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Applications of the Concrete Origami Concept in Structures

Application du concept d'origami dans des structures en béton

Anwendung des Origami-Konzeptes auf Betonbauten

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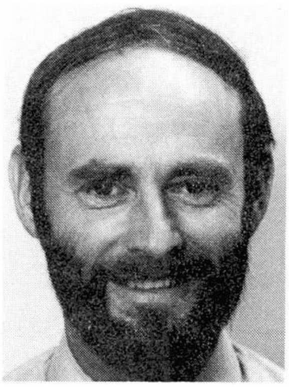

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SUMMARY
The "concrete origami" concept recognises in concrete slabs the characteristics of paper. Paper sheets can be curved and folded from flat surfaces into three-dimensional shapes. This paper demonstrates how these ideas can be turned into concrete realities and suggests practical applications in concrete structures.

RÉSUMÉ
L'origami est un ancien art japonais de plier le papier. La notion d'origami appliquée au béton reconnaît les propriétés du papier dans des dalles en béton. Des feuilles de papier peuvent être courbées et pliées en structures à trois dimensions. L'article montre comment ces idées peuvent se réaliser sur des structures en béton. Des applications pratiques sont également indiquées.

ZUSAMMENFASSUNG
Origami ist die alte japanische Kunst des Papierfaltens. Der Origami-Begriff auf Beton angewendet erkennt in Betonplatten die Eigenschaften von Papier. Papierblätter können zu dreidimensionalen Strukturen gewölbt und gefaltet werden. Dieser Beitrag zeigt wie diese Vorstellungen für Betonstrukturen Wirklichkeit werden können. Auf praktische Anwendungsmöglichkeiten wird hingewiesen.

1. INTRODUCTION

Origami is the ancient Japanese art of paper folding. The "concrete origami" concept recognises in concrete slabs the characteristics of paper. Paper sheets can be curved and folded from flat surfaces into three-dimensional shapes.

On an intellectual level all structural engineers will acknowledge the flexibility of concrete slabs. They are used to thinking of concrete slabs returning to their original shape once the loading is removed. Yet most will have witnessed, as students, the remarkable ductility of an under-reinforced concrete beam or slab in laboratory experiments carried out with loading beyond normal working loads.

Such loadings are normally thought of as "aggressive" tending to destroy the fabric of the material. Alternatively this behaviour can be seen as an opportunity to create curved concrete structures by a new method which offers dramatic cost savings.

This paper takes the folding and bending notions associated with origami and shows how they can be achieved in concrete. Many and varied are the possible applications opened up by this new approach.

2. THE CONCRETE ORIGAMI CONCEPT

2.1 General

The concrete origami concept extends the usual range of concrete fabrication methods very considerably. Designers may now contemplate complex shapes with folded and curved surfaces without the problems of complex and intricate formwork. Simple flat formwork is the key.

The advantages of concrete origami are:

(i) economical casting of horizontal slabs
(ii) ease of finishing
(iii) a great variety of surface textures and finishes are possible at low cost
(iv) a high quality concrete because of the ease of casting, compaction and curing
(v) the speed of construction

2.2 Folded Concrete Slabs

The term "folded-plate" is in common usage to describe what appears to have been done in creating such structures. A genuine concrete folded-plate structure is shown in Fig. 1. It was created from a single flat casting. The flat segments were cast horizontally with open joint lines between them. The mid-plane reinforcing mesh crossed the open joints. About seven days after casting the folding was carried out. The yielded reinforcement forms the hinge along each joint which permits the folding to take place. The joint lines were then filled with mortar to hold the joint rigid.

Using this technique any developable three-dimensional shape is theoretically possible.

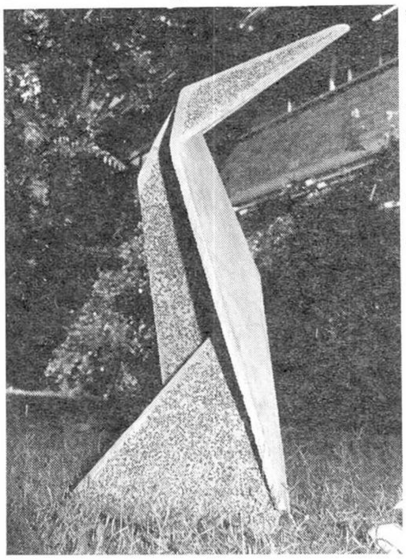

Fig. 1 A folded-plate structure

2.3 Curved Concrete Slabs

A thin concrete slab initially cast flat could easily be lowered over curved templates or lifted at its edges to hang freely in a curved shape.

If, for example, a 30mm thick slab which is under-reinforced, has an effective depth to steel reinforcement of 25 mm it can be bent into an arc of 1m radius. As illustrated in Fig. 2 it will be extensively cracked on the tension face but the compressive surface will not show any distress.

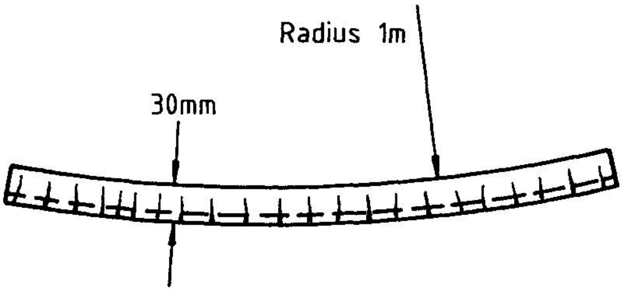

Fig. 2 A curved concrete slab

This cracking would be of no consequence if the curved slab were then used as permanent formwork for further concreting. Alternatively, treatment of the cracked surface to render it waterproof may be all that is required, using materials such as epoxy resins.

By inducing prestress in the slab it is possible to bend the slab without causing cracking at all but the radius of curvature is much larger. A 30mm thick slab, for example, with a uniform compressive stress of 15 MPa induced by prestress can be curved to a radius of about 30mm (assuming an elastic modulus of 30 MPa for the concrete).

Any radius of curvature between these two limits is possible depending on the extent of cracking regarded as acceptable. Concrete creep will, of course, tend to dissipate stresses induced by bending.

3. PRESTRESSED CONCRETE TENSION MEMBERS

The notion of using concrete in tension members or membranes seems to be a paradox. Everyone knows that concrete is weak in tension. When that notion is combined with the ideas embodied in the "concrete origami concept" of folding or bending hardened concrete some interesting and valuable structural possibilities emerge.

Surprisingly little work has been published on the behaviour of prestressed concrete tension members and yet there are many examples of their use in practice. [6][7]

Without doubt tension members are the simplest of structural elements which demonstrate the principles of prestressing. By prestressing it is possible to make dissimilar materials work together in many ways which have advantages over the behaviour of either.

High tensile steel is by far the most economical and efficient material for carrying tension forces. It is not, however, available in sheets or plates or rolled sections like mild steel and it cannot be joined by welding. Its very high strength is achieved in the form of wires by drawing, yet the elastic modulus remains virtually that of mild steel.

While the cross-sectional area of high tensile steel required to carry a given tension will be about one fifth that of an equivalent mild steel the elongation under load will be five times greater.

Concrete, on the other hand, has an elastic modulus around one eighth that of steel. It has a reasonable compressive strength but low tensile strength. It is a cheap, widely available material. It is dense, it can protect steel from corrosion, and it may be cast into many shapes. Even though it is cheap its cost is very much dependent on the quality and shape required since labour and formwork costs make up a very large proportion of its total cost. In combination high tensile steel and concrete can be used to create tension members with desired ultimate strength and load-elongation behaviour characteristics.

Provided a residual compressive stress remains in a prestressed concrete tension member then it is possible to bend that member as indicated in the previous section.

4. FOLDED STRUCTURES

Many applications come to mind of structures which may be cast flat and then "folded into final shape. One possibility is described.

Fig. 3(b) illustrates the finished cross-section of a box culvert. Fig.3(a) indicates the casting of the base slab and the side walls on the prepared base. The middle wall is then cast on top of the base slab. The next step involves lifting and rotating the walls into their final position. The areas shown shaded in Fig. 3(b) are concreted as the final step in making a culvert.

Many commonly used shapes are developable in this way. Among them are barges and pontoons and the structures used in sewage and water treatment plants. Formwork costs are minimal while the additonal lifting operation need not be onerous.

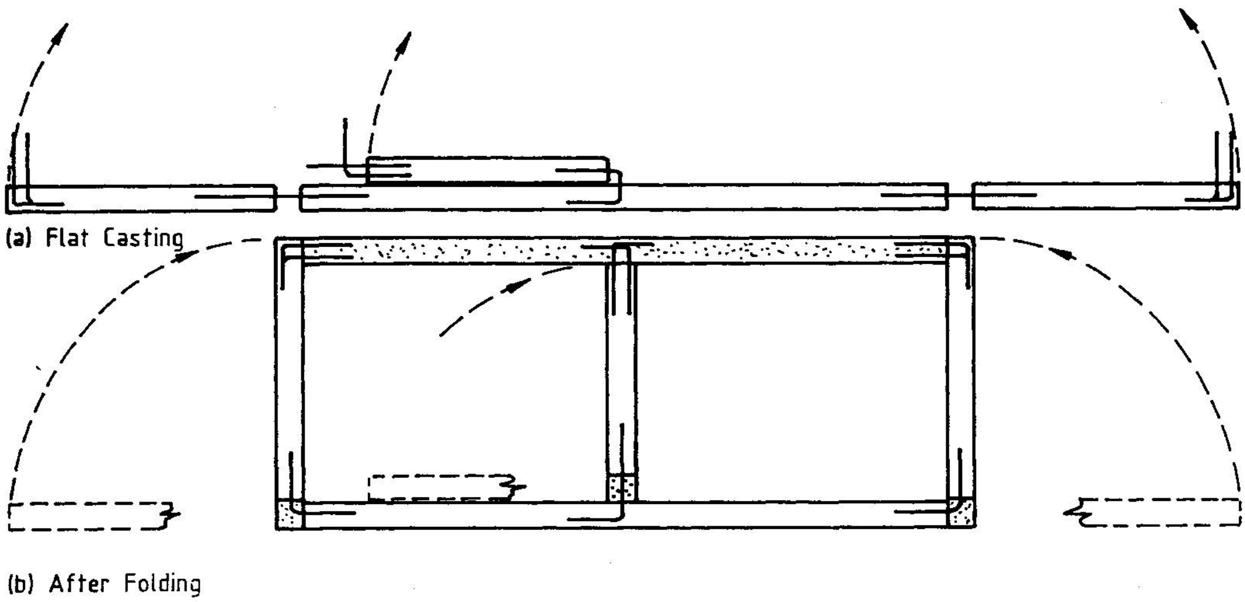

Fig. 3 Box culvert walls "folded" into place

5. CURVED STRUCTURES

Among the many possible curved structures two examples are briefly described. Fig. 4 shows a dome made up of reinforced concrete segments which were cast horizontally on flat formwork. Adjoining segments are joined by concreting in-situ around overlapping reinforcement which projects from both segments. The segments may be lowered onto curved templates and held in the curved shape until effectively joined.

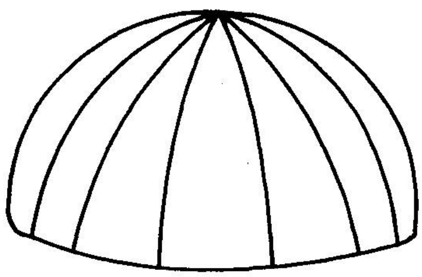

Fig. 4 Segmented Dome

The same principle could be applied to create a barrel vault as suggested in Fig. 5. A semi-circular barrel 10m in diameter could be constructed from 15m long by 2m wide by 30mm thick flat concrete slabs. Each such slab element only weighs about 2 tonnes and is therefore easily lifted into position.

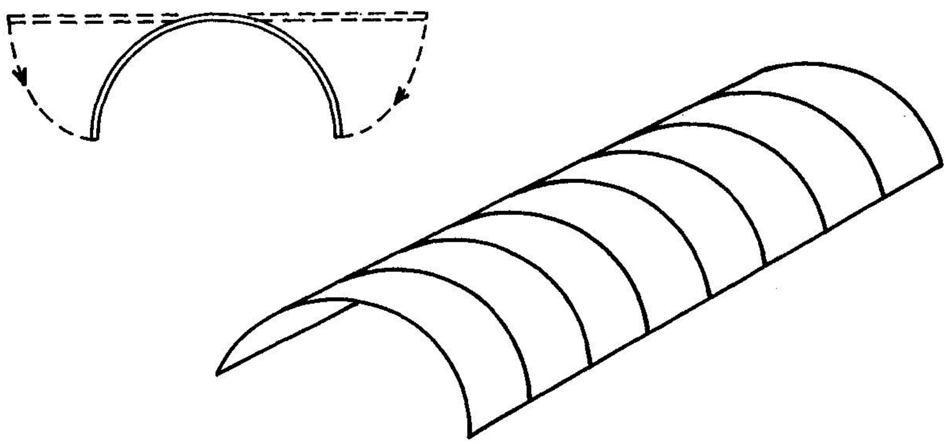

Fig. 5 Barrel vault roof from flat segments

6. TENT-LIKE STRUCTURES

The possibilities for long-span prestressed concrete tension membrane roofs which follow on are based on an extremely economical construction method. The method envisages the lifting of a flat thin prestressed slab under tension allowing it to sag under its own weight yet retaining its structural integrity. Long span tent-like structures can be created using this method which combines already well-proven technologies.

The original description of the concrete origami concept [1] envisaged the casting and stressing long relatively thin prestressed concrete slabs on flat formwork. Provided that a substantial anchoring force is maintained along opposite edges if the slab it was considered possible to either lower the formwork from the slab or alternatively to lift the slab from the formwork allowing it to hang freely in a catenary shape.

Experiments carried out have clearly demonstrated the feasibility of such lifts. This was done by casting a 12m long slab with a 150mm x 50mm cross-section. The slab was pretensioned with 5mm diameter high tensile steel wires. A lifting yoke was located at the midpoint which bore directly on the prestressing wires in a short region which was not concreted. After the concrete hardens sufficient prestress is transferred into the concrete to prevent subsequent cracking.

In a succession of prestress release and lift operations the slab was lifted clear of the formwork to give two symmetrically balanced catenaries.

The experiments were designed to test features of the tension membrane roof idea which were deemed critical to the whole concept. Once demonstrated further development of the idea was undertaken.

The lifting procedure is illustrated diagrammatically in Fig. 6. The experimental work referred to above confirmed that there is no untoward behaviour as the slab is progressively lifted from the formwork along its length.

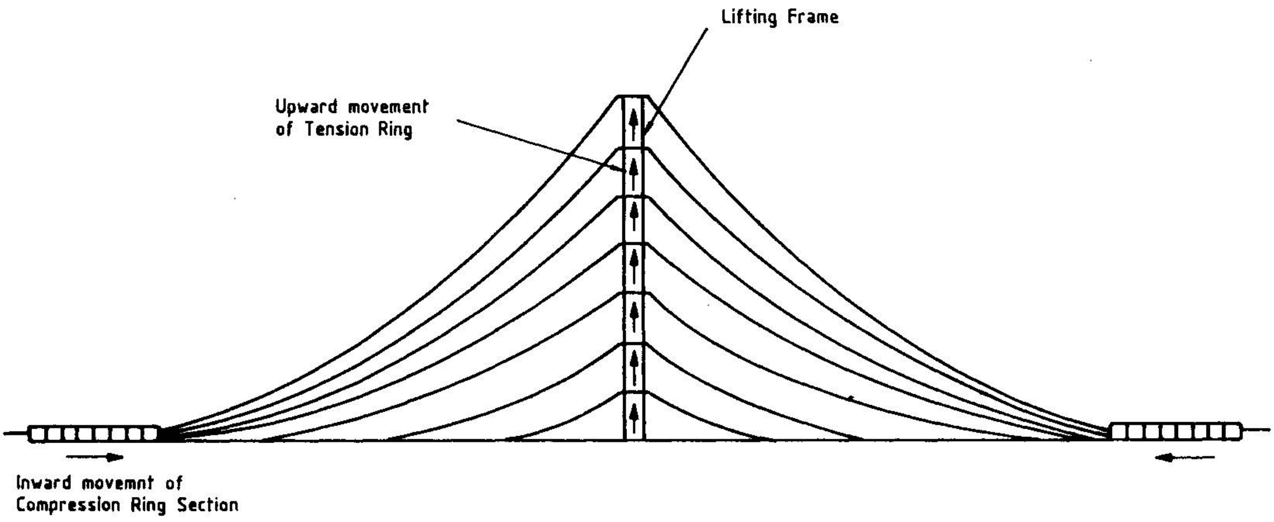

Fig. 6 Progressive lifting of prestressed concrete "tent"

Two forms of roof structure have been considered. The first, illustrated in Fig. 7 is made from pretensioned sector elements cast on the ground. Once cured and after transfer of some of the prestress the elements can be lifted on a central column.

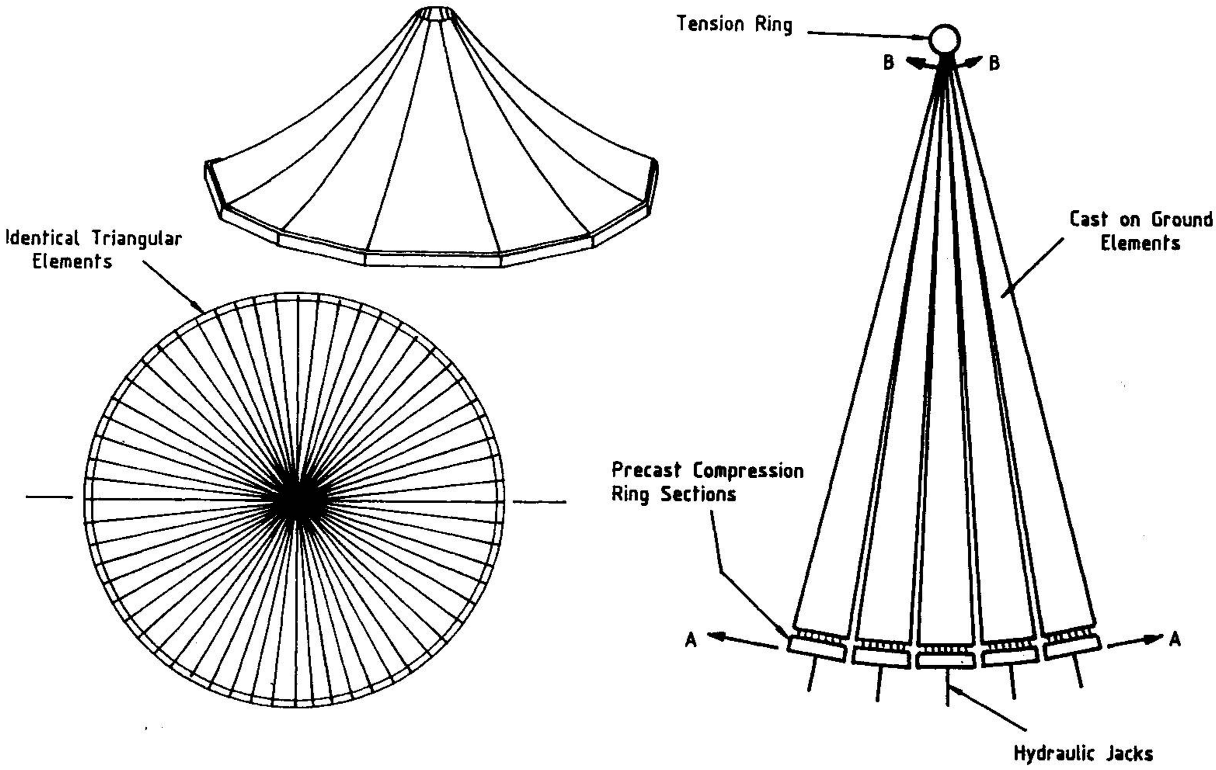

Fig. 7 Conical roof

It is not possible to cast and lift all elements simultaneously because the sector geometry causes edge overlaps. A simple solution is to cast, stress and lift two sets of elements each set consisting of every alternate element.

Joining the edges of the elements is done once all of them are in place. Care must be taken with these joints since they are potentially vulnerable to leakage in heavy rain. One simple solution is the casting in-situ of a capping strip which would bridge the joint between the elements. This capping strip is easily and economically cast since the formwork required is very simple. Advantage could be taken of these strips to make them serve the function of stiffening ribs if required.

The second form of roof structure is illustrated in Fig. 8. Again progressive lifting from the flat formwork along the ridge line of the "tent" is intended.

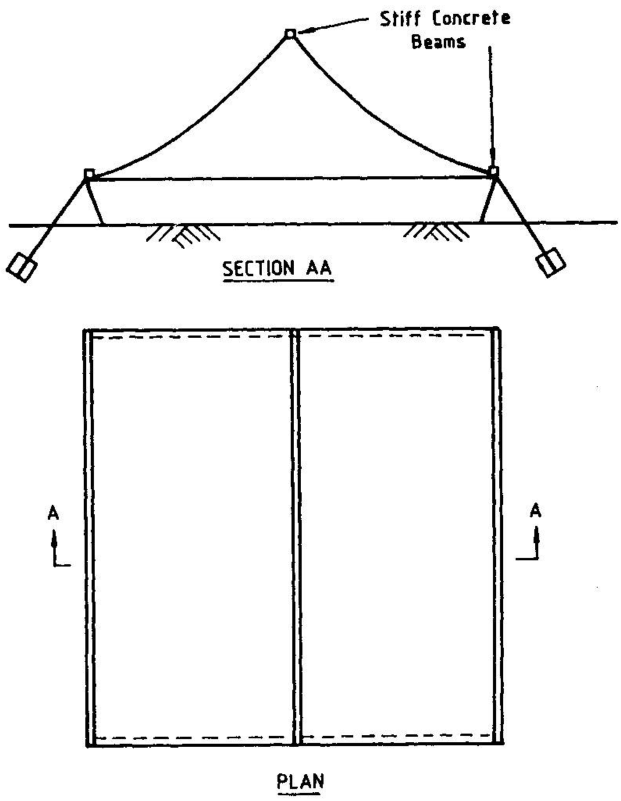

Fig. 8 The prismatic tent structure

A substantial anchoring capacity at the "tent pegs" must, of course, be provided.

Unconventionally thin concrete slabs are proposed. A minimum thickness of around 35mm is possible provided great care is taken to prevent the onset of corrosion. Since concrete cover is already well below code minimum values reliance on the protection that the concrete alone affords is insufficient.

In the first instance a cement-rich mix is called for (economies) in the concrete mix itself are undesirable). In addition partial transfer of prestress to the concrete at very early age is needed to obviate the formation of cracks due to restrained shrinkage.

Despite the fact that very good quality concrete will be achieved (ease of placement, ease of compaction, good thickness control etc.) a further line of defence against the ingress of water is thought prudent. Shortly after casting the concrete an epoxy resin coating reinforced with glass fibre can be applied to the top surface. This coating will serve a dual role. It will limit the loss of moisture from the conrete at early age promoting curing and minimising early age shrinkage. Subsequently it will prevent the penetration of rain water into the concrete.

7. CONCLUSIONS

The concrete origami concept opens the way to a whole new range of concrete products and structures whose scope is limited only by imagination. Major savings are possible since the simplest of formwork can be used.

Where structures are folded from flat elements care is required in detailing the joints which are to be rotated and subsequently frozen by concreting.

Recognition of the fact that concrete slabs can be permanently deformed without damaging their fabric leads to dome and barrel shaped roofs and many other applications.

The final outcome has been the tent-like formwork to hang freely in the catenary shape. Critical features of these ideas have been explored experimentally and have been found to work as expected.

Roof spans as large as 50m and beyond are possible using these techniques. Applications such as for the roofs or sporting arenas, grain storage buildings and aircraft hangars seem immediately feasible.

8. ACKNOWLEDGEMENTS

My colleague, Associate Professor R.Q. Bridge, has played a major part in the development of the ideas which have flowed from the original enunciation of the concrete origami concept. His contribution is gratefully acknowledged. In addition undergraduate students I. Archer. G. Arena, D. McDonald and R. Anderson have added significantly to the work through their undergraduate thesis projects.

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