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BDR TENSILE STRUCTURE CONCEPT FEASIBILITY STUDY

EDWARD N. KUZNETSOV

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This report discusses the feasibility of using a thin-sheet membrane as a bridge across a bomb crater in a runway. The first step of the study was to determine the tension in a membrane required to support an F-4E load. Given the tension forces, membrane thickness was determined. The next step was to determine a feasible system for anchoring a membrane to pavement surrounding the crater. The final part of the study was discussion on membrane fabrication, handling, and installation procedures.

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PREFACE

This research program on rapid runway repair using the the tensile structure concept was conducted by the Stress Analysis and Fracture Section, Transporatation and Structures Department, Battelle's Columbus Laboratories, Columbus, Ohio. The work was performed under Contract No. F08635-30-C-0109. The program was administered by the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida. Captain Thomas E. Bretz, Jr., provided the technical liaison. This report summarizes the work performed during the period from March 21 through August 21, 1980.

The author acknowledges the assistance of Mr. M. E. Tuttle and the technical direction provided by Mr. R. E. Mesloh.

This report has been reviewed by the Public Affairs officer (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public including foreign nations.

This technical report has been reviewed and is approved for publication.

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INTRODUCTION

Structural stiffness necessary to bridge a span to support a vertical load over it can be obtained in two ways. The first employs a conventional, geometrically stable structure (beam, truss, arch, plate, shell, etc.). The second way, different in principle, is to stiffen a flexible system (kinematic chain) by introducing an appropriate prestressing force. High strength obtained in certain modern materials makes it feasible for the stiffness of a prestressed tensile structure to approach that of conventional structures. Furthermore, the continuing trend of increased material strength is clearly favorable for the second alternative, particularly so because buckling is not a consideration for the latter kind. Also, light weight and flexibility prior to prestressing make tensile structures portable and deployable.

This research effort is directed towards establishing the technical feasibility and practical implications of the tensile structure concept as applied to runway bomb repair. Specifically, the structure consists of a thin-sheet membrane placed over a bomb crater in the runway, stretched (prestressed), and anchored. One of the attractive features of the concept is its insensitivity to the crater pattern and, to a certain extent, to the individual crater size and shape. Also, it is possible that the repair time could be reduced considerably, as compared with other repair methods.

The following sections contain an outline of the concept, its basic features and structural behavior, some suggested structural details, and such pertinent aspects as fabrication, transportation, and deployment.

SECTION II

TENSILE STRUCTURE CONCEPT

This section provides the technical background necessary to understand the somewhat peculiar features of tensile structures in general and the proposed structure in particular. Consider a simple chain shown in Figure 1(a). It allows a variety of configurations and its kinematic analysis shows (Reference 1) that it possesses

$$n = 2p - c = 2 \times 3 - 4 = 2$$

degrees of freedom. Here p is the number of pins, each possessing two degrees of freedom (in plane), and c is the number of constraints (bars), each one depriving the system of one degree of freedom.

Now consider a slightly modified system of Figure 1(b), the configuration of which is rectilinear. This system also possesses two degrees of freedom; however, these cannot be realized and the system lacks kinematic mobility. In other words, if made of an ideal undeformable material, the system possesses a unique configuration in spite of the fact that it has two degrees of freedom. The system in consideration is the simplest representative of a wide class of structures ("quasi-variant") comprising, in particular, the so-called "tensegrity structures" patented by R. B. Fuller (Reference 2). Their structural behavior is quite unusual. Some of its relevant features (References 3 and 4) are exposed and discussed in the following paragraphs with simple structural models for illustration.

Like any structure made of a real material, these systems develop elastic (as opposed to kinematic) displacements owing to material pliability. However, the basic relations between displacement, strain, stress, and load carrying capacity are rather peculiar. Loads that the system is capable of balancing in its initial configuration are called equilibrium loads. Under such loads, the system behaves conventionally, e.g., it develops elastic displacements but no kinematic displacements, etc. Shown in Figure 2 is a cable(or a unit width membrane strip) with fixed

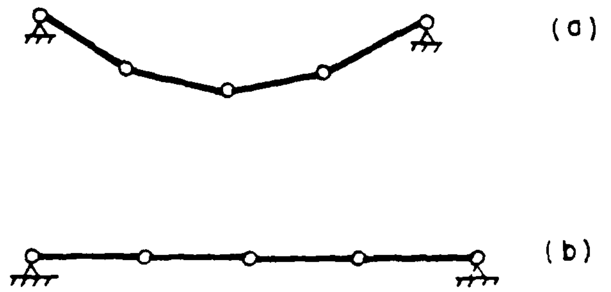

Figure 1. Tensile Structure Concept

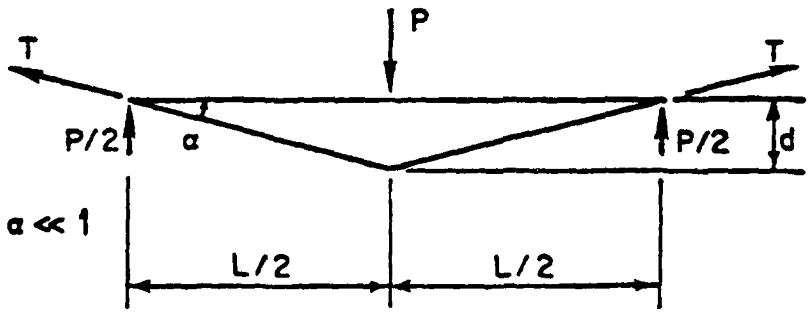

Figure 2. Unit Width Membrane Strip Over the Crater

ends and initially rectilinear configuration. The equilibrium loads for this configuration consist of forces acting along the cables, and only elastic displacements take place.

Loads involving transverse components, like a concentrated force, P, at the midspan, are nonequilibrium loads; hence, to balance them, the system must change its configuration. For the final deformed configuration of the cable (Figure 2), conditions of statics require that

$$d = \frac{PL}{4T}, \qquad \alpha = \frac{P}{2T} \tag{1}$$

where d is the midspan deflection, α is the slope (assumed small), and T is the final value of the cable tension. Simple geometric consideration shows that the elastic elongation of the cable, ε, and the corresponding increase ΔT of the tension are, respectively,

$$\varepsilon = \frac{1}{\cos\alpha} - 1 \simeq \frac{\alpha^2}{2} = 2\left(\frac{d}{L}\right)^2, \quad \Delta T = EA\varepsilon \tag{2}$$

where EA is the axial stiffness of the cable.

These formulas suffice to demonstrate the above-mentioned peculiar features of the structural behavior of the entire class of systems in hand under the action of nonequilibrium loads.

(1) As follows from the load-displacement relations, Equation (1), the tension plays the role of a stiffness parameter; both the deflection and the slope are directly proportional to the external load and inversely proportional to the tension.

(2) It is readily seen from Equation (2) that the strain and the corresponding axial force induced by a nonequilibrium load are proportionate to the square of the linear or angular displacement; thus, a small displacement gives rise to the strain and internal force of the second order of smallness.

(3) Bearing in mind that T in the above formulas is the final value of the tension force, it is obvious that doubling the external load does not double either displacement or, even more importantly, the tension in the cable. This characteristic feature, called "geometric strain hardening," provides an inherent, built-in,

additional safety factor.

(4) It is convenient and justified to state that, because of geometric strain hardening, the load carrying capacity of the system under consideration is determined by the material's ultimate elongation rather than its ultimate strength. In other words, upon reaching the yield stress, there still exists a tremendous reserve of load carrying capacity; for a material (steel) with the ultimate elongation of 18 percent and the yield strain 0.33 percent, even conservatively disregarding material strain hardening, the ultimate load exceeds the yield load by a factor of about

$$\sqrt{\frac{\varepsilon_u}{\varepsilon_y}} = \sqrt{\frac{0.18}{0.033}} \simeq 7 \quad .$$

The model of Figure 2 is utterly simple. Nevertheless, it reveals the quintessence of the tensile structure concept, accurately reflects its basic properties and features, and explains their origin and meaning without unduly complicating and obscuring them with accompanying details irrelevant for the moment.

With regard to the thin-sheet membrane of interest, two important practical implications follow from the above general description:

- The governing factor determining the membrane thickness is the allowable slope rather than (what one might expect) the crater span or the membrane load carrying capacity.

For the tensile structure concept, the lateral stiffness is proportional to the amount of prestressing and is therefore inversely proportional to the allowable slope [Equation (1)]. The maximum allowable slope of a bomb damage repair ranges from 0.33 percent to 3.3 percent. This allowable slope is critical in the design of the tensile structure concept, as a reduction of the allowable slope from 3.3 to 0.33 percent requires more than a 10-fold increase in the prestress level. This produces a corresponding increase in membrane thickness and anchoring requirements. Therefore, throughout this study it was assumed that a 3.0 percent slope would meet all runway repair requirements.

Some reduction of this slope may be possible, depending primarily upon runway pavement strength characteristics. It would appear, however, that reduction in the allowable slope to less than 0.33 percent would impose excessive requirements in terms of increased membrane thickness and anchoring requirements. A viable alternative to these increases would be the use of a water bag underneath the membrane.

The second part of Equation (1) shows that, for a cable, the slope simply does not depend on the crater size; this is basically (albeit not exactly) true for the membrane as well. With regard to the allowable slope of 3 percent, for an initially stress-free membrane, it would be achieved long before the ultimate elongation and, hence, the load carrying capacity of the membrane is approached. This clearly suggests the second implication.

- The membrane should be prestressed to a level close to the yield stress. Specifically, additional strain resulting from the 3 percent allowable slope should bring it to yield within a nominal safety margin designated to avoid actual yield, which would be undesirable but far from fatal.

Thus, the membrane is prestressed almost to yield before its main (and practically the only one) load is applied. Such is the specificity of the tensile structure in consideration. In this way, both the utmost utilization of the material strength and the maximum achievable stiffness of the membrane are attained.

In light of the above, some requirements of the membrane material become apparent. It must have as high a yield stress as possible, yet be weldable without degrading strength and, above all, must not be brittle. Orthotropic materials like fabric or fiber-reinforced films are not good because of their relatively low shear resistance. This practically narrows the selection to some sort of steel, such as the USS T-1 constructional alloy steel (minimum guaranteed yield stress F^{ty} = 100 ksi, ultimate elongation e^u = 18 percent) or the somewhat more expensive, but far suprior 9Ni-4Co-0.20C steel (F^{ty} = 180 ksi, e^u = 10 percent) (Reference 5).

The utmost utilization of the membrane strength is achieved under biaxial tension; this is highly desirable for yet another reason, the minimum deflection and slope. As a first cut, a rough (though conservative) evaluation of the biaxially stressed membrane can be obtained by representing it with two perpendicular, crossing, unit width strips and using the above formulas. This, however, requires that the membrane be biaxially prestressed and securely anchored in every direction. The feasibility and practical implementation of such anchoring is discussed in the next section.

To get an idea of the magnitude of membrane forces and stresses to be dealt with, consider those produced by the F-4E (single wheel load, 27,000 pounds; tire pressure, 265 psi). The tire imprint area is roughly 100 in^2 (assumed 10- x 10-inch square) and the total load carried by the most stressed, unit-width longitudinal strip of the membrane can be taken

$$P = 265 \times 10 = 2650 \text{ lb/in} \quad .$$

At the 3 percent allowable slope this results in membrane tension, Equation (1)

$$T = \frac{2650}{2 \times 0.03} = 44,167 \text{ lb/in}$$

for a uniaxially stressed membrane and

$$T = 22,083 \text{ lb/in}$$

for a biaxially stressed one. In the latter case, the required thickness of a membrane of T-1 steel is of the order of 3/16 inch. The conservatism of this crude estimate was confirmed by a more accurate finite element analysis. Note that calculated stresses do not reflect the dynamic load action, which could be accounted for as a first approximation by introducing a dynamic load factor. This was not done, however, since there is no doubt in the load carrying capacity of the membrane and a more rigorous dynamic analysis is one of the subjects of Phase II of this project.

The horizontal braking forces have also been neglected in the analysis. It is assumed that the additional stress induced in the membrane by the braking loads is negligible when compared to the total membrane stress, or even prestress alone. Inclusion of these braking forces would therefore unduly complicate this analysis. However, should it be desirable to include braking forces in a more comprehensive analysis, they can be accommodated easily.

SECTION III

ANCHORING

Rather high tension force is the manifestation of yet another characteristic feature of the type of structure in hand; its action is such that each pound of vertical load translates into many pounds of tension with the amplification factor of the order of the inversed slope. Now the problem is to support this tension force externally, i.e., *to anchor the membrane.* Basically, there are only two possibilities: edge anchoring or surface (continuous) anchoring. These must be carefully weighed against each other.

The edge anchoring requires a structural adaptor transferring the membrane tension to a supporting structure. It would be highly advantageous to employ the surviving runway as an anchor, e.g., by attaching the membrane at the runway expansion slab joints which form a regular pattern. Significant effort was made in an attempt to find a practically sound structural solution along this line; however, no satisfactory solution was found. Some of the difficulties encountered are:

- The concrete slab edge would have to be considerably modified and reinforced to render it capable of supporting the required force. The modification would be reasonably feasible for a new construction runway, but does not look practical for retrofitting an existing runway.
- Since the damage pattern and location are more or less random, all the slab edges would have to be modified in order to provide the necessary versatility while using modular membrane lengths. Therefore, cost would become a serious factor.
- Attempts to design a system of edge anchors independent of the runway proved to be discouraging; their construction volume and complexity would be comparable to the runway itself.

Surface anchoring implies bonding the membrane to the runway pavement, thus utilizing the entire surface area of the membrane except for its portion over the crater. The continuous character of this connection suits perfectly the continuous nature of the membrane; in addition, it provides biaxial anchoring (it would take four edge anchors to do the same). This "spread" anchor uses the existing attribute of the membrane (its surface) and requires neither additional structural parts (adaptors) nor runway modifications. It is less vulnerable to possible damage (local damage to the edge anchor might be fatal for the entire membrane).

So far the recognized disadvantages and problems of the continuous anchoring are:

(1) Some preparation of the pavement surface will be required prior to bonding (to remove loose gravel, sand, or dust; to dry the surface in order to achieve full adhesive strength, etc.)

(2) To preclude the possibility of brittle rupture, the adhesive must undergo considerable elongation, shear deformation, before its ultimate strength is achieved.

(3) Rheologic effects (creep) in both the adhesive and, maybe even more so, in the asphaltic concrete must be carefully evaluated and controlled; otherwise, considerable loss of prestress in the membrane can occur.

Pavement surface condition and necessary preparation represent an important consideration. Actually, this aspect is about the only advantage of the edge anchoring, which is practically insensitive to the surface condition. However, both this and the second aspect (adhesive toughness) become somewhat less critical in the light of very moderate requirements to the adhesive strength. The fact is that the available, though rather scattered, data suggest that the shear strength of asphaltic concrete (Reference 6) can be conservatively taken in the range of 200 to 300 psi, so that the bonded connection can be easily as strong. Having the adhesive bond stronger than the asphaltic concrete does not make sense, because in this case the asphalt becomes a weaker link. Therefore, the easily obtainable reserve of the adhesive strength may be used to partially offset the strength reduction owing to the pavement surface condition, thus enabling the otherwise stringent requirements to be relaxed to a certain extent.

Taking the above figure of 200 psi as a representative one for the time being and assuming the membrane tension force to be 22,000 lb/in, the necessary anchoring length can be evaluated as

$$\frac{22{,}000\ \text{lb/in}}{200\ \text{psi}} = 110\ \text{inches} \quad .$$

This length can be afforded easily. Actually, it shows that factors other than the bonded connection strength are likely to govern the required amount of the membrane area beyond the crater. Two such critical topics of immediate concern are:

(1) The creep rate of the asphalt, especially at high ambient temperatures, and its brittleness at low temperatures. Of these, the first one seems to be of a lesser concern since the asphalt pliability at elevated temperatures enhances a more uniform shear stress distribution over the large bonded area. The lower stress level will, in turn, reduce the creep rate. With regard to brittleness, it must be carefully evaluated experimentally and minimized by all possible means. The hazard is the possibility of an abrupt brittle failure, e.g., in peeling mode. Note that both the potentially hazardous features are associated with asphalt and are much less critical in the case of concrete pavement.

(2) The amount and the pattern of runway damage must not exceed certain limits within which the surviving runway is capable of supporting reaction forces induced by the pre-stressed membrane. There are compression forces and bending moments in the runway slab and slab-subgrade friction (Figure 3).

To improve the reliability of the membrane bonded connection, it might be complemented with explosively driven studs "riveting" the membrane to the pavement. These would be especially efficient in preventing the peeling mode of failure. However, this would introduce an additional "technology," increase the repair time, and in case of poor installation jeopardize the aircraft tires by possible protrusion. Far more preferable is another structural solution which would cut through all the above-mentioned difficulties and problem areas by appreciably

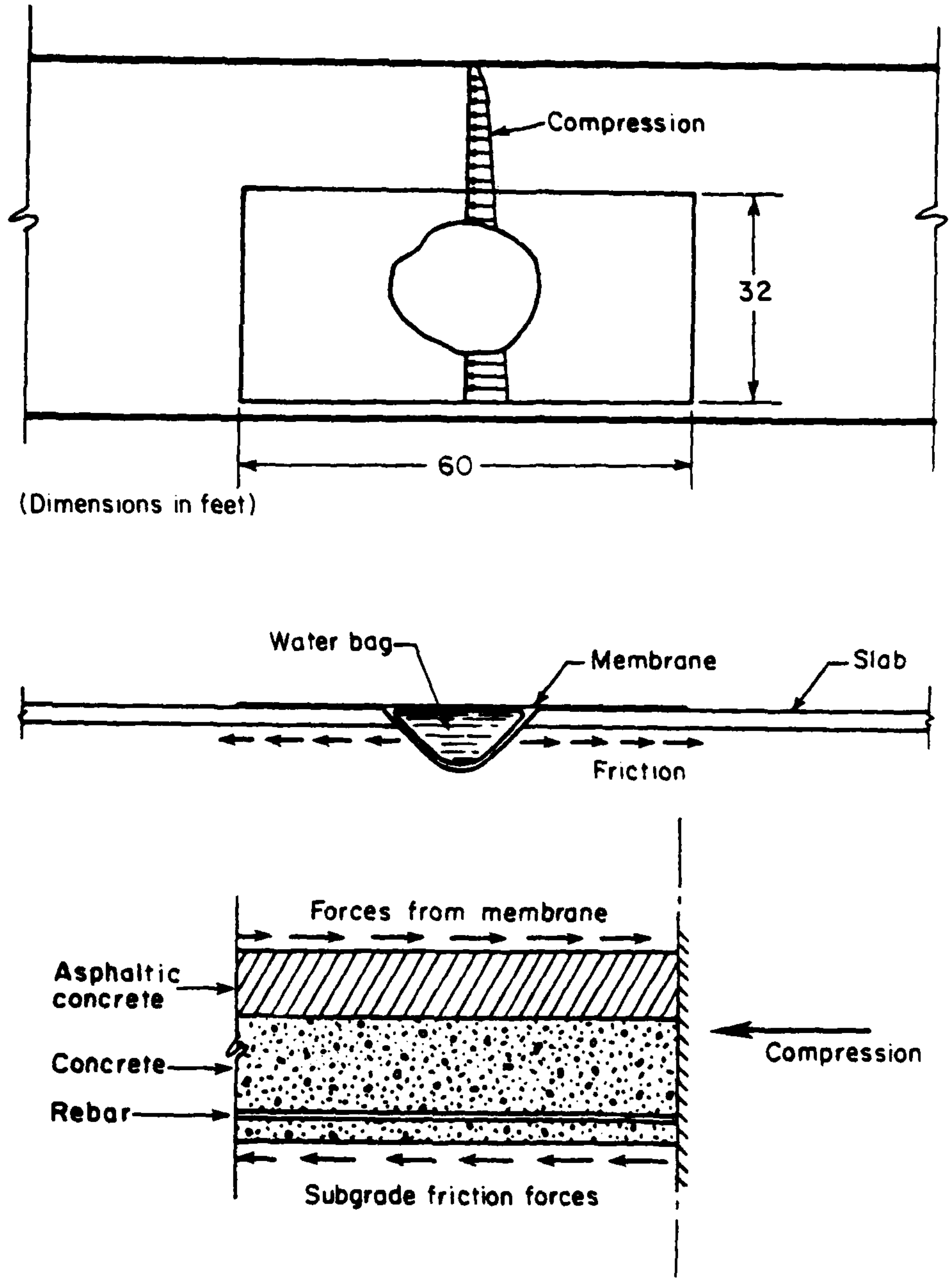

Figure 3. Forces in Structural Members

reducing the membrane tension requirements. This solution is rather simple and straightforward: to introduce a lateral support by installing a water bag in the crater (Figure 3).

First, some midspan support of the membrane is required to prevent it from sagging in the crater during installation; the absence of such support would complicate both the deployment and, especially, the prestressing. Employing a water bag appears to be the most practical way of accomplishing this task.

Second, introducing this additional support affects in the most favorable way the entire chain of involved problems--amount of prestress, membrane thickness, anchoring, pavement strength, and creep.

Third, it will smoothen considerably the bump produced by the landing gear passing over the crater edge, the bump which is potentially damaging to both the aircraft and the membrane. Interestingly, it is reasonable to expect that, the higher the aircraft speed, the stronger the smoothing effect of the water bag.

Taking into account the simplicity of the water bag installation, as well as the just listed advantages, it should be considered as a highly desirable feature, especially for larger craters.

SECTION IV

FINITE ELEMENT MODEL AND ANALYTICAL RESULTS

The formulated analytical model simulates a thin prestressed membrane bonded to a 4-inch-thick layer of asphaltic concrete. Analyses were performed using the contractor-developed finite element program SHELL, comprising two types of finite elements: a constant-strain, prestressed membrane triangle and a truss element. Accordingly, the layer of asphaltic concrete (together with a thin layer of adhesive) was represented by an arrangement of truss elements.

Data on the mechanical properties of asphaltic concrete (modulus of elasticity, shear modulus, yield stress, etc.) are scattered. These properties are also strongly temperature dependent. In the absence of more accurate data, some assumptions were made on both the properties of asphaltic concrete and its bonded connection with the steel membrane. The Young's modulus of asphaltic concrete was taken as E = 500,000 psi for one group of cases and E = 100,000 psi for another. The contribution of the thin layer of adhesive to the compliance parameters was disregarded, i.e., the bond was assumed to be much more rigid in shear than the asphaltic concrete. The underlying layer of concrete was also considered absolutely rigid. These simplifying assumptions were made not because of the complexity of the analysis (which is relatively simple) but as a matter of being consistent with the accuracy of the above-mentioned input data.

The smallness of the allowable slope and, hence, deflection makes the problem geometrically linear, albeit not in the conventional, straightforward meaning of this definition (identifying the initial configuration of the structure with the final one). Obviously, the two configurations are different (Figure 2) and this must be taken into account. However, the additional elastic elongation of the membrane induced by the live load is small as compared with that induced by prestressing. Therefore, the membrane stress figuring in the stiffness parameters (which must be the final stress value) can be identified with its initial value. This is what makes the problem geometrically linear. Of course, the final values of stresses in the membrane obtained by this analysis are different from the initial ones and their difference shows how well justified is the disregard of geometric nonlinearity. Last note that, for this type of structure under consideration, the geometrically linear approach is conservative; both the deflection and the membrane stresses are slightly exaggerated.

As far as material nonlinearity is concerned, it is not an issue with the membrane. Though it would not be fatal if the membrane yielded (because of geometric strain hardening), the resulting permanent waviness would be detrimental to its stiffness and could also reduce the operation life span by facilitating fatigue and crack growth in welds, especially if the latter are embrittled. Accordingly, in the analysis, the membrane was always assumed elastic.

Unlike steel, asphaltic concrete exhibits complex material behavior involving both rheologic features (visco-elasticity and viscoplasticity) and material nonlinearity. It was decided, however, at this stage of the project, to represent it as a linearly elastic material while reflecting both the material nonlinearity and the effect of creep by an appropriately reduced value of the modulus of elasticity.

One of the implications of the above assumption is the fact that calculated shear stresses in the asphalt in the vicinity of the crater edge can be expected to considerably exceed the ultimate shear stress while rapidly decaying with distance (Figure 4). The actual shear stress diagram taking into account the elasto-plastic behavior is shown by the broken line, assuming equal shadowed areas above and below the shear yield stress τ^y. Strictly speaking, this assumption is true if the stresses in the membrane are the same in both cases, which is a reasonable working assumption considering the local character of the above shear stress redistribution. Thus, disregarding the material nonlinearity of asphaltic concrete, while considerably reducing the computational volume, results only in a local redistribution of the shear stress

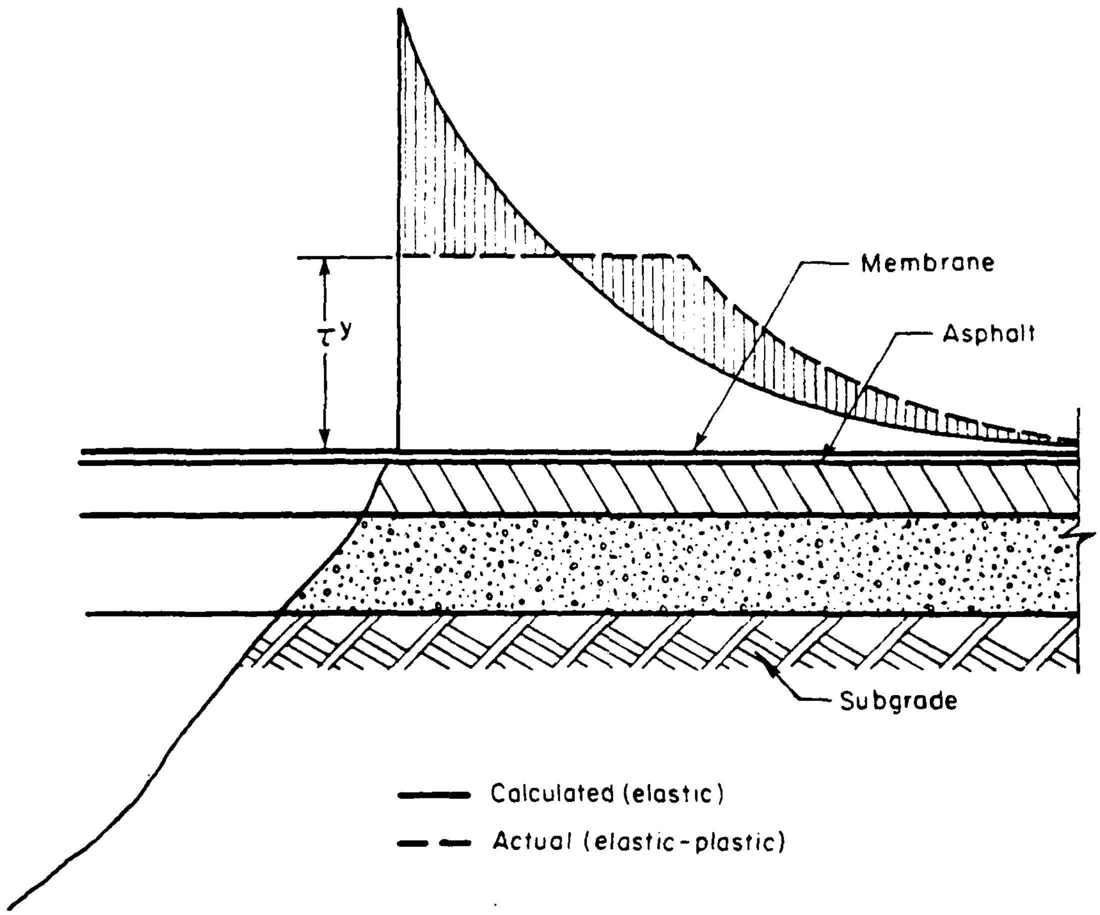

Figure 4. Shear Stress Diagram in Asphaltic Concrete

and hardly any distortion in the membrane stress state. For this reason, the assumption is regarded as fully appropriate at this stage.

For all the crater sizes and aircraft loads to be tested, it was decided to use just one 60- x 32-foot, 3/16-inch-thick steel membrane. A number of considerations were taken into account when sizing the membrane (in particular, fabrication, transportation, and deployment). Though some adjustments of the sizes are possible as a result of a more detailed design, the analyses carried out so far show that, basically, the sizing is correct.

Three finite element meshes were generated, according to the three designated crater sizes--5, 20, and 40 feet in diameter (Figures 5, 6, and 7, respectively). The first mesh (5-foot crater) assumes four axes of symmetry and, accordingly, comprises one-eighth of the analytical model. The two remaining meshes assume only two axes of symmetry and represent one-quarter of the analytical model. As seen in the figures, the crater contours, compatible with their respective finite element mesh patterns, are intentionally made only approximately circular which is consistent with the real, somewhat irregular, crater shapes.

The loading sequence was the same in all three analyses. First, thermal prestressing of the membrane was simulated to a more or less uniform initial stress of around 100 ksi (recall that 100 ksi is the minimum guaranteed yield stress for T-1 constructional alloy steel, and 180 ksi is the same for 9Ni-4Co-0.20C steel). Then the vertical load from the aircraft was applied at the assumingly most unfavorable location over the membrane. The configuration of the load corresponded to the landing gear tire pattern with the loaded area equal to the gear load divided by the given tire pressure (in Figures 5 through 7 the loaded elements are shadowed).

For 5-foot and 20-foot craters, the bonded area of the membrane outside the crater was more than sufficient to provide complete biaxial anchoring. As a result, the membrane performance was superb, with rather uniform stress distribution and small deflection. Following are some data on the 20-foot

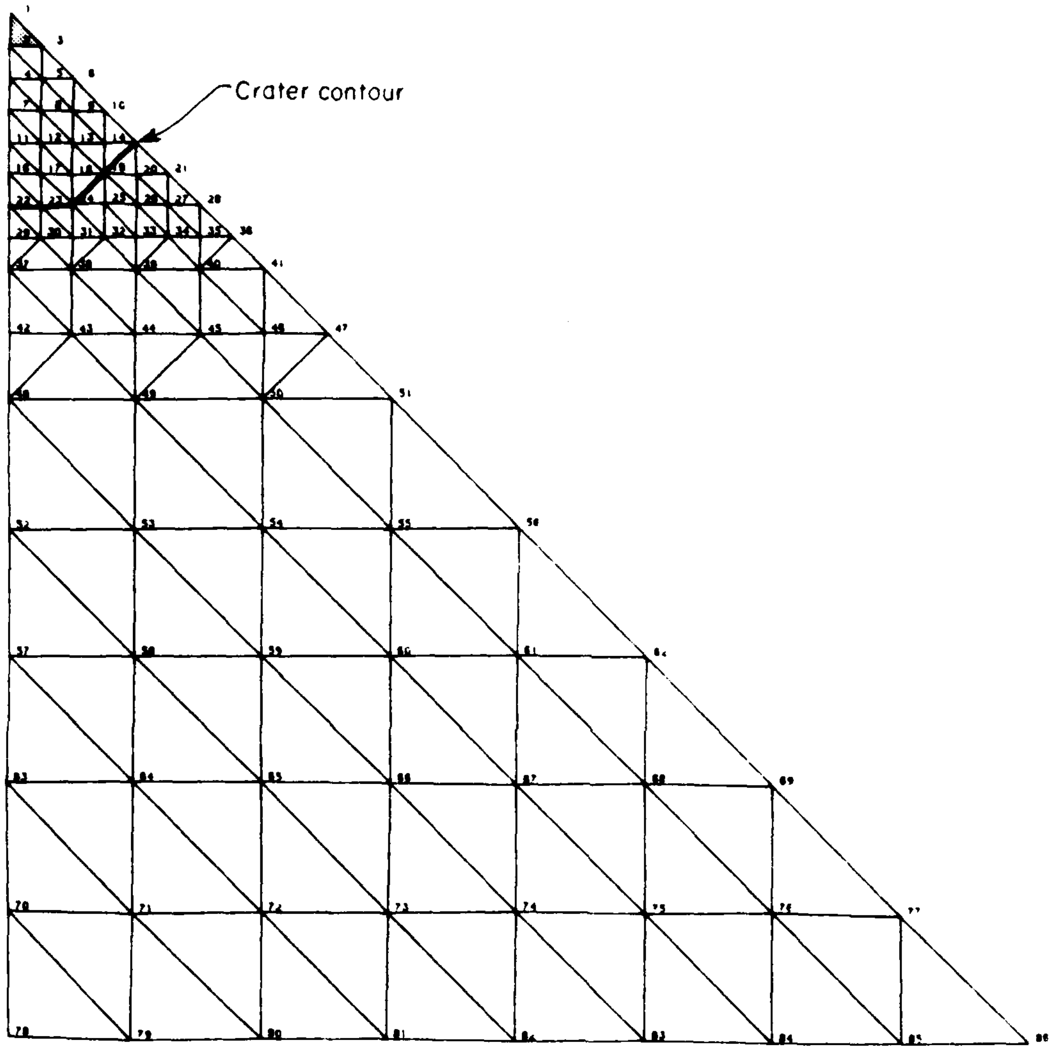

Figure 5. Finite Element Mesh for 5-Foot Crater

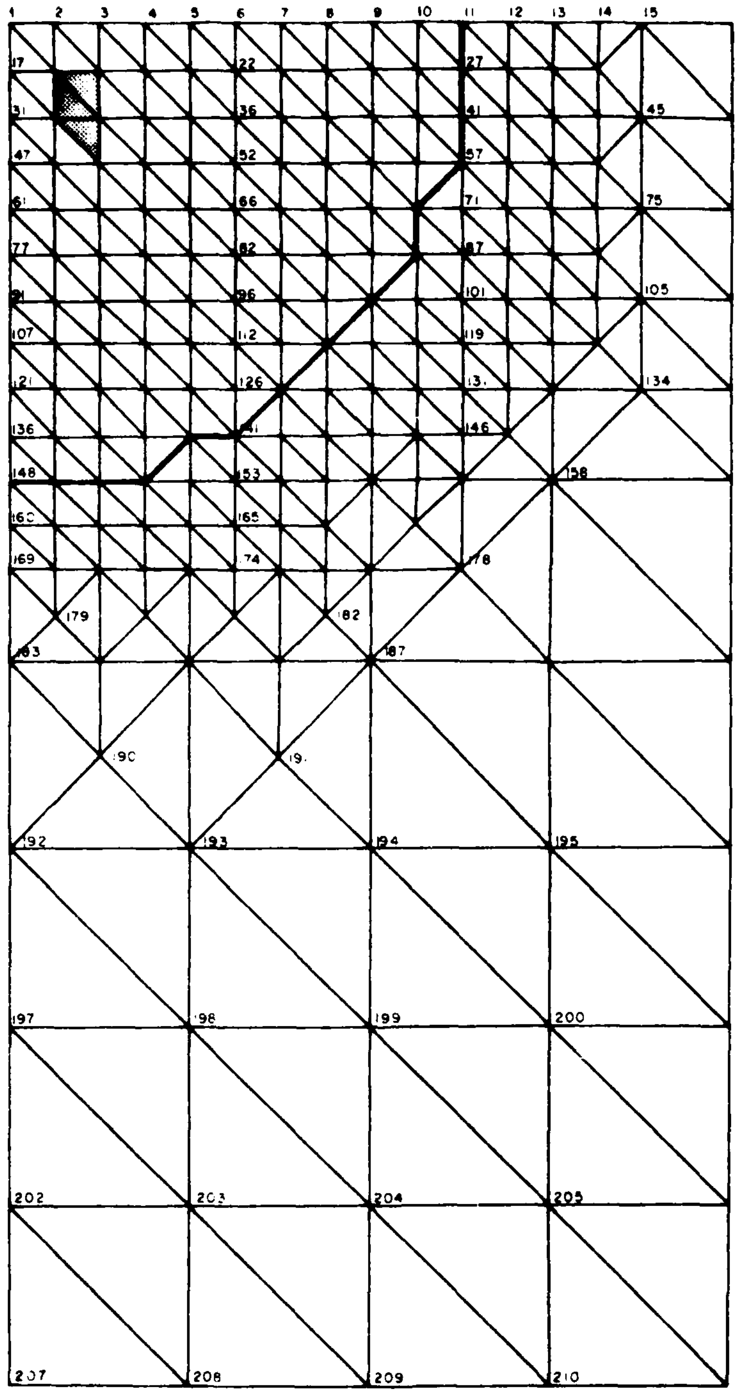

Figure 6. Finite Element Mesh for 20-Foot Crater

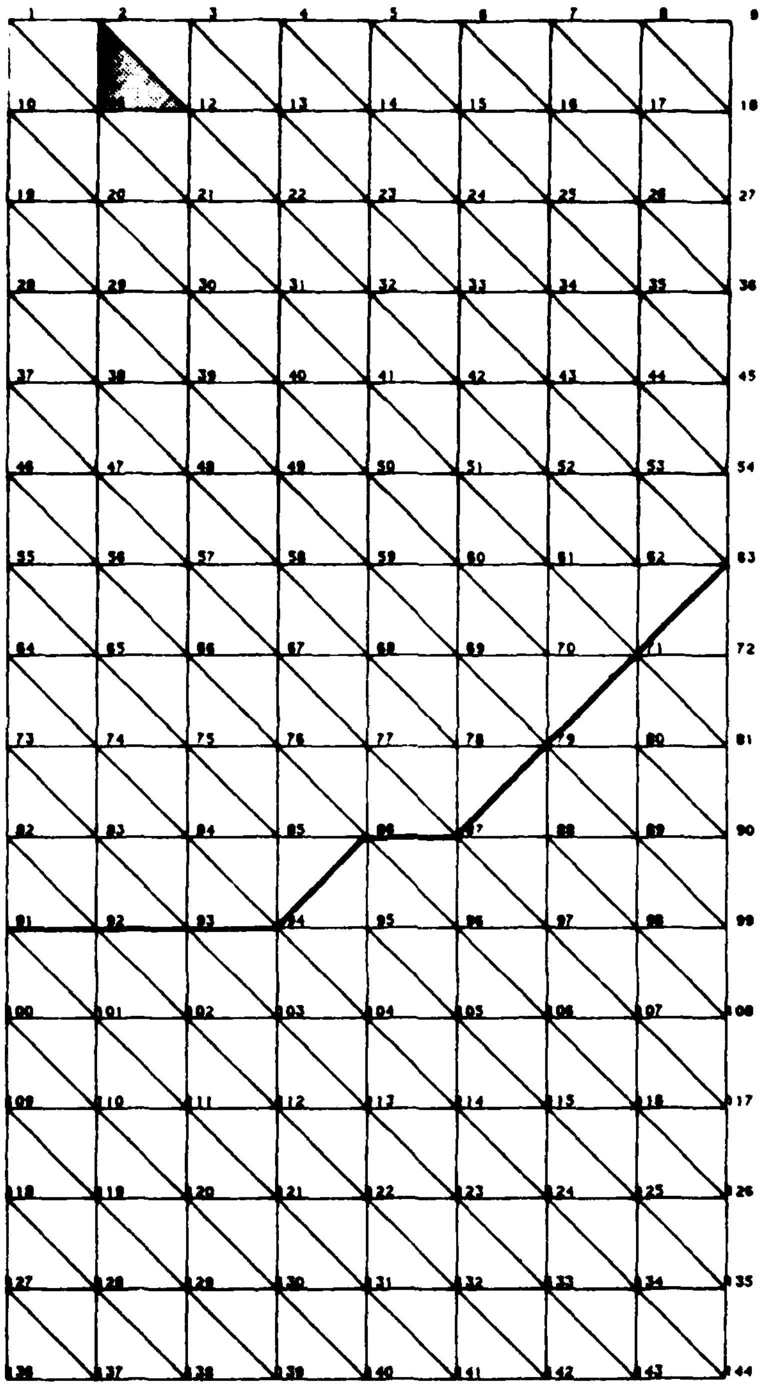

Figure 7. Finite Element Mesh for 40-Foot Crater

crater under C-141B load (Figure 6).

The maximum stress in the membrane occurred in Element 33-49-50 where the principal stresses in ksi rose from $\sigma_1 = 117$ and $\sigma_2 = 110$ in the state of prestress to $\sigma_1 = 132$ and $\sigma_2 = 117$, respectively, under the main gear load. The maximum deflection in the membrane occurred at Node 18; it is $d_{max} = 1.72$ inches, which is only 0.014 of the crater radius, so that the slope is just under one-half of the allowable slope of 3 percent (advantage of biaxial stress state).

The repair pattern and its performance were somewhat different for the 40-foot crater. It was found impractical (though not ruled out) to have a single membrane of the size necessary to cover this crater. Instead, two membranes measuring 60 x 32 feet can be combined to do the job with two possible arrangements as shown in Figure 8. The first (criss-crossing) arrangement seems advantageous, but it is not always feasible, e.g., when the crater is close to, or goes beyond, the longitudinal edge of the runway. Nevertheless, this arrangement was analyzed for C-141B load.

Assuming that each of the two criss-crossing membranes supports half the total load, only the first quadrant of one membrane was modelled (Figure 7). As expected, the state of prestress came out much less uniform, because one edge of the membrane is not anchored at all. Therefore, the initial stress state varies from a uniaxial stress along the free edge to a rather nonuniform biaxial one at the middle of the membrane. The most highly stressed element is 10-20-11 with its principal stresses in ksi risen from $\sigma_1 = 115$ and $\sigma_2 = 16$ in the state of prestress to $\sigma_1 = 138$ and $\sigma_2 = 36$, respectively, under load. The maximum deflection (Node 2) is $d_{max} = 4.46$ inches or 0.019 of the crater radius, which is considered reasonable for an almost uniaxial stress state and confirms the conservatism of the first-cut estimate based on the elementary analysis of a unit width membrane strip.

The asphaltic concrete performance was in line with expectations. With its modulus of elasticity taken as E = 140 ksi,

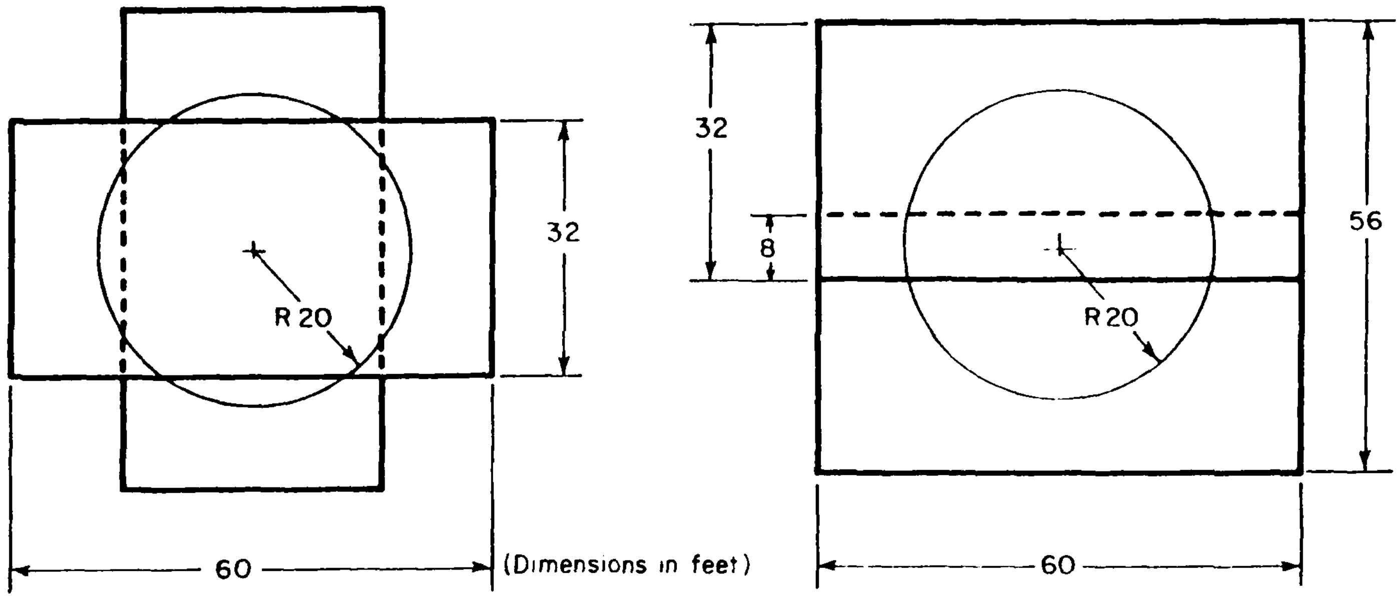

Figure 8. Membrane Arrangements for 40-Foot Crater

it developed a peak shear stress of only 375 psi, rapidly decaying with distance from the crater edge. The stress redistribution, similar to the one shown in Figure 4, would certainly take place if viscous and nonelastic behavior was taken into account.

The objective of the described analytical effort was to quantitatively characterize the tensile structure concept and to establish the major features and trends of its structural behavior. This has been done at the level of accuracy adequate to the feasibility study and sufficient for tentative material selection and member sizing. To this end, the membrane stresses may be scaled up (9Ni-4Co-0.20C alloy steel) or down (T-1 alloy steel) with the corresponding adjustments in the membrane thickness. Addressing the problem with all the rigor of modern stress analysis will be in order when (and if) the feasibility is proven and more complete data on membrane-pavement interaction are obtained.

The analytical results of this study appear encouraging, although the dynamic phenomena have not yet been considered, and the properties of asphaltic concrete have not been fully accounted for; however, the significant structural support possible through the use of a water bag installation has not been considered either, and there is every reason to expect that its effect will be rather far-reaching.

SECTION V

FABRICATION, INSTALLATION, AND OPERATION

All these aspects are directly related to the membrane material selection. So far, the best candidate material for the membrane remains the 9Ni-4Co-0.20C alloy steel. It leaves little more to be desired from every respect taken into consideration, except its cost which is discussed below. Some of the most important (for this particular application) properties (Reference 5) of the 9Ni-4Co-0.20C alloy steel are:

> "The alloy was developed specifically to have excellent fracture toughness, excellent weldability...it can be readily welded in the heat-treated condition with pre-heat and post-heat usually not required...The alloy may be exposed to temperatures up to 900°F...without microstructural changes which degrade strength."

The properties just listed suggest that the membrane can be prefabricated by welding it from parallel sheets arranged longitudinally. It will easily sustain the elevated temperature necessary for prestressing without loss of strength.

An attempt was made to provide a direct cost comparison between the 9Ni-4Co-0.20C alloy steel and the T-1 constructional alloy steel. It was found that to make such a comparison at this early conceptual stage is not practical. This is due to two factors. First, the T-1 alloy steel is a widely available, common constructional steel, whereas the 9Ni-4Co-0.20 alloy has been developed primarily for use in the aircraft industry. At present 9Ni-4Co-0.20 alloy is considered a "speciality" steel, and is neither commonly used nor widely available. A firm price for the 9Ni-4Co-0.20 alloy could therefore not be established.

Second, the cost for either the T-1 alloy or the 9Ni-4Co-0.20 alloy will vary greatly depending upon the quantity of steel required. Should the proposed use of tensile structural membranes be adopted and put into large-scale operation, the price per pound of both alloy steels would undoubtedly decrease. It is also reasonable to assume that the price for the 9Ni-4Co-0.20C alloy steel would decrease in a relative sense more than the T-1 alloy steel. However, the specific amount of such a reduction in price has not been determined.

For the above reasons, a direct cost comparison of the two steel alloys has not been made. It should be assumed that the 9Ni-4Co-0.20C alloy steel will be more expensive than the T-1 alloy steel. Selection between the two alloys will have to be delayed until specific requirements in terms of material strength, configuration, and quantity have been established.

Transportation, storage, and deployment methods, most likely, will be those used routinely in the construction of large prefabricated steel reservoirs (Reference 7). The only difference is that the prefabricated reservoir sheets are up to 60 meters long, 12 meters wide, and 6 to 7 millimeters thick which makes their weight in excess of 30 tons. To compare, a 60- x 32-foot, 3/16-inch-thick membrane weighs under 8 tons, which enables more conventional equipment (lighter trucks, tractors, and trailors) to be used for transportation and deployment.

Upon fabrication, the sheets are coiled on a ring-stiffened cage necessary for the right coil formation and preservation of the sheet's form in loading, unloading, and shipping. The minimum allowable coil diameter is determined from the condition that no permanent strain should be induced by coiling; thus, the diameter depends on the sheet thickness and the ratio of the modulus of elasticity and the yield stress for the material in hand:

$$D \geq \frac{E}{F_{ty}} t \quad .$$

For T-1 constructional alloy steel:

$$D \geq \frac{30,000}{100} t = 300 t \ ,$$

and for 9Ni-4Co-0.20C alloy steel

$$D > \frac{28,800}{180} = 160\ t \quad .$$

For a 3/16-inch-thick sheet, the two respective minimum diameters become $\sim$ 60 inches and 30 inches, both more than adequate to keep the sheet far from the oversize load category (recall that the coil length, i.e., the membrane width, is 32 feet).

Some operations associated with coil handling at loading/unloading, transportation and deployment, as applied to the above-mentioned, much heavier prefabricated parts of large cylindrical reservoirs, are shown schematically in Figures 9 through 12. These are reproduced from Reference 7 which contains some further details and references.

An operation both peculiar to and crucial for the tensile structure concept is prestressing. It was briefly discussed in one of the preceding sections, in connection with anchoring. Basically, there are only two ways of prestressing the membrane--mechanical and thermal. Generally speaking, either one is compatible with both edge and surface anchoring. However, mechanical prestressing requires some edge adaptors, which transform continuously distributed membrane stresses into discrete, concentrated forces acting at a number of anchors. This results in several serious disadvantages associated with mechanical prestressing.

First, because of the huge total prestressing force in the membrane (tension per unit width, $\sim$ 22 kips/inch, times the membrane width, 32 x 12 inches, i.e., 8,448 kips), either the size or the number of individual anchors (or both the size and the number) would be large. Accordingly, either the individual capacity or the number of hydraulic jacks required for prestressing would be large. All the equipment units would have to be operated synchronously, requiring a lot of well coordinated manpower and pumping station power. The possibility of biaxial prestressing would become more then problematic.

Second, it would not make sense to prestress the membrane

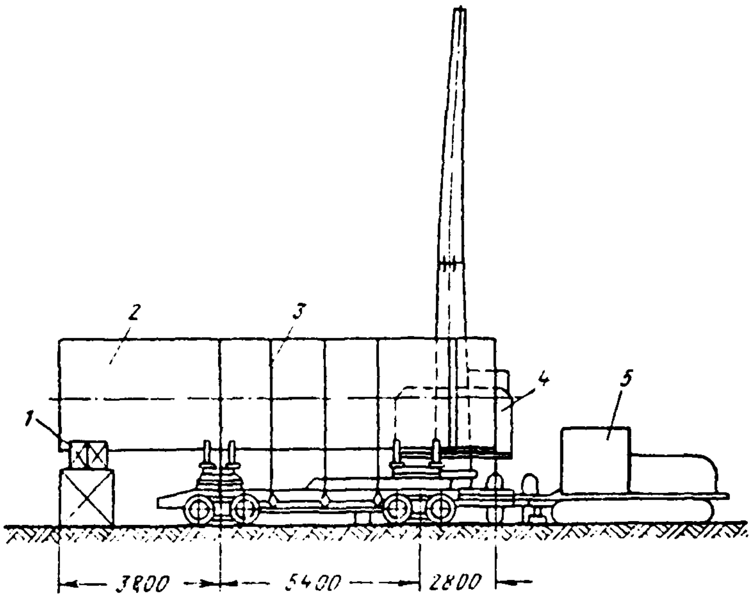

Figure 9. Coil Loading on a Trailer

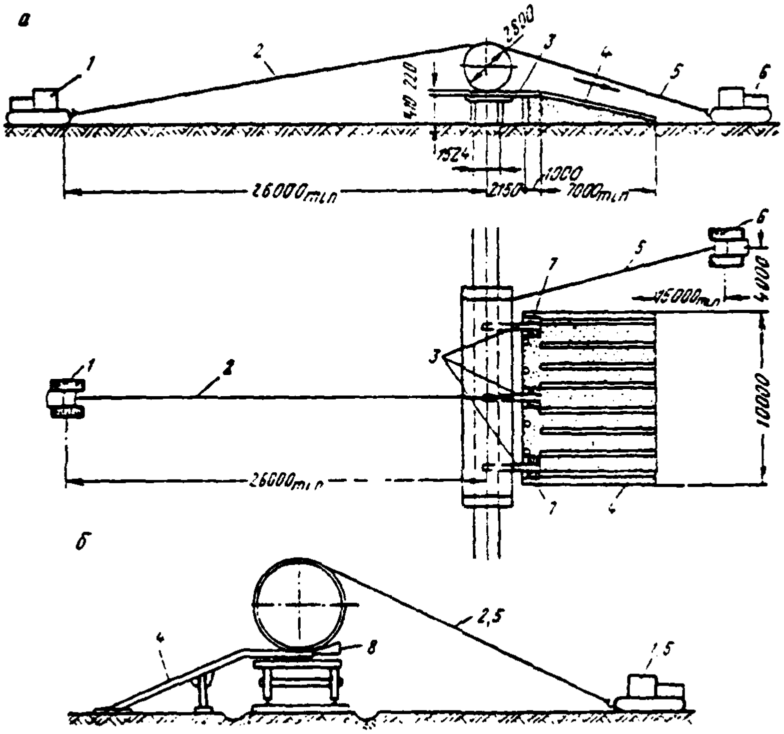

Figure 10. Coil Unloading From a Railroad Car

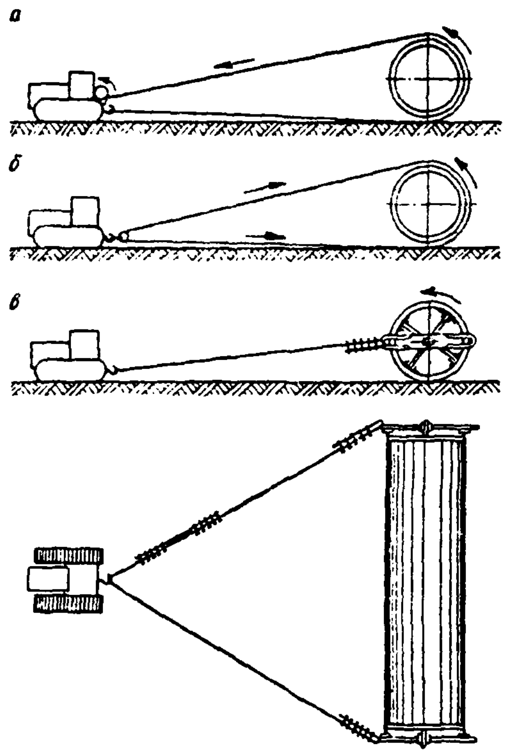

Figure 11. Coil Rolling

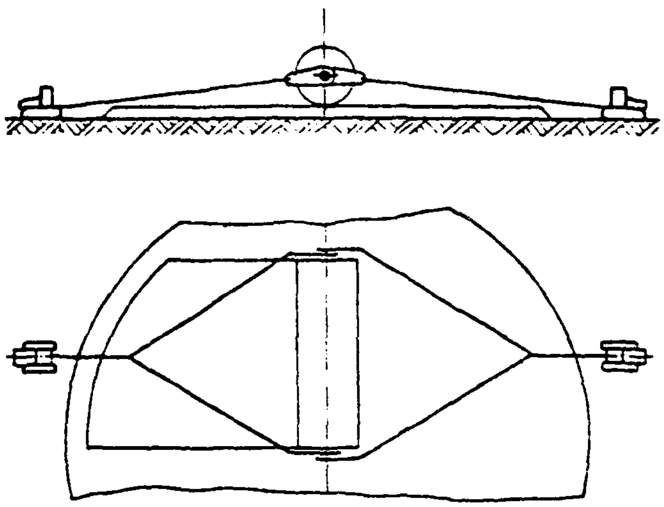

Figure 12. Coil Deployment

mechanically and employ surface anchoring (bonding). Indeed, to invest so heavily in the structurally complex system of mechanical anchors and use them only for prestressing and not for anchoring seems illogical and wasteful (the anchors would have to be removed). As mentioned earlier, edge anchoring, as opposed to surface anchoring, is much less versatile because it would require some modification of all the concrete slabs and thus would practically rule out retrofitting the existing runways. Moreover, it does not look trivial to embed the anchors in the pavement to provide a smooth flat surface.

Hence, the only remaining alternative--thermal prestressing--must be assessed very carefully. Technically, it looks both feasible (it takes only about 300°F above ambient temperature to produce the necessary thermal expansion) and attractive (almost effortless as compared to the mechanical means necessary to induce the required thousands of kips). The possibility of combining the membrane heat-up with thermal cure (mandatory for many adhesives and requiring roughly the same temperatures as prestress) renders the method even more attractive. This method, however, is not as simple and straightforward as it appears.

The fact that, in order to acquire a uniform prestress, the membrane must be reasonably flat (stress free) in the heated condition. Only a linearly varying temperature distribution (uniform temperature, for the purposes of this application) leaves the membrane stress free. Suppose, for instance, that only the circular membrane area over the crater is heated up. This would give rise to a thermal stress field with some of the stresses (mainly in the heated zone) compressive. This area would buckle out of plane, that is, bulge or sag. Now, if in this state the membrane was anchored and cooled down, the bulge would disappear but virtually no prestress would be induced.

One the other hand, heating up the whole membrane has disadvantages too. Upon cool down, the procedure would induce excessive but unnecessary stress in the pavement (much more than the anchoring requires), thus aggravating pavement strength and creep problems. Fortunately, many of the adhesives requiring thermal cure (Appendix A) do not acquire appreciable strength in the course of cure. This means that the bonded area of the membrane might cool down and shrink without experiencing much resistance from the bonded connection, i.e., not inducing much stress in the pavement. If the middle segment (say one-third of the total length) of the membrane is kept hot until the adhesive acquires a certain strength after which the membrane is cooled down, the desirable prestress in the membrane will be obtained. It will not be uniform, however, because of the complicated temperature patterns and different anchoring actions in the longitudinal and transverse directions of the membrane.

Heating up the whole membrane has one more side effect: it will be accompanied by heating at least the top layer of asphalt. This necessitates assessing and, possibly, controlling the whole chain of consequences (reduced modulus of elasticity, increased creep rate, and the like).

It is possible to avoid heating up the whole membrane by employing an adhesive which cures at ambient temperature (epoxy based adhesives). In this case only the middle segment of the membrane will have to be heated and a uniaxial prestress will be obtained. In any event, some additional effort and more information on the properties of materials involved (mainly, asphaltic concrete and adhesive) are required before a suitable combination of heating and bonding patterns is developed to optimize the membrane state of prestress. With regard to the heating-up process itself, the main problem is to identify a suitable combustible material from the standpoint of burning temperature and time. It could have a consistency (and, maybe, other properties) similar to that of sterno paste, which burns quietly, and is simple to handle and apply.

The envisioned installation procedures are as follows. After initial preparation of the runway surrounding the crater site, consisting mainly of removal of debris or loose gravel, the tensile membrane will be positioned over the damaged area. The anchoring adhesive and combustible material will then be applied simultaneously. Details related to application of the adhesive will depend upon the specific adhesive chosen, but it is likely that an adhesive coating will be applied to both the runway surface and the underside of each end of the membrane. The combustible material will be applied to a narrow band across the middle segment of the membrane.

Once the adhesive and combustible materials are in place, the combustible material will be ignited. The middle segment of the membrane will be required to reach about 400°F. The middle segment can be heated to this temperature in a matter of seconds, since the membrane is so thin. Once the middle segment has reached the proper temperature, the membrane will have lengthened in a uniaxial fashion, and the adhesive-coated runway and tensile membrane surfaces will be brought in contact. The anchored ends will be relatively cool, since the distance from the ends to the middle segment is about 20 feet. It is likely that any heating of the ends will in fact be beneficial, since heating normally accelerates the bonding process and in most cases strengthens the bond. In some cases, bond pressure during the adhesive cure is also beneficial. It may be possible to obtain this pressure by driving a tractor or truck over the anchored ends of the membrane during cure. Equipment of this nature will already be in the immediate area, since it will have been used to move the tensile structure to the crater site initially.

It is critical that the adhesive bond reaches a significant percentage of its ultimate strength prior to membrane cool down, since it is by this mechanism that the tensile prestressing of the membrane is achieved. Given the present wide variety of adhesive types and adhesive properties, there is little doubt that a suitable adhesive can be identified during Phase II of this project.

The above installation procedures are admittedly at a conceptual stage. However, it is felt that these procedures will be simple and straightforward and that a total of three personnel with rudimentary training should be able to perform these required tasks quickly.

An important aspect of the tensile structure performance is its durability. In this case, it is the physical time life span rather than the number of operating cycles (takeoffs and landings). The reason is that the creep, with the resulting loss of prestress, is the most probable critical factor for the structure being operable. Since the stress fluctuations are neither large nor long, it is the induced prestress level that, other things being equal, determines the creep rate. Again, it will take additional information and effort to resolve the question. For the time being, it would be reasonable to consider this repair as temporary, with a variety of ways to increase its longevity or to render it permanent (e.g., by pumping some solidifying foam or concrete mixture beneath the membrane).

Judging by the anticipated number of loading cycles, fatigue failure should not be a major consideration. To accommodate membrane weakening due to bullet holes or other possible damage, some reserve of membrane thickness should be allowed. Repairing a membrane damaged to a point where a considerable part of the prestress is lost is not practical. In such a case a new membrane should be installed.

The ultimate goal of a 1-hour repair time appears to be quite feasible. Given that the proper materials are on hand and ready for deployment, installation procedures such as removal of debris, positioning of the membrane, and application of the adhesive should be accomplished in a matter of minutes. The critical link in achieving a 1-hour repair time is adhesive bonding, that is, the time required for the adhesive bond to gain the necessary strength. Taking into account the rather large assortment of candidate adhesives and the current state of the art of bonding technology, the prospects are encouraging.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

The conclusions of this feasibility study are enumerated below.

1. Analysis of the tensile structure concept--prestressed thin membrane--indicates that it may be an alternative to the existing methods of bomb damage repair, with potential for considerable reduction in repair time requirements.

2. Since the lateral stiffness of the membrane is proportionate to its prestress level, the latter must be maximized. Owing to the phenomenon of "geometric strain hardening," it is possible to prestress the membrane close to the yield and still maintain a more than adequate reserve of load carrying capacity.

3. Membrane anchoring is the critical aspect of the concept, from the standpoint of both its reliability and practicality (installation time). In its present state of development, the anchoring system for the tensile structure concept appears to be only suitable for the repair of concrete runways without asphaltic pavement.

4. Surface anchoring (bonding the membrane to the pavement) is found preferable to its one alternative--edge anchoring.

5. Heating up and anchoring the expanded membrane is the only practical way of prestressing it to the required high level.

2. RECOMMENDATIONS

This feasibility study resolved some of the structural problems and provided unequivocal answers to many questions. The results obtained so far look encouraging.

At the same time, a new problem area has emerged, the one associated with the capacity of the surviving runway, in general, and asphaltic concrete pavement, in particular, to support the high tension in the membrane patch. If further work is done on the tensile structure concept, this problem area must be addressed with all the appropriate attention.

The work to be done consists of (1) collecting the available data on the relevant properties of asphaltic concrete used in runway pavements, (2) staging rather simple and straightforward, but crucial, experimental studies of the bonded connection between steel membrane and concrete or asphaltic concrete, and (3) any bonding system validation must be applicable under a wide range of environmental conditions including rain, freezing to very hot ambient temperatures, etc.

REFERENCES

1 Timoshenko, S. P., Theory of Structures, NY (1939), (1965).

2 Fuller, R. B., Synergetics, NY (1957).

3 Kuznetsov, E. N., Introduction to the Theory of Cable Structures (in Russian), Stroiizdat, Moscow (1963).

4 Kuznetsov, E. N., International Journal of Solids and Structures, Vol. 15, pp. 761-767 (1979).

5 MIL-HDBK-5C, pp. 2.53-2.58 (1978).

6 Meukelon, W., Proceedings of the Second International Conference on Structural Design of Asphaltic Pavements, University of Michigan (1967).

7 Suvorov, A. F. and Lialin, K. V., Construction of Large Reservoirs (in Russian), Nedra, Moscow (1979).

APPENDIX A

DATA ON CANDIDATE ADHESIVES

Selected adhesives which will bond steel to concrete (or asphalt) are listed below. Bond strength of adhesives will depend greatly on what kind of cure can be obtained. Adhesives having potential for the present application under ideal conditions of cure, surface preparation, and application are:

- Hughson Chemical Veralok® 200 and 202 (acrylic adhesive-structural type).
- Hughson Veralok® 506 (acrylic).
- DuPont Cavalon® 3001 S plus catalyst 3300 S or 3303 S (acrylic).
- B. F. Goodrich Plastilok® 610 Nitrile unsupported film adhesive (polyethylene liners) 16 inches wide, 8 to 40 mils thick (cure 6 minutes at 425°F).
- Goodyear Chemical Pliobond® 30 Nitrile adhesive in methyl ethyl ketone (15 minutes at 350°F).
- Uniroyal Royal® M6214 elastomer-epoxy (2 part cure 5 minutes at 380°F).
- Hughson Chemlok® 305 and 304 (2 part cure 3 minutes at 380°F).

Lab work would be required to check the lap shear strength on substrates (steel concrete and steel asphalt) and to shorten the cure time.

Adhesives which will bond steel and concrete without regard to lap shear strength are:

- polyester-isocyanates
- polyisocyanate
- silicone resins
- elastomeric contact adhesives (all but natural rubber and chlorinated natural rubber)

- polyimide
- epoxy
- acrylic structural adhesives.