# Design Report

**Shelters for five churches in Lalibela, Ethiopia - restricted design competition.**

**Identification no.: 91131**

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(7th European Development Fund, Project Number 7.ET…).

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### Table of contents



### List of drawings and illustrations presented on boards



### Attachments (as included in separate envelope)

## Shelters for five churches in Lalibela, Ethiopia.

### Design concept.

The rock-hewn churches at Lalibela are severely weathered and the structural condition as well as the wall paintings are in a critical condition. Furthermore, the present wooden scaffolding structures and their roofs need to be replaced. Under these circumstances the degradation of the site is accelerating.

We propose the new shelters made as pre-stressed fabric membrane structures - referred to as tent structures in the following. In our opinion, this particular type of structure possesses the required qualities, providing the best option for a medium term protection of the Lalibela churches at a reasonable cost.

Tent structures are simple structures of great architectural clarity with a geometrical form that follows the flow of forces. They are materialised according to the internal stresses and are totally free from material-consuming bending forces. They consist of compression members such as columns or arches, and tension members such as wires and fabric membranes and are probably the lightest type structure of all. They can be designed so they are easily assembled and dismantled. When packed they occupy relatively little space, allowing easy transport to a new place.

The semi-translucent membranes and the double curved surface allow a considerable amount of light into the surroundings of the churches with a maximum reflection of light during early morning and late afternoon, when the sun is low on the horizon. Additionally, the very open structures provide for the best possible view of the roofs and the immediate surroundings of the churches.

Historic sources provide evidence of the previous use of special tents, which served as churches, when the residence of the king was moving from place to place. For some decades at the end of last century, the Lalibela churches were also protected under large tents made from sheepskin. Tents, also widely used during religious gatherings and for dances performed by the *dabtaras*, thus provide a precedent for reviving this tradition for the temporary material protection of the most endangered churches in Lalibela, but also justifying the continued use of tents elsewhere as shelters for pilgrims and tourists during the time of religious festivals and ceremonies. Inspired by the local tradition, application of coloured patterns on the membranes may be considered.

Technological simplicity and undisputed flexibility are considered the key features of the design proposal. We have analysed three alternative approaches:

1. A very symmetrical modular tent concept with standard masts and standard membrane units. Due to the undulating and non-rectilinear requirements of each church it would be necessary to be quite creative with the foundation positions.

2. Custom designed shelters for each of the churches. Afterwards reuse of the rigid masts and steel boundary cables (which make up the majority of the costs) together with new membranes for a pilgrim centre or as shelters for other structures in need of protection.

3. Custom designed shelters for each of the churches taking account of a possible alternative use where the tents can be combined to make one or several shelters.

It is our conviction that alternative 1 is problematic as the restrictions regarding shape, functionality and aesthetics will be too limiting for a satisfactory result. Alternative 2 is appropriate, but with relatively few adjustments the tents can be designed to comply with the requirements of the far more attractive alternative 3.

On this assumption we have designed the tents with maximum flexibility and tested the possibilities of an alternative use as a pilgrimage centre or a tourist amenity space after the temporary use as protective shelters of the churches.

The possible future use is demonstrated by the computer animated illustrations. The five tents can be assembled in a number of different combinations on level ground and the flexibility of the design also allows adaptation to an undulating terrain. Depending on needs, additional tents can be added as shown in the illustration.

**Authenticity of the site and archaeological documentation.**

In no places are the masts positioned within the trenches that surround the churches and in only a few cases are anchors drilled into the external wall of the trenches. This implies minimum interference in any rock surface previously belaboured by man.

Considerable work was carried out at the historic site of Lalibela in the 1960s without adequate archaeological investigations and documentation. Any future work at Lalibela, whether this includes the erection of covering structures, improvement of drainage and access or structural repairs, will require full archaeological involvement. If this is not done, evidence may be destroyed which might enable controversies about the date and sequence of the churches to be settled, and their associated above-ground structures illustrated.

**Construction method and materials.**

The high technology needed for the production of the proposed tents is not available in Ethiopia. Most likely the tents will be pre-fabricated in Europe and ready-made for assembling on site. A local taskforce can assist with the setting up of the tents under supervision and be responsible for maintenance and the subsequent dismantling of the structures.

The tension wire-anchors are drilled into the rock. However, the tent structure is probably the structural type that requires the least intrusion on the ground. As the foundation load is concentrated in points, interference with trees, trenches, channels can be avoided and anchors are not being introduced in places of specific archaeological concern. Depending on the properties of the rock the casting of some limited concrete foundations with steel founding plates may be needed as a base for the pointed column.

When there is no more use of the tents all the holes for the rock anchors can be plugged with a lime mortar that is sympathetic to the texture and colour of the natural rock surface, leaving no visible trace on the rock surface. The foundations of masts are treated likewise.

The tents are supplied with welded or glued flexible barriers near the boundary leading rain water to the lowest cornerpoints, which are generally positioned with easy access to the existing trenches and water drainage system.

**Transportation**

The standard mast measures 12 metres in length to allow easy shipment in containers. Smaller masts of 3 metres in length allow people to pass underneath the connecting cables when erected and create no specific problems for transportation. Designed with a circular cross sections with conical ends the standard masts are ready made by the manufacturer, while the long masts of 17 metres are assembled on side.

The total weight of the 5 tents, including a total of about 13 masts is estimated at about 35 tons (10 t for the membrane, 10 t for the masts, 10 t for the cables and additionally about 5 t for foundations and accessories). The pre-fabricated tents may be contained in two containers.

**Maintenance and durability.**

After erection of the structure the stresses of the cables need readjustment once or twice. After these initial adjustments the maintenance is minimal, except for occasional cleaning of the fabric when dirty, which can be done by local manpower. The required maintenance will be specified in the Maintenance Manual.

Possible incorporation of energy producing components, such as photovoltaic cells or the like, as referred to in the design criteria, is not appropriate in combination with the flexible tent surfaces, neither is it considered as complying with the requirements of simplicity, flexibility and low maintenance .

The guaranteed lifetime of the fabric will be a minimum of 10 years, but the actual durability is probably much longer, justifying the reuse of the constructions for other purposes. The shelters can then easily be removed, packed, transported and re-erected.

The sophisticated structural system requires specialists to direct the assembling and disassembling of the tents, but manual work can be done by a local task force under qualified supervision.

**Security measures.**

Cables and masts are clearly visible and should not produce any specific obstacle or danger to pedestrians. In places where the cables are grounded soft bandages can be applied up to a height of about two metres.

Masts and cables cannot be climbed easily and the position of the fabric is not within reach.

People often gather dangerously on the top of the rocks around the churches. This situation will not become worse by the erection of the tents. If the problem gets worse due to the growing number of tourists some sort of fence may be required. Also introduction of special tourist trails or special itineraries may need to be considered in a future management plan for the whole World Heritage Site.

**Estimated cost and time of production**

| **Item** | **Cost ETB** |
|---|---:|
| Membrane | 12,064,500 |
| Steel Construction | 2,349,705 |
| Transport, preparation at site and dismantling of existing covers | 1,544,256 |
| Foundation and assembly | 2,435,880 |
| Connections to existing drainage system, and archeological work | 973,203 |
| Sub-total | 19,367,544 |
| Contingencies 10% | 1,936,754 |
| Grand total | 21,304,298 |

We estimate factor "n" = 20 and factor "m" = 10. This gives a total time for design period from inception report to the advertising of the Works Tender of approximately 13 months.

**Preliminary structural calculations**

Resistance to earthquake is excellent for tent structures because of their low mass and high flexibility. Even in case of collapse of the structure, the consequential damage of the monuments will be minimised.

The preliminary statical calculations are based on loadings according to Eurocode 1: Basis of Design and Actions on

Structures. The design wind speed is 50 m/s. The calculations result in the design of the pre-stressed anticlastic surfaces, fabrics, columns, anchors etc. as illustrated on the posters

The unusual high design wind speed may give reason to some concern regarding the structural behaviour of tent structures in relation to the proposed shape and free span. Further the successive positions of tents in group 2 might create dangerous wind turbulence. The mast-to-mast span is difficult to reduce as long as we keep the immediate surroundings of the churches free of any masts, but the shape and extent of the membrane-covered area may be adjusted according to detailed computation. No data on wind form-factors are available for such tent structures, and the actual conditions are on the upper edge of the present knowledge. It is considered to test the actual design under simulated conditions in a wind tunnel to verify the design.

The exact position of the drilled tension anchors depends on the actual mechanical properties of the rock surface and on the archaeological findings.

These uncertainties mean that we have reservations regarding the actual shape of the individual tents, the position and height of the masts, the position of the foot points for anchors and masts and the choice of foundation type. In exceptional cases gravitational concrete mass foundation may be needed eventually. For the large shelter of Medhane-Alem and the combined shelter of Maryam/Masqal an alternative design may come into question. One alternative shape may be the 'wave-shaped', central structure used for the future pilgrim centre proposal. We are firmly convinced that the design concept for the shelters can be maintained.

**The tents.**

The pre-stressed anticlastic tent structure derives from the nomadic tents made from woven fabric from sheep and goat hair. The structure has proven to have a very suitable shape for resisting wind forces. The structural principle was taken up by the German architect and engineer Frei Otto, who in the sixties turned this structural type into modern architecture. Since then thousands of these structures have been built around the world. With the development of computers, modern fabric materials and assembling techniques, the tent type of structures are today being built in large scale as e.g. the airports at Rhiyadh and Denver. The principle is simple as the membrane stresses in one direction stress the membrane in the orthogonal direction. The stresses are collected in forces in the edge steel cables, which are transferred to the lower point's masts or anchors – and to the higher points masts and anchor bars.

The structural calculation is performed by an internationally recognised software based on the so-called "Force Density" method. The Force Density theory is developed by Stuttgart engineers close to Frei Otto, and used for the first time for the German Pavilion at the World Exhibition in Montreal in 1967. This software calculates the shape, cutting pattern, stresses and deflections, and gives therefore the basis for the choice of mast heights, wire dimensions, fabric strength and the forces for the surrounding structures: masts, tension bars, anchors and foundations.

The suggested membrane is a high quality PVDF coated Dtex PES HT yarn such as Ferrari 1502 Floutop T, which is protected against fire and UV radiation. The computer-cut fabric strips are welded together. The fabric performs well in a hot climate and the surface is resistant to sandstorms. The guaranteed lifetime is at least 10 years, but the actual durability is probably much longer, justifying the reuse of the constructions.

**Masts, tension bars, anchors and foundation.**

The design is based on Eurocode 2: Design of Concrete Structures, Eurocode 3: Design of Steel Structures, Eurocode 7: Geotechnical Design including the relevant additional standards.

The forces delivered to the masts are of the magnitude up to 1200 KN in an almost horizontal direction. With an appropriate angle for the mast and tension bars, the forces in these elements are roughly of the same magnitude.

The steel quality of the masts and plates is S 355 JO according to DS/EN 10025 or similar standards. The surface is hot dip galvanised. The masts' ends are conical in order to give a lighter appearance.

The tension bars and fittings are made from stainless steel specified according to EN 10088 or similar standard.

Anchor bolts are threaded and made by stainless steel. Chemical anchors may be such as system HVA from HILTI. Similar anchor systems may be considered.

**Principles for assembly of shelters.**

The churches shall be protected during assembly of the shelter against falling objects, tools. etc.
Assembly can be carried out with the use of light tools, small cranes, etc.

1. The existing shelters shall be taken down first and the masts shall then be erected. The masts will be stabilised using their permanent tensile elements and by the use of temporary wires.

2. A temporary light construction of scaffolding and wires will be erected around the monument in question.

3. A protective net will be installed above the monument to protect it.

4. The membrane will be rolled out on top of the net. The net does not need much tightening as it can easily bear this light load.

5. The membrane is raised to its final position and pulled into place by means of the special corner fastenings. Tensioning of the membrane and the tension members is adjusted to the designed values.

6. The protective net and the temporary construction is taken down.

Alternatively, the masts may be erected after installation of the protective net. In this way the monuments are protected during the entire assembly.



"Shelters for five churches in Lalibela" - International design competition: Under-shelder plan of tents at site A and B

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