multi-storey air-supported building construction

by J. G. Pohl and H. J. Cowan

Recently, over a three-year period, a new concept of multi-storey building construction based on pneumatic principles was investigated in the Department of Architectural Science at the University of Sydney, Australia. The results of this research, which formed the basis of an author's thesis and various technical publications, have indicated that multi-storey buildings supported by internal air pressure and surrounded by a thin, flexible or rigid membrane acting both as structural container and external cladding, are feasible and highly economical for a number of building applications. This article by Jens G. Pohl, Faculty of Architecture, University of New South Wales, Kensington, and Henry J. Cowan, Department of Architectural Science, University of Sydney, Sydney, describes those elements of the thesis which are useful for practitioners.

The simplest form of multi-storey air-supported building is best described as a flexible plastic tube sealed at both ends by means of circular discs and pressurised internally as shown in Fig. 1. Similar to a pressure vessel, the resulting column experiences tensile stresses over its entire curved surface. If the internal pressure is continuously increased and the sealing discs are sufficiently stiff to resist dishing, eventually the column wall will burst as a result of material failure in tension. Naturally, in its inflated state the membrane column is capable of supporting vertically loads applied externally to the upper end or suspended from the same internally. The transition, therefore, from the simple model shown in Fig. 1 to a multi-storey, air-supported building with suspended floors (Fig. 2) is direct and rather obvious. It appears that existing structures such as gasometers, hydraulic car hoists and rocket fuselages incorporate similar principles. Nevertheless, the employment of a pneumatic container as the primary structure of a large building varies with a number of significant problems related to the physiological effects of an hyperbaric environment, maintenance of the design pressure, fire protection, mechanical equipment, structural pressure-utilisation efficiency of the system and the disposal of wastes.

At the same time, it is apparent that the multi-storey, pneumatic building described here in its simplest form as a single-skin structure immediately suggests a number of related building types of a double-skin or cellular nature which would, no doubt, lead to a reduction in the complexity of most of these problems.

However, before investigations could be undertaken in this direction, it was decided to come to terms with the difficulties inherent in the practical implementation of the multi-storey, single-skin, pneumatic system which, from a purely structural point of view, would appear to hold most potential. Accordingly, the design of a 10-storey office building, in which the environment has been pressurised for structural purposes might be prepared on an intuitive basis as shown in Fig. 3. Access to this building is gained by means of an airlock tunnel at ground floor level.

The necessity of changing from one pressure to another on leaving or entering a pneumatic building will present problems to the designer, hitherto not considered in connection with building construction. Basically, the lock can be described as an air tight chamber fitted with a door at each end, both doors opening toward the pressure. Through valves at each end, the pressure within the lock may be equalised with that of the building or with the external atmosphere. When the pressure in the airlock is the same as that of the pressurised zone, the inner door may be opened to allow persons and material to enter the lock from this zone. The inner door is then closed and the pressure within the lock reduced to atmospheric conditions allowing the outer door to be opened to complete the exit operation. Both doors of an airlock can never be opened at the same time, because when either of the doors is closed it is held tightly against a gasket by air pressure.

Although the development of this type of airlock in tunnelling operations has been based on a considerable amount of practical experience, existing designs will need to be very much refined and automated before they can be incorporated in the design of multi-storey, pneumatic buildings. While rates of decompression will be fast and therefore little time will be spent in airlocks by persons entering or leaving the building, the visual airlock environment must not differ in principle from the interior building environment.

It is likely that at the present time people would reject the mechanical

![Figure 1](image-url)
appearance of an airlock system designed purely on the basis of functional criteria. Therefore, it will be necessary at least during the early stages of the development of multi-storey, pneumatic buildings, to disguise some of the outstanding mechanical characteristics, although this must not be to the detriment of the safe operation of the pneumatic system of construction. It is reasonable to assume that the rate of pressurisation will be slightly less than the time required for an adult person to walk at a comfortable pace the distance between airlock doors. Having entered the ground floor lobby, access to other floors is provided in the normal manner, namely, via lifts and staircases.

Figure 2 Working model of multi-storey, membrane-cable-network building incorporating a suspended floor system

Each suspended floor level is planned to incorporate a centralised service space; comprising all sanitary requirements, ducts, fire-escape staircase and storage facilities; vertical transport systems and a series of sliding screens at the perimeter for the purpose of providing acoustical and visual privacy. Since it is intended for the entire floor-to-floor volume to be pressurised, sanitary and dry waste disposal installations will need to receive special attention. Under present conditions, no authority could tolerate the discharge of excremental matter into a public sewerage system at pressures considerably above atmospheric pressure. The provision of airlock mechanisms within waste pipes would appear to be the simplest solution. In this case, the function of the water seal is preserved and the waste will reach the sewer after passing through one or more stages of decompression. This procedure can be further improved by combining a number of similar waste pipes at a central decompression unit. It seems highly probable that these waste pipes would require artificial ventilation at the same pressure and therefore in conjunction with the central air-conditioning system.

It is unlikely that an hyperbaric building environment will significantly modify water supply, apart from the necessity of providing pumps of slightly greater capacity (i.e. in proportion to the environmental pressure) than in an orthodox building. The rate at which the water must be boosted will no doubt exceed the limit of draw permitted by the water authorities; however, a break tank system is not necessarily required. Although water authorities are willing to accept a considerable drop in the mains pressure for emergency situations, near negative pressures cannot be tolerated. Therefore, even purely from the point of view of fire services, the multi-storey, pneumatic building will require considerable tank storage. In this case there is unlikely to be an alternative to low-level storage, the actual amount being determined by agreement with the fire-fighting and water authorities.

Since there is a need for storage at low level, it will be worthwhile to make it adequate and reduce that at high level in the building, thereby reducing the load to be carried by the internal pressure of the building. As shown in Fig. 3 considerable space has been allocated at basement level for mechanical plant including air-conditioning, pressurisation, airlock and lift equipment, and it seems plausible that water storage tanks could likewise be located at this level.

For reasons of maintenance and general accessibility, it would appear to be logical that the plant area should operate at ambient atmospheric conditions.

Structural considerations

The application of pressurised, membrane columns to multi-storey building construction will require a convincing knowledge of the failure mechanism under both vertical and horizontal loads and the pressure-utilisation ability under vertical load alone. Both of these are naturally dependent on the slenderness ratio of the column and the ratio of load to internal pressure.

Figure 3 Typical multi-storey pressurised membrane-cable-network building

Figure 4 Rigid, membrane column (membrane thickness 0.01 in; diameter 9.5 in)
While rigid membrane columns (Fig. 4) will normally retain their shape under self-weight loading conditions even in the absence of internal pressure, the flexible membrane column (Fig. 1) depends upon fluid pressure for its shape and resistance to bending, local buckling and torsion. For short columns this resistance has been found to be a function of the internal pressure, membrane thickness and elasticity of material.4 Under vertical load (Fig. 5) first stage failure of a flexible membrane column will occur at the instant when the tensile stress due to internal pressure is negated by the dual action of axial compression and deflection moment, on one side of the column perimeter (Fig. 6). Accordingly, the column will become unstable, not when there is an unequal stress distribution in the membrane wall, but as soon as any section of the membrane experiences no stress at all in the vertical direction.

After the formation of folds the load-bearing capacity of the membrane column decreases rapidly (Fig. 7) since any increase in displacement will produce a larger lever arm and consequently a greater bending moment. When pressurised, flexible membrane columns are displaced by a horizontal force acting at the free end (Fig. 8) the fibres on one side of the column are stretched, while again on the opposite side a corresponding unloading action takes place. Folds can occur only after the tensile stress due to the internal pressure can no longer absorb the compressive stresses induced by the horizontal force. It is therefore clear that the load-bearing capacity of short membrane columns is largely determined by the internal pressure. The question then arises, what proportion of this pressure acting on the inside face of the upper seal can be directly utilised for the support of a vertical load? Theoretical predictions followed by experimental investigation1-4 have shown that the approximate pressure-utilisation factors (k) given in Table
Table 1 Pressure-utilisation factor \((k)\) as a function of the slenderness ratio of multi-storey, single-skin, pneumatic buildings (i.e. load-bearing capacity \((W\ \text{lb}) = k\cdot P\cdot A\); where \(P\text{ psig} = \text{internal pressure}\) \(A\text{ in}^2 = \text{area of inside surface of upper-end seal}\

<table>
<thead>
<tr>
<th>Slenderness ratio</th>
<th>Height utilisation factor ((k))</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.85</td>
</tr>
<tr>
<td>20</td>
<td>0.80</td>
</tr>
<tr>
<td>25</td>
<td>0.75</td>
</tr>
<tr>
<td>30</td>
<td>0.70</td>
</tr>
</tbody>
</table>

1 hold within the normal range of 2- to 12-storey buildings.

These factors can now be calculated precisely on the basis of design equations published elsewhere.4 If it can be reasonably assumed that the normal floor load (i.e. dead and live load) considered in the design of high-rise buildings is in the vicinity of 140 pounds per square foot \((psf)\), then an internal pressure of close to 1 pound per square inch \((psi)\) of 144 psf, above ambient atmospheric pressure will be required for the support of each floor of a multi-storey structure. This is so, because the area of a typical floor, as shown in Fig. 5, cannot be greater than the area of the inside surface of the upper seal (i.e. the bearing floor). For example, the required internal pressure for a typical eight-storey, pneumatic, membrane building of 50 ft diameter and 100 ft height can be calculated to be 8.85 psi, with a corresponding pressure-utilisation factor \((k)\) of 0.90.

Similarly, the tensile hoop stress of the membrane enclosure in this example would be approximately 2700 psi/ft. Assuming the membrane thickness to be 0.13 in, the yield strength of the material would need to be around 25,000 psi, with a corresponding ultimate strength of some 40,000 psi. Where high tensile strength is the primary criterion, a suitable membrane material is likely to be found among the laminates and reinforced plastics. However, a survey of commercially available materials has shown that it is difficult and costly to manufacture plastic membranes to this specification. At this time, nylon scrim-based laminates capable of developing a yield strength of more than 1000 lb/ft² seem to be most suitable for this application, even though they are well below the strength requirement. For most membrane buildings it will therefore be advisable to resist the hoop stress due to internal pressure by means of an external cable-network (Fig. 9) while the membrane serves simply as a non-porous envelope. Under these circumstances the required tensile strength of the membrane material will be substantially lowered, allowing the use of a much wider range of plastic materials.

As shown in Fig. 9 cables are inclined at an optimum angle, symmetrically about the vertical axis to fulfil the further function of stabilising the building laterally against the action of wind loads.4 For the ensuing membrane-cable-network building, design equations are adapted to transfer the primary structural function from the membrane to the cable-network.

The hyperbaric building environment

Although it might have been established previously as a rule of thumb that for every 1 psi internal pressure it will be possible to support one floor of a multi-storey, pneumatic building, the question of what effect this compressed air environment will have on the building's occupants remains to be considered. From a structural point of view (Table 1) it appears that a height to diameter ratio of 3.5 with a pressure-utilisation factor \((k)\) of 0.80 might be reasonably considered to approach an economic limit. Nevertheless, it would be expected that the physiological effects on man living in a compressed air environment will constitute the more critical design criterion.

Figure 9 Three-storey, experimental, membrane building with external cable-network for reinforcement and bracing purposes

A long history of experimental investigations and experience with caissons must assure us that the appearance of any long-range effects, such as compression sickness, bends syndrome and oxygen-poisoning, can be generally discounted if the ratio of environmental to external atmospheric pressure is small.2 According to Dewey,3 symptom-producing nitrogen bubble formation in the blood stream will not occur unless a threshold-pressure-gradient of 2:1 is exceeded. This means that if the building environment is pressurised to less than two atmospheres absolute (i.e. approximately 14 psi) long-range physiological effects are not likely to occur even if this change of pressure is produced instantaneously. Furthermore, since the rates of compression and decompression are the primary variables which determine the occurrence of decompression sickness, it would appear that higher environmental pressures and therefore taller buildings are feasible, provided the rate of change from one pressure to the other is sufficiently slow. Nevertheless, present research has been limited to pneumatic, membrane buildings involving pressures below 14 psi, with a maximum of ten to twelve storeys.

Pressure maintenance and safety

General safety considerations for multi-storey air-supported buildings are considered from three principal aspects; firstly, the establishment of factors of
Multi-storey, pneumatic buildings are basically mechanical buildings and it is therefore unlikely that factors of safety required by existing building codes should apply. It would seem that at the present time their application might be considered primarily for providing immediate shelter in disaster areas or wherever low cost, speed of erection and mobility are the foremost design criteria. With the rapid increase in world population, there seems little doubt that such conditions will preoccupy the building industry in the twenty-first century. Faced with a critical situation authorities will be forced to align factors of safety in building construction with normal risks undertaken in everyday life.

Is it reasonable to prescribe a factor of safety for a building, which would make failure less likely than the probability that a person might be hit by a golf ball as he is walking down the street and die as a result of this accident? Surely the time will come when we will have to provide buildings in such large numbers that the required rate of construction will preclude the use of orthodox materials, such as concrete and steel, as a sheer impossibility. It is suggested that factors of safety for multi-storey, pneumatic buildings must be established on a statistical basis. A suitable criterion might be the multi-engined aircraft, which is capable of operating with part of its power system out of action. This would imply that pneumatic buildings will require strict maintenance and inspection programmes, similar to those now applied only to mechanical products. For the single-skin, multi-storey, pneumatic building, puncture of the membrane naturally constitutes the most serious risk of total collapse. A starting point would be to establish an effective size of puncture which has a sufficiently small probability of occurring during the limited life-span of the building.

On the reasonable assumption that the membrane would resist tearing and that the puncture would therefore remain localised, it only remains to provide pressurisation plant of sufficient capacity to maintain adequate air pressure in the building, before the puncture is repaired. The provision of standby plant operating from an alternative energy source is mandatory.

Similar precautions are taken in hospitals to ensure a continuous electricity supply for operating theatres. In the pneumatic building the necessity for ventilation will require the provision of a controlled leakage valve, which could conceivably be shut off during an emergency situation. In the event of the membrane being punctured, the standby plant would automatically come into operation, and, if necessary, the ventilation valve could be closed. Accordingly, three to four times the normal pressurised air-input would be available instantaneously. Further, it is highly unlikely that the building would be fully loaded at this critical time, or indeed at any time during its life-span.
Consideration has also been given to a number of related building types incorporating pneumatic, cellular structures (Figs. 10 and 11) in which the building environment is not pressurised. For these the risk of total collapse is much reduced, although naturally at the expense of structural efficiency. The three-storey residential building shown in Fig. 12 is supported by a rigid membrane, central column pressurised hydrostatically to 30 psig, and fabricated from 4 in (thickness) mild steel plate. This building, which is proposed to be erected by architecture students in Australia, is a compromise solution and should be acceptable to building authorities in any country.

The central column in the unpresurised condition is just capable of supporting the self-weight of the building and a limited live-load. When pressurised to 30 psig, the building structure incorporates a factor of safety similar to orthodox systems of construction. Even in this limited form the pneumatic structure leads to considerable economies, although an unreasonably high price has been paid to comply with present standards of safety.

The fire hazard
In fact, it is the potential fire hazard which has emerged as the most critical safety consideration in multi-storey, pneumatic buildings of the type shown in Fig. 3. No doubt it will be necessary to provide a clear air-space around the perimeter of a pneumatic building, so that radiation from external fires will not impair the membrane wall. Similar town-planning regulations are presently being enforced in a number of countries for buildings of orthodox construction. However, the danger is much more critical from fires which might start inside the building. In the case of small flames which might originate from cigarette lighters or matches, it is sufficient for the membrane to be sparkproof. Most commercially available membrane materials comply with this requirement and some (e.g. teflon-coated) can withstand temperatures up to 500°F.

Apart from the existence of a small gap of 1–2 ft between the membrane and the perimeter of the floor (Fig. 3), it is envisaged that suitable heat-resistant coatings could be applied to the internal surface of the membrane if required. Larger fires will emit radiation from which the building membrane must be shielded. For this reason, it is convenient to allot a further function to the sliding partitions provided at the circumference of each floor for acoustical and visual reasons. It is intended that these screens be fire-rated and automatically controlled by a smoke- or heat-detection system. Accordingly, each floor may be completely sealed off as a separate compartment.

The possibility of assigning a limited, structural application to these partitions has been considered, but temporarily rejected on economic grounds. In any case, the time taken for this compartmentation process to be completed must be minimised. At the same time, both
high-pressure and low-pressure sprinklers (Fig. 13) activated by the same detection system will come into operation. The high-pressure sprinklers will deluge the membrane and external surface of the fire-rated partitions as they slide into place, while low-pressure sprinklers will spray the entire floor area of the sealed compartment. At this time or after a specified degree of danger has been reached, an alarm system will warn occupants to evacuate to a fire-rated, self-supporting shelter at basement level. Escape from this mass shelter to the outside will occur through one or more emergency airlocks, continuously throughout the duration of the fire. Apart from these precautions, it is envisaged that the normal requirements of alternative means of escape (to the basement shelter), fire-rated staircases, etc., will apply equally to multi-storey, pneumatic buildings.

Rigid membrane buildings

Multi-storey, pneumatic buildings incorporating rigid membranes (i.e. un-plate, rigid PVC, etc.) fall into two classes, namely buildings in which the habitable spaces are pressurised as shown in Figs. 14 and 15, and buildings in which the habitable spaces are under ambient atmospheric conditions (Figs. 16 and 17). When the building environment is pressurised, normally the entire building enclosure acts as a short pressurised cylindrical shell under axial compression (i.e. the building load) and lateral wind load.

In the case of a rigid membrane we are able to calculate the required internal pressure as a function of membrane thickness rather than total building load. Since the cylindrical shell is self-supporting in the deflated state, pressurisation will serve to extend this range of stability to include the case of superimposed loads, by increasing the critical buckling stress of the shell. Whereas flexible membrane buildings derive their form and resistance to buckling, torsion and bending from the internal pressure, rigid membrane buildings are stable in themselves, provided the cylindrical wall is sufficiently thick.

Although the structural variations illustrated in Figs. 14, 15, 16 and 17 appear to differ only marginally from the flexible membrane building types discussed previously, in respect to the design and integration of mechanical services, construction techniques and prefabrication, there are nevertheless a number of secondary considerations which apply to rigid membrane construction, alone.

1. Individual floors may be attached directly to the rigid, membrane wall (Fig. 14). Therefore, it will be possible to develop a built-in floor system, allowing complete continuity between floors and building enclosure. Some thought has been given to the development of cable-network floor systems for incorporation in multi-storey, pneumatic construction. It is intended to provide the required reaction at the periphery of each floor (where the cables are supported) by means of fluid pressure, thus obviating the need for a heavy edge-beam construction. Preliminary, theoretical calculations have indicated that for spans (i.e. diameter) of 60-80 ft the self-weight of the floor structure could be reduced to less than 15 psf per floor area. Model tests on such lightweight, pneumatic, cable floors are scheduled to be conducted in the near future.

2. The rigid membrane column will resist lateral fluid pressure applied externally to the curved surface. This particular property is of importance in the type of pneumatic building shown in Fig. 17, where floors are supported by a pressurised annulus, while the building environment remains at atmospheric conditions.

3. Rigid membranes will allow the designer to increase the material thickness well beyond the limits which must apply in the case of flexible membrane. It will therefore be possible to employ inherently weaker materials with other, more advantageous, properties.

4. Whereas an exterior cable-network has been proposed for the reinforcement and bracing of flexible, membrane buildings, a similar procedure may be adopted in the case of rigid membrane
Figure 14  Rigid, membrane building with built-in floor system

Figure 15  Rigid, membrane building with suspended floor system. Cable loads are distributed over dome surface by edge beam or equivalent

Figure 16  High pressure rigid, membrane, central core supports suspended floor system. Building environment is not pressurised

Figure 17  Rigid, membrane, annulus construction; inside skin of annulus subjected to hydrostatic compression
structures using circumferential and longitudinal stiffeners. Although it is unlikely that an optimum solution will be obtained by giving primary structural significance to such stiffeners, nevertheless a reinforced system may be favoured where the resistance of stress concentrations (e.g. due to the attachment of floors to the membrane) or the minimisation of direct solar penetration, are major design criteria.

There has been much interest recently in the rediscovery of Van Der Neut’s early theoretical observations regarding stiffened cylindrical shells under axial compression. His findings, now well confirmed by test data, included the supposition that external stringers are much more effective than internal stringers in stiffening a cylindrical shell against buckling.

Sample elevational treatments are shown in Figs. 18 and 19 for pressurised and unpressurised building environments incorporating structural and non-structural enclosures. It is apparent that the designer of multi-storey rigid membrane buildings will be able to draw on a number of interesting and functional themes, which highlight the combination of transparent and opaque surfaces. The distinctive features (Fig. 18) such as dome-roof and double-storey exterior tension rings occur as a direct consequence of the intrinsic characteristics of this form of pneumatic construction.

References

Figure 18 Typical pressurised, rigid membrane buildings. Hoop rings and dome shaped roof are a direct result of structural considerations (areas shown black are transparent)

Figure 19 Possible non-structural and structural enclosures for rigid, membrane buildings in which the habitable spaces are not pressurised