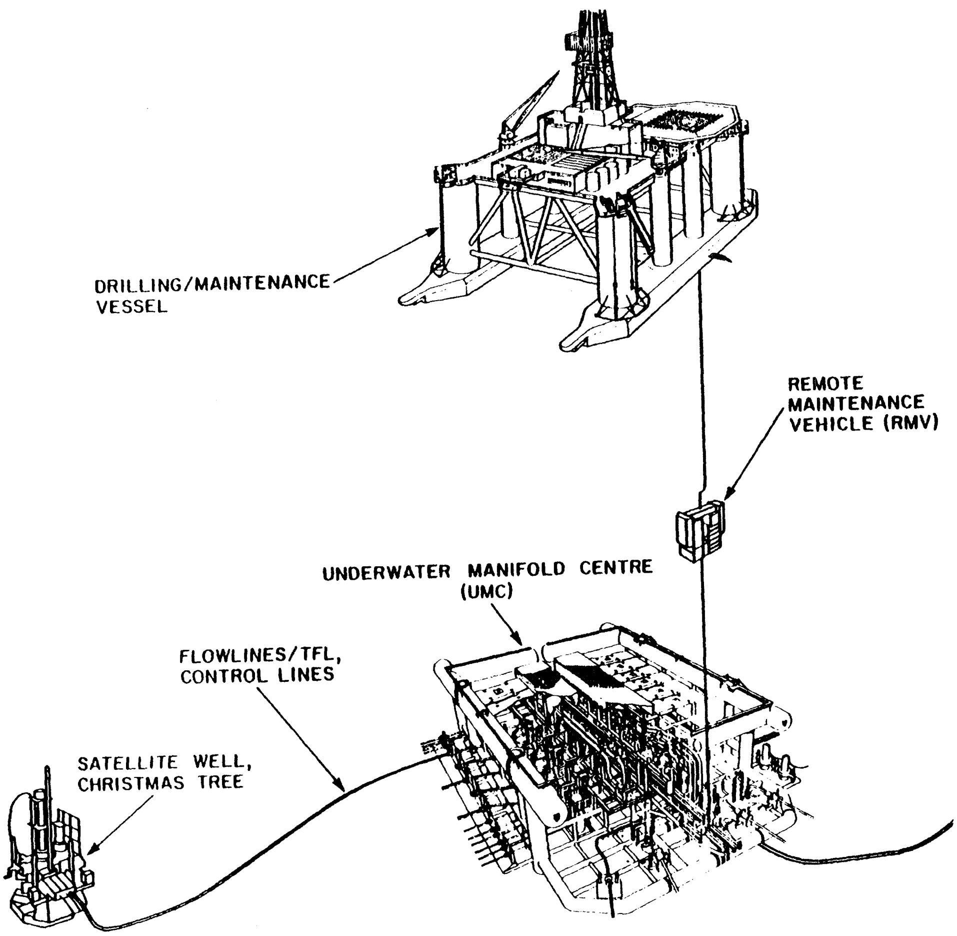

Figure 9. Cormorant underwater manifold centre production system.

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The confidence of industry in dynamic positioning systems, using propulsion devices and acoustic or other position-indicating systems, is progressing as a result of experience. Problem areas are recognized and reliability improved. Such dynamic systems are expensive and would embody quick-release apparatus, implying probable intermittent operations that, though acceptable for drilling operations, would be less desirable for production in most circumstances.

The need for some above-water space does not obviate the need for seabed-based facilities, particularly for well control and related functions. Such facilities may be more or less complex, comprising one or many wells, possibly manifolding or oil–gas–water separation facilities, or both. Such equipment requires maintenance for continued operations and this presents the most challenging aspect of design.

Figure 9 shows the underwater manifold centre (UMC) being installed by Shell/Esso in the U.K.'s Cormorant field. Although many equipment maintenance jobs can be done from the remotely situated South Cormorant platform, using through-flow-line tool techniques, a special unmanned remote maintenance vehicle is available for deployment from a service vessel to carry out some rather complex external maintenance tasks. This kind of system is intended to be usable in practically any water depth.

Other concepts have been put forward in which all production facilities might be operated by men working continuously within air-filled containment vessels on the seabed. This approach would require a substantial reconsideration of operational thinking by oilmen but may, perhaps, be adapted for some circumstances.

5. Final remarks

There are indeed many concepts for deep-water exploitation. Implementing these concepts in the form of real projects requires the application of engineering skills and knowledge of physical sciences in new ways. Universities are educating engineers who are well versed in some of the knowledge and skills of the science and analytical tools that are essential ingredients for completing the kind of thoroughly developed designs that innovation requires. This knowledge and capability needs to be tempered by the experience gained in application to actual design, where analytical formalism appropriate to research must give way to the demands for clear decisions, requiring the exercise (and acquisition) of engineering judgement. Because advanced engineering projects call for contributions from so many specialities, communicative skills must also be developed to ensure a balanced and economical design, as well as a thorough one.

It is a formidable task to bring together and coordinate the talents that must be applied for the challenging job of design and analysis of systems that will be deployed to produce offshore oil and gas in the 1990s, whether improved conventional schemes for shallow water or novel ones for deep water. The task will be done and those involved should find the job stimulating and rewarding.

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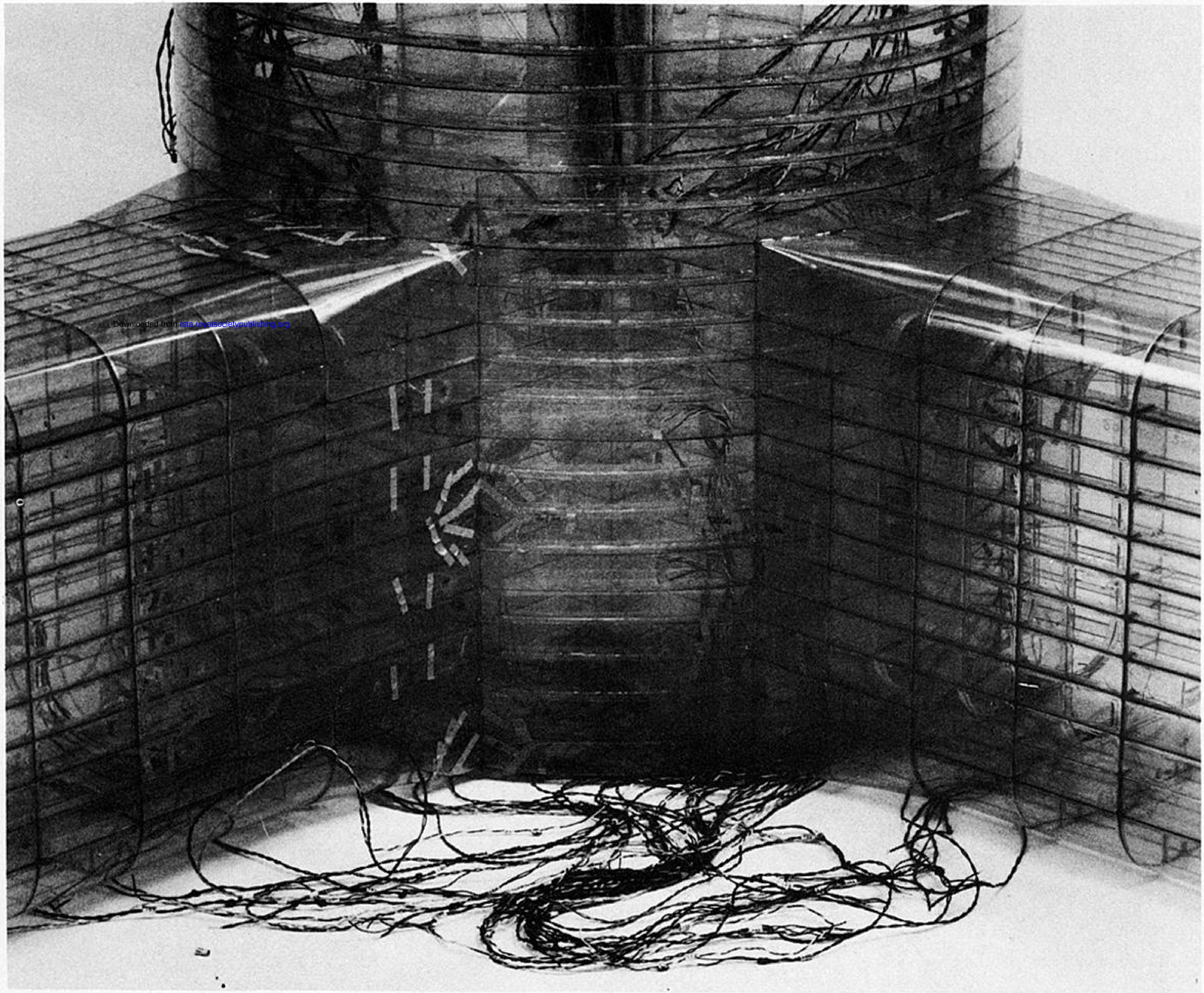

FIGURE 6. Acrylic structural model, with 400 strain gauges, which was tested to provide data to check finite element stress analysis. (Photograph courtesy of Lloyd's Register of Shipping, Research Department.)

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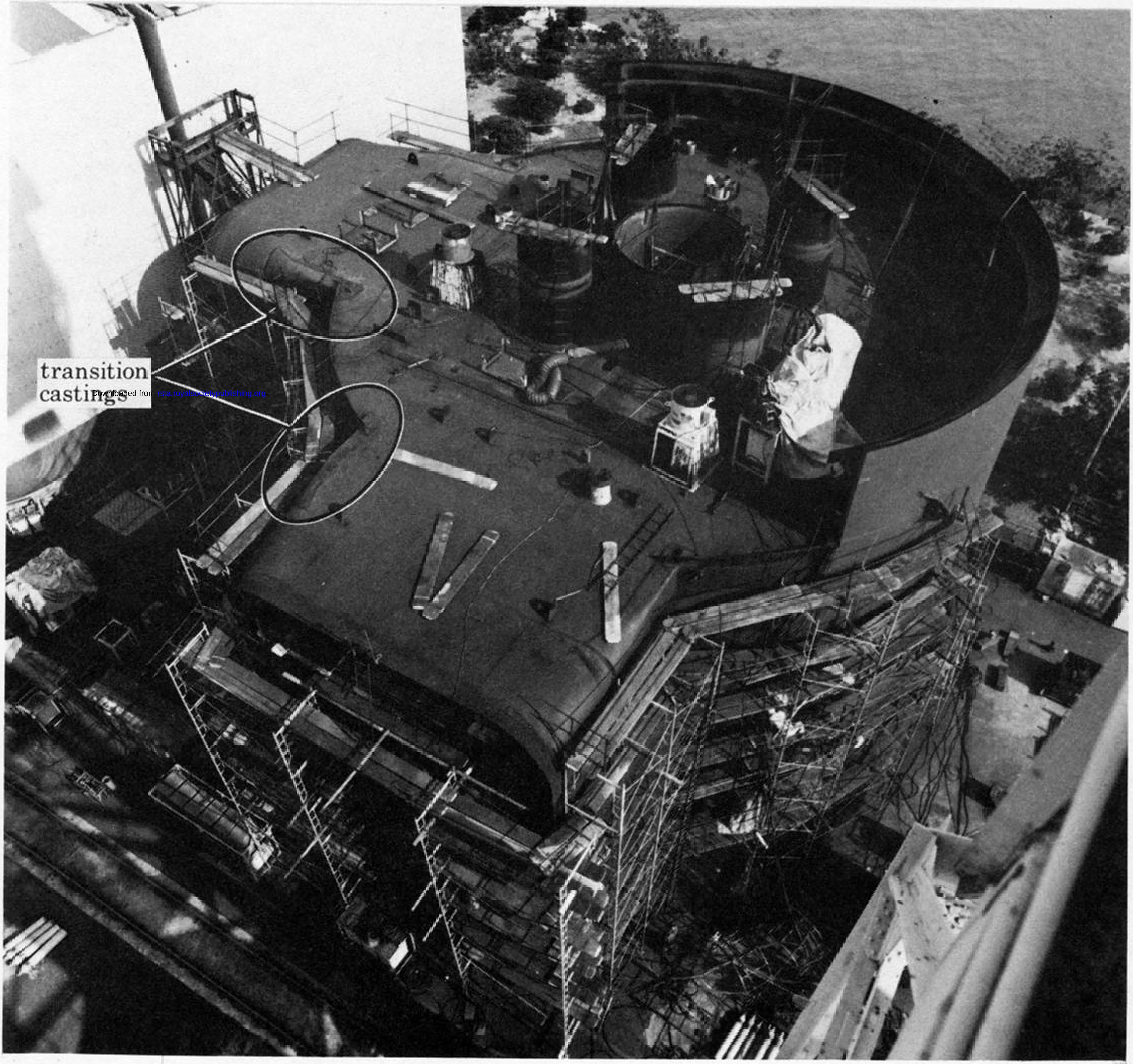

FIGURE 7. Corner column to pontoon joint subassembly. Note transition castings inserted at intersections of cylindrical column and pontoon top and side shell plating, to avoid welds at stress 'hot spot'.

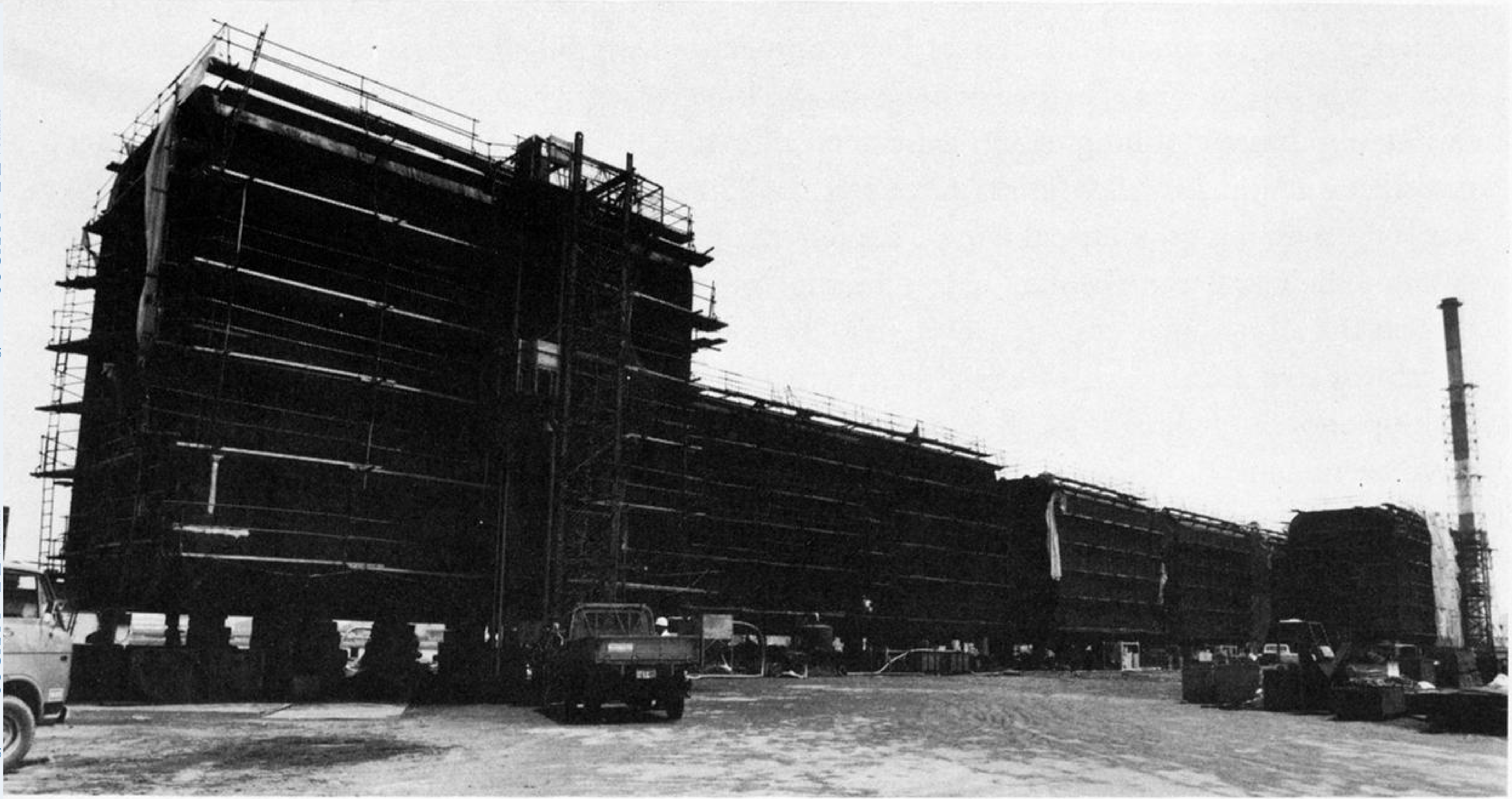

FIGURE 8. Pontoon subassemblies, ready for shipment, are similar to sections of small tankships.

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