

Fusée Ceramic Vaults and Domes in the Netherlands

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Summary

This paper gives an overview of the fusée Ceramique vaults and domes constructed in The Netherlands just after World War II and describes the technique of construction as well as the advantages and disadvantages. Using only a minimum of concrete and steel, the environmental load of the vaults is quite small. Probably this study can contribute to the development of form-active systems, constructed of varying materials to reduce the environment load of buildings in the next decades.

Keywords: *Barrel vaults; domes; ceramic elements; technique of construction; sustainability.*

1. Introduction

Nowadays the Fusée Ceramic system seems to be nearly forgotten. Just after World War II this system was applied successfully in The Netherlands. A fusée is a cylindrical tube of ceramique which was embedded in concrete walls and roofs, mostly barrel vaults and domes, to reduce weight, cement and cost. The fusées were patented by the architect Jacques Couëlle. During the fifties of the twentieth century building industry was booming, the cost of materials were rising and architects had to find alternatives to save cement and steel. Thanks to the ceramique bottles, the self weight and the need of mortar could be reduced considerably. Structurally these roofs are designed very efficient. The fusée barrel vaults are form-active structures, strengthened with steel ties to resist the thrust. The concrete roofs are compressed and the steel ties are tensioned, so both parts are loaded according to the properties.



Fig.1: Barrel vault, workshop former Military complex, Woerden, The Netherlands.

Nowadays these buildings seem to be old fashioned and aesthetically not very interesting. Nevertheless these buildings are an essential part of our cultural heritage [1]. It would be a pity in case all these buildings are pulled down and lost forever. Especially because we can learn much from the technique of design and construction. In this paper attention is given to the sustainability. In the following decades saving materials will be an important issue again to reduce the embodied energy and the emissions of CO₂, NO and NO₂ during the production. Possible these composite vaults can be developed further to reduce the environment load of buildings.

2. Historical overview

During the fifties of the twentieth century building industry was booming, consequently the cost of materials was rising and architects, engineers and contractors had to find alternatives to save cement and steel. In 1940 the French architect Jacques Couëlle invented a system to built structures of cylindrical ceramic elements, the so-called Fusées Ceramique, which were laid in concrete walls, floors and roofs [9]. Jacques Couëlle was inspired by the branches of bamboo, which can be considered as tubes, stiffened by nodes.

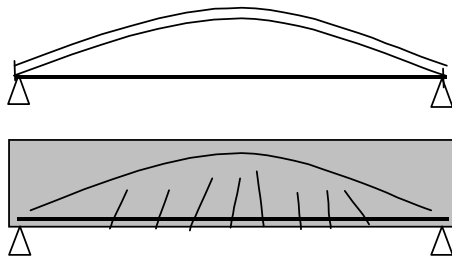


Fig. 2: Comparing the load transfer for an arch and a reinforced beam.



Fig. 3: Barrel vault for the St. Joseph church in Sittard, The Netherlands, 1951 [10].

Outside France, the fusées were introduced in North Africa too [9]. Especially the improved heat insulation, due to the hollow core elements, was appreciated, to drop down high temperatures inside during the summer. A few years later the system was introduced in Belgium and the Netherlands. A factory "De N.V. Nederlandse Fusée Ceramique Maatschappij, Nefumij" was erected in Echt, which could produce 10 millions of fusées yearly [6]. The technique of engineering and building was described in journals and technical books [8] and many barrel vaults were made, mostly for warehouses, factories, garages, swimming pools and churches. For example the St. Joseph church in Sittard, designed by the architect Huysmans, was roofed with a fusée barrel vault [10], see figure 3. The fusées were applied in domes too. For example the St. Raphael-Exodus church, designed by the architect Herman van Wissen was roofed with a dome in 1959 [13], see figure 4. Also the dome roofing the entrance building of the railway station in Arnhem, designed by Schelling [3], was constructed with fusées, see figure 5. Recently this station is renewed and the entrance was removed, probably this pavilion will be rebuilt in a park, Presikhaaf, in the city of Arnhem [12]. During the sixties the cost of labour was rising and roofs of steel and timber became competitive for low rise buildings, consequently this system was obsolete in the last quarter of the XX century.

Actually hollow ceramic elements were applied 15 centuries before by the Roman engineers, for example into the church of San Vitale in Ravenna, Italy [5]. Nevertheless the joints of fusées ceramique are without precedent. The bottles had a conical top to joint the elements by shoving the conical top into the rear of the next bottle. Thanks to the conical top these elements could be rotated slightly at the nodes, so these elements could be applied easily in curved roofs as barrel vaults and domes. Structurally the barrel vaults and domes are very sophisticated. Concrete can resist compression very well, but the maximum tensile stress is poor. To resist bending concrete is mostly reinforced, nevertheless the tensioned parts are often cracked. The fusée barrel vaults can be considered as concrete arches supported at the ends with steel ties to resist the thrust. The concrete arches are compressed and the steel ties are tensioned.

Comparing the load distribution of an arch with a beam shows the efficiency of the arch using less material than a beam, see figure 2.

Thanks to the form the concrete vaults were mainly compressed and not cracked. Consequently for these roofs the need of maintenance was minimal too. Already during World War II the advantages of the Fusées Ceramique were recognized by the army to build bridges, barracks and shelters.

A large factory was built in Marseille and just after the war, a lot of the fusées were in stock, ready to use. Many people had lost their homes and architects, for example Andre Bruyère and Fernand Pouillion, used these elements for temporary houses. In Marseille a large resort, the Arenas Camp, was built for emigrants from North Africa.



Fig. 4: Dome, the St. Raphael Exodus church 1959 [13].

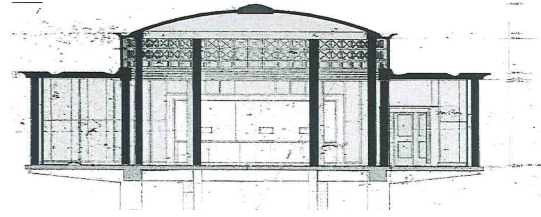


Fig. 5: The entrée-building of the station in Arnhem. This swallow dome is mainly compressed [3].

Table 1 shows some vaults and domes built in the Netherlands. Alas most of these buildings are pulled down. The list is not complete, more research is needed to fill in the missing facts.

Tabel 1: Examples of fusée roofs in the Netherlands

	name, location	span	built	Architect	pulled down
barrel vault	Kantine Nederlandse Persil mij.				pulled down
barrel vault	Sportcomplex BPM Sportpark, de Vijfsluizen, Vlaardingen.		1953	S. van Riet	pulled down
3 barrel vaults	Ruwgoed magazijn N.V. Twentsche Stoombleekerij Goor.	16,2	1949		pulled down
2 barrel vaults	Exportafdeling N.V. Twentsche Stoombleekerij Goor`.	12,6	1953		pulled down
barrel vault	Blauwhal, Akcros complex, Roermond.	22,0	1950	G.Klaarenbeek	pulled down
barrel vault	de Bonte Kleurenfabriek, Akcros complex, Roermond.	14,5	1950	G.Klaarenbeek	pulled down
barrel vault	St Joseph kerk, Sittard.		1951	Huysmans	pulled down 2002
barrel vault	Timmerwerkplaats en spuitrij, gebouw Q, Defensierrein Woerden.		1954		will be pulled down in 2011
barrel vault	Goederenopslag, Gebouw R, Defensierrein Woerden.		1954		will be pulled down in 2011
barrel vault	Garage, Oosterhout				still in use
dome	St Raphael-Exodus kerk, Groningen.		1959	H. van Wissen	still in use
dome	Entrée railway station, Arnhem.	8,8	1954	H.G.J.Schelling	pulled down 2009

4. The technique of construction

Fusées are cylindrical elements with a length of 350 mm, an outward diameter of 80 mm and a thickness of 10 mm [6]. To joint the fusées, one of the ends was narrowed conically, to shove this end into the open rear of a second element. The joints could be rotated slightly to follow the curvature of a barrel vault. The fusées were embedded in concrete, the construction was as follows:

at first the scaffolding was erected and the mould was greased. A thin layer of about 25 mm of mortar was poured. Next the elements were made wet and pushed into the mortar with a twist, starting at the gutter.



Fig. 6: Construction of a barrel vault [6].

At the top the elements were connected with a tube with open ends at both sides. After finishing six rows the second layer of mortar was poured. Sometimes a second and a third layer was made. The mortar of the second layer is poured when six rows of fusées are laid on the formwork. The top layer was smoothed with a straightedge. The mortar had to be hardened for at least 36 hours before the formwork could be stripped [6]. Sometimes the cost of formwork was decreased with a sliding mould, which could be moved on rails to reuse the mould several times.

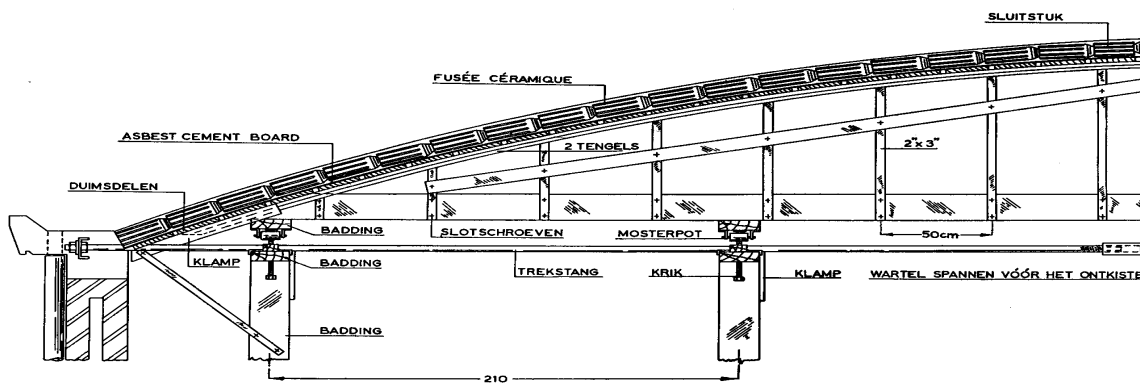


Fig. 7: Section of a barrel vault showing the formwork and the anchoring of the tie into the edge beam [5].

5. Form, curvature and dimensions



Fig. 8: The workshop of the former military complex 'het Defensie-eiland' in Woerden, the roof lights run parallel to the span.

Generally the barrel vaults were curved according to a segment of a circle, a parabola or a funicular line. Mostly the barrel vaults resting on the ground floor were supported by the foundations. Otherwise the vaults were supported by walls or frames, composed of beams and columns. For vaults resting directly on the foundations the thrust could be resisted by the foundations or a reinforced concrete ground floor. The thrusts acting on vaults, supported by frames or walls, were resisted by steel bars, generally with a centre to centre distance of about 1,0 m. The anchoring of the ties had to be detailed carefully. By preference the tension rods were connected halfway the height of the beams to avoid twisting moments [7], see figure 7.

To enlighten the inner space, roof lights, running parallel to the span of the roof, could be made, as showed in figure 8.

The number of layers of the fusées was chosen according to the span and load. According to Van Eck [5] one layer of fusées could be applied for vaults with a span of maximal 15 m. For larger spans and heavy loads two or three layers were needed, see figure 10. The thickness of the shells was chosen according to the number of layers. For a vault with one layer a thickness of 110 mm, with two layers a thickness of 180 mm and for a vault with three layers a thickness of 250 mm was recommended [6]. Generally the barrel vaults were reinforced, nevertheless some vaults were constructed without reinforcement, just like vaults of masonry. According to Langejan [6] a barrel vault with 3 layers of fusées and a span of maximal 15 m could be constructed without reinforcement. Van Eck[5] recommended a reinforcement of $\phi 6$ -180 for a span larger than 10 m and a reinforcement of $\phi 8$ -180 for a span above 15 m. For reinforced vaults the minimal thickness was slightly larger. According to the Dutch code of 1950 [2] the minimum covering c on the bars had to be at least 10 mm for a plate with a thickness of maximal 120 mm. For a vault, reinforced with rebars positioned between the fusées, the minimal thickness of a vault with one layer of fusées was:

$$t = 10 + 80 + 10 = 100 \text{ mm} \quad (1)$$

For a vault reinforced with distribution bars $\phi 6$ and rebars parallel to the fusées the minimal thickness of a vault with one layer of fusées had to be:

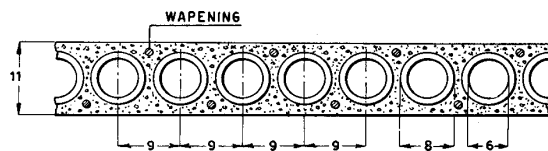
$$t = 10 + 6 + 80 + 6 + 10 = 112 \text{ mm} \quad (2)$$

For plates with a thickness of 120 mm or more the coverage c on the rebars must be at least 15 mm [2]. For a reinforced vault with two layers of fusées the thickness could be reduced in case the fusées were built in stepwise, see figure 10. The centre to centre distance of the elements had to be at least 90 mm. The centres of the staggered element could be positioned into an equilateral triangle. The distance between the horizontal lines through the centres of the layers was equal to $90/2 * \sqrt{3} = 78$ mm. Thus for a vault with two layers of staggered fusées the minimum thickness t was about:

$$t = 15 + 40 + 78 + 40 + 15 \approx 190 \text{ mm} \quad (3)$$

The main reinforcement can be laid between the fusées, but the distribution bars run perpendicular to the fusées. If distribution bars were used then the minimum thickness of the vault had to be increased with the diameter of the distribution bars. For a vault with two layers of staggered fusées and distribution bars $\phi 6$ the minimum thickness is equal to:

$$t = 15 + 6 + 40 + 78 + 40 + 6 + 15 = 200 \text{ mm} \quad (4)$$



Doorsnede fuseedak met verspringende wapening.

Figure 9. Section barrel vault with one layer of fusées [8].

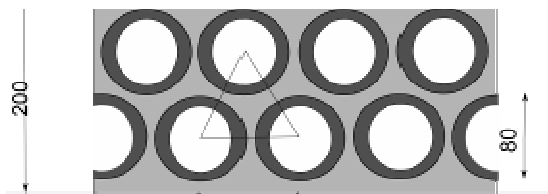


Fig. 10. Section barrel vault with two staggered layers.

6. Advantages And Disadvantages

During the introduction the benefits of this system were emphasized. Firstly the fusées were applied to save cement and steel. Due to the booming market for buildings saving materials was an important issue.

Langejan [6] described the following advantages:

- a reduction of the self weight of 25% -40%;
- saving cement up to 50% -70%;
- an increase of the heat resistance of 30%-40%;
- the uncomplicated construction;
- the formwork can be stripped earlier.

Further Van Eck [5] mentioned the acoustic resistance was practically identical to the acoustic resistance of massive structures. During the fifties the vaults were made on the site so the construction was quite labour-intensive. Finally this disadvantage was decisive, during the sixties the cost of labour increased and this system could not stand the competition with timber and steel roofs.

7. Future

Nowadays most roofs are flat, vaults and domes seem to be a relic from the past. Otherwise curved roofs are very practically to drain rainwater. In the Netherlands every year some flat roofs collapse due to the accumulation of rainwater. For roofs a shallow curvature is ideal. Structurally concrete vaults strengthened with steel ties perform very well. The concrete roof is mainly compressed and the steel ties are tensioned, consequently the materials are loaded according the properties. Especially for large spans the self weight is a substantial part of the load, so reducing the dimensions is very profitable. In the future minimizing materials and self weight will be an important issue again.

Nowadays the better part of the environment load of buildings is caused by the use. Owners has to reduce the energy needed to heat and cool buildings. At this moment buildings can be constructed which do not need fossil energy for heating and cooling. Possible in the future buildings can produce energy. Consequently the contribution of the production of the materials concerning the environment load will rise. Structures need the better part of the materials, about 60%. In future structural designers have to reduce the environment load of structures. Reducing the quantity of cement and steel in concrete will reduce the emissions of NO_2 , NO and CO_2 during the production.



Fig. 11. Workshop roofed with barrel vault, formal military complex known as 'het Defensie-eiland' in Woerden, The Netherlands.

Shells perform very well, the self weight is minimal and curved roofs drain the rain water very well. The form and surface active structure can resist heavy loads. Also the weight of a green roof can be transferred efficient. The construction of a single or double curved roof can be expensive in case the roof is made in situ, mostly because of the cost of the formwork and scaffolding.

Prefabrication of the shell will reduce the cost of the formwork considerably. Barrel vaults can be split easy into transportable prefabricated elements. Nowadays trucks can transport huge elements and heavy loads. Further the capacity of cranes is increased too, so the assembling of huge elements is not to hard anymore. Barrel vaults can be partitioned into longitudinal elements, constructed in a workshop with a sophisticated mould, which can be adapted to meet the specific demands of the projects concerning curvature and length. A mould for a circular vault can be reused often even for several spans provided the radius does not vary.

Structurally the bending moments in a circular vault will be larger than the moments in a parabolic vault. Consequently the circular vault will need a larger reinforcement, but calculations show that the bending moments are not very large. Reusing a circular mould with constant radius will be cost effective and compensate the cost of the reinforcement needed to resist the bending moments due to the difference of the line of the system and line of thrust. Probably prefabricated barrel vaults are

competitive, especially in case the permanent load is substantial, for example if the roof is loaded by solar panels or vegetation.

8. Conclusions

In the following decades minimizing the embodied energy needed to produce building materials will be an important issue. Form-active structures can be dimensioned very slender, for roofs these structures can be competitive again, especially in case the structure is prefabricated. The self weight of structures can be reduced with light infill elements further. The Fusée Ceramique system shows the advantages of structural elements composed of varying materials to create light structures. Learning from this system is inspiring and will be helpfully to create composite structures meeting the demands of the future.

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