# Fixed Channel Road Link

7.58. e

Volume V: Ventilation Structure Foamed Concrete Protective Ring

August 1987

M.L. Witjens





Faculty of Civil Engineering Offshore Technology

## FIXED CHANNEL ROAD LINK

volume 5

Ventilation Structure Foamed Concrete Protective Ring

M.L. Witjens

Thesis Committee:

prof. ir. Ch.J. Vos, chairman ir. C.J.P. van Boven prof. ir. A. Glerum ing. H.C. Jager W.W. Massie M.Sc., coordinator

Delft University of Technology Department of Civil Engineering Offshore Technology

august 1987

## PREFACE

This part of the report concerns the study of foamed concrete as collision protection of the ventilation structure of a road link between France and England across the English Channel.

It is the fifth, and last, part of the thesis reports of W. Guijt, M.A.P. Mol and M.L. Witjens written during their study of civil engineering at the Delft University of Technology.

This study is particularly carried out by M.L. Witjens

The author wishes to express his thanks to Mr. H.H.M. Soen of the MEBIN for his cooperation.

#### SUMMARY

Foamed concrete is a material on basis of cement with a density which varies with the amount of air brought into the concrete mechanically.

With foamed concrete a collision mechanism in which ship and wall both absorb energy can be realized.

A 318,000 dwt. oil tanker travelling at 15 knots has a kinetic energy of 9.8 \* 10\*\*9 Nm. To adjust the strength of the foamed concrete to the bow strength of a tanker, the compressive strength may not exceed 0.4 N/mm\*\*2. To achieve this value, the average density of the concrete must be 300 kg/m\*\*3.

The crash cushion ring has a height of 42 metres, 15 metres above mean sea level, an outer diameter of 104 metres, a width of 25 metres and consists of 96 elements which can be replaced when damaged.

An outer skin of normal concrete protects the crash cushion against damage by collisions of small vessels and wave attack.

## CONTENTS

Preface

Summary

Introduction

Chapter	1	Foamed Concrete		8
	2	Fabrication of foamed concrete		14
	3	Fender system		19
	4	Energy and bow strength of ships		22
	5	Energy dissipation		27
	б	Crash cushion of foamed concrete		33
	7	Design of crash cushion ring		40
	8	Costs		49
	9	Conclusion		51
Bibliogr	apl	лу		52

6

### INTRODUCTION

In the study of a road link across the Channel between Dover and Calais, a combination of a bridge and a submerged tunnel came out as best solution. A ventilation structure in the middle of the Channel is then needed to ventilate the tunnel part of the link (see first report).

Collision risk in combination with the consequences of a collision between ship and structure, make it necessary to protect the structure. A 'protective wall', integrated into the design of the concrete ventilation gravity structure, is the most attractive way to protect the ventilation structure against ship impact (see second report).

There are various possibilities to construct such a wall. In this report the feasibility of the use of foamed concrete as fender material is studied.



- 7 -

## 1 FOAMED CONCRETE

Foamed concrete is a material that exists for over 50 years. Its application however has always been limited. The interest in foamed concrete has increased lately with as result new developments in equipment and foaming agents.

Foamed concrete is frequently used as:

- working floor
- on roofs
- floor foundation
- filling of old sewer systems
- road foundation



fig. 2 working floor of foamed concrete



road foundation fig. 3



fig. 4 floor foundation RAI complex Amsterdam



fig. 5 foamed concrete applied on roofs

The specific properties of foamed concrete are:

- good fluidity, which makes it easy to work with and makes densifying unnecessary. The concrete can also be pumped without any difficulties.
- low density
- high thermal insulation as a result of the large amount of air in the concrete

Foamed concrete is a material on basis of cement with a density which varies between 400 kg/m\*\*3 and 1800 kg/m\*\*3. These values are low compared to normal concrete with a density of 2300 kg/m\*\*3. The low density is achieved by bringing mechanically large amounts of air into the concrete. A cement paste is mixed with foam, which creates

bubbles in the mixture. The foam is obtained by mixing intensively a concentrated foaming agent with water.

The cavities in foamed concrete are more or less round and vary in size. They are smaller than 0.2-0.5 mm., depending on fabrication method and foaming agent. Foamed concrete is not the same as aerated concrete, although the structures of both materials look alike. The cavities in autoclaved aerated concrete are created by a chemical reaction of cement, chalk, water and aluminium under increased pressure and temperature. In foamed concrete air is added by mechanical means, instead of chemical, under normal atmosferic circumstances.



fig. 6 structure of foamed concrete

The different components of foamed concrete are:

- foam
- cement
- water

and when necessary

- aggregates
- additives

The foaming agents are carefully selected chemicals on a proteine or synthetic basis. The proteine foams have a higher density, 60-100 kg/m\*\*3, than the synthetic foams with a density of 20-60 kg/m\*\*3.

The same cement that is used for normal concrete can be used for foamed concrete.

The water may not contain impurities in such quantities that they influence the stability of the foam negatively or affect the reinforcement, if applied. Aggregates have to meet the following two requirements:

it may not contain impurities in harmful quantities
the grain size and mass must be such that a stable mixture is obtained

Sand is the most applied aggregate. It has to be smaller than the usual concrete sand, in the range of 0-2 mm. There are many other aggregates like, for example, expanded clay, expanded polystyrene, fly ash or vermiculite.

As additives, the same can be used that are commonly used for normal concrete.

#### 2 FABRICATION OF FOAMED CONCRETE

As mentioned earlier, foamed concrete is made by mixing 'basic mortar' with foam. This basic mortar is a cement paste, a sand-cement mortar or a mortar with aggregates to which the foam has to be added.

In the beginning, foamed concrete was also made by agitation. With this method, bubbles are created in the basic mortar by means of mixing or agitating the mortar with a foaming agent. The foaming agent is added as a powder or liquid to the mortar, after which it is intensively mixed in a special mixer.

This method has as disadvantage that the maximum amount of air that can be brought into the concrete is about 30 to 40 % of the total volume, which means that the minimum density is some 1500 kg/m\*\*3.

Another disadvantage is that the agitation time is long.

Modern methods are based on mixing of the basic mortar with a beforehand made foam. There are three methods of mixing the basic mortar with the foam:

- foam injection in a truckmixer The foam is injected in a truckmixer filled with basic mortar. The mixing of foam and basic mortar takes place in the truckmixer, after which it can be poured in the work.



fig. 7 truckmixers

- foam injection in a pump circuit
  - During the pumping of the basic mortar on the building site, foam is injected into the pump circuit, preferably behind the pump. The mixing takes place in a steel pipe with a length of about a metre in which special plates bring the basic mortar and foam into turbulence.



fig. 8 foam injection in pump conduit

- mixing in special mixers on the building site The basic mortar is made on the building site in a specially designed mixer. Foam is injected into the mixer and mixed with the basic mortar into foamed concrete mortar, which is pumped to its location.



fig. 9 foamed concrete mixer

### Pumps

The great fluidity of foamed concrete mortar makes it possible to be pumped by a hose pump. The capacity of the pump, depending on the diameter of the tube, can be as much as 40 m\*\*3 per hour. Usual diameters are 76 and 102 mm. (3" and 4").

The plunger pumps which are used to pump normal concrete mortar, can not be used for foamed concrete mortar, unless the valve system is adjusted. The capacity is then 10-20 m\*\*3 per hour.







fig. 11 plunger pump

## Foam generators

Foam is made by bringing foaming agent, dissolved in water, and compressed air into turbulence in a jet pipe. The way the system works is shown in fig. 12 There are foam generators of various dimensions. Their capacities vary from 100 to 1000 liter foam per minute.





#### 3 FENDER SYSTEM

A structure in the middle of the Channel which takes care of the ventilation of a 20 km. long road tunnel has to be protected against possible ship impacts. The ships that can collide with the structure vary from small supply boats to 318,000 dwt. tankers.

When a ship hits the protective wall of a structure, three different mechanisms can take place, depending on the strength ratio of structure and ship.

- when the structure is much stronger than the bow of the ship, the kinetic energy of the ship will totally be absorbed by plastic deformation of the ship.
- when the ship's hull is the strongest, the ship will enter the protective wall and most of the energy will be absorbed by crushing of the wall.
- when ship and wall equal each other in strength, part of the energy will be sbsorbed by plastic deformation of the ship and the rest by crushing of the wall.

In the first mechanism the damage of the wall is limited to some local damage on the outside. The ship however, will be damaged severely with all accessory consequences, such as casualties among the ship's crew, explosions, fire and severe pollution of the water in case of a loaded oil tanker or carrier of toxic substances. The rigidity of the wall will make it necessary to dimension the structure on high local stresses and a high total force exerted by the ship.



## fig. 13 collision with rigid wall

The second mechanism is favourable from a ship's point of view. The wall acts as a large cushion so the ship is only slightly damaged.

The dimensions of such a wall are many times that of a rigid wall, which increases the costs and the chance of collision. The repair costs after collision will be large and because of the low strength of the wall, even small ships will cause great damage. The large dimensions of the wall also increase the wave forces on the structure.



fig. 14 collision with energy absorbing wall

The third mechanism is a sort of compromise of the previous two. Ship and wall absorb both half of the energy. This way, the damage to the ship can be restricted to the bow and the repair costs of the wall are limited, as is the necessary diameter.



fig. 15 collision in which ship and wall both absorb energy

The density of foamed concrete can be adjusted to give the concrete the required properties.

One of the properties which varies with the density is the strength. It is therefore possible to adjust the strength of a foamed concrete protective wall to the mechanism required, depending on the strength of the considered ship.

The third mechanism, in which ship and wall are both damaged, is the most preferable. The detrimental effects of a collision on the environment are limited as are the costs of construction and repair.

To ensure that the collision takes place as assumed above, the wall has to be of the same strength as the considered ship. 4 ENERGY AND BOW STRENGTH OF SHIPS

In the second report of this study has become clear that all kinds of ships sail through the Channel. Three types of ships are taken into account:

- supply boat
- container carrier
- tanker

Two aspects are important for the design of a collision protection wall:

- kinetic energy
- bow strength

The kinetic energy of a sailing ship can be expressed as:

E = 0.5 \* m \* (v \* \* 2)

in which m = mass of displaced water
 v = velocity

The ultimate strength of bow constructions has scarcely been analysed. In Japan, Ohnishi, Kawakami, Yasukawa and Nagasawa have

carried out experiments using 1/10 scale bow models.

A supply boat has a small mass and therefore a small amount of kinetic energy, compared to the other two vessels. The total force exerted by the bow of a supply boat is also much smaller than the forces by a container carrier or a tanker. The collision of a supply boat with the structure is therefore not important for the design of the structure as a whole.

The bow strength per unit of area of a supply boat however is high. This means that the outside of the protection wall has to be made strong enough to withstand this small, but locally high, impact force.

When this is not done, every small collision will cause disproportionate damage and repair costs. A reinforced outer wall will also reduce local damage by wave attack.

The kinetic energy of a ship depends on its velocity and mass displacement. For a container carrier and a tanker the following table can be made:

ship type	draught (m)	dwt (ton)	spaed (knots)	kinetic energy (Nm)
container carrier	12.0	35,000	25	$3.0 \times 10^9$
tanker	22.75	318,000	15	9.8 × 10 <sup>9</sup>

## table 1 kinetic energies

A 35,000 ton container carrier and a 318,000 ton oil tanker are considered representable for the container ships and tankers in the Channel. Table 1 shows that, despite the lower speed, the tanker has the highest kinetic energy, due to its large tonnage.

The comparison of bow strength is based on the results of the Japanese experiments mentioned earlier. Ohnishi, Kawakami, Yasukawa and Nagasawa used bow models as shown in figure 16.



## fig. 16 bow models

They translated the experimental values of 1/10 scale models to values for full sized bow constructions. The principal dimensions of the container carrier and the tanker for which they calculated the bow strength are shown in table 2.

Item	Container carrier	Tanker		
Lpp(m)	248.0	360.0		
B (m)	32.2	69.0		
D (m)	19.9	28.7		
d (m)	12.0	22.75		
DWT (ton)	35,000	409,000		

#### table 2 principal dimensions

The collapse loads vary with the sectional position. When the collapse load arising midway between forepeak and collision bulkhead is taken, the values of table 3 are obtained. In this table, A is the area of the section perpendicular on the direction of propagation.

	P(MN)	A(m <sup>2</sup> )	$P/A(MN/m^2)$
container carrier	88	74	1.19
tanker	245	602	0.41

#### table 3 comparison of bow strength

The total collapse load of the tanker is the largest, but per unit of area, the container carrier is stronger. When a protection is required that may not collapse partially but has to stay intact during collision, the container carrier determines the minimum local strength of the structure.

When a system is applied in which the energy is partially absorbed by the protection, the maximum local strength is determined by the tanker.



fig. 17 tanker "skyron" after collision

#### 5 ENERGY DISSIPATION

The tanker has a large kinetic energy, 9.8 \* 10\*\*9 Nm. This energy has to be dissipated during collision, assuming that the velocity of the vessel after collision is zero and neglecting dynamic effects.

When the structure is considered rigid, the energy is dissipated through deformation of the bow. When the wall is not rigid, energy will also be dissipated through crushing of the concrete.

Dissipated energy can be discribed by:

 $E = \int_{0}^{r} F(x) dx$ in which: E = dissipated energy x = distance covered during collision F(x) = collision force as function of x

The function F(x) versus x is determining for the amount of energy dissipated. When the results of bow strength research are simplified, the load versus deformation curves of the bow of a container carrier and of a tanker are as presented in fig 18 and fig 19.



fig. 18 deformation load of container carrier



fig. 19 deformation load of tanker

In order to calculate the deformation of the ship after collision, the following phenomena are not taken into account:

- energy dissipation by friction
- energy dissipation by rotation of the ship
- energy dissipation by uplifting of the ship
- energy of the ship after collision
- hydrodynamic damping
- lateral displacement of the structure
- dynamic aspects

These assumptions make that all energy is dissipated by deformation, which yields:

E kin = E dis

With 350 MN as maximum collision force by a 318,000 dwt tanker, the deformation of the tanker after a head-on collision with a rigid wall will be 35.5 metres. The oil spill resulting from such damage and the chance of explosion and fire is very large.

A better solution is to make a protective ring with a

crushing strength smaller than the ultimate bow strength. When a crushing strength of 250 MN is chosen, the load deformation curve of the ring will be as presented in fig 20.





When a tanker collides head on with this wall, both the ship and the wall will be deformated:

deformation tanker = 16.7 metres
deformation ring = 25.7 metres

Calculation shows that a "soft" protection can limit the deformation of the tanker, depending on the "softness" of the wall. Here 250 MN is chosen as crushing strength, to ensure that the ultimate strength of the ship is larger, with as result a deformation of "only" 17 metres. The first bulkhead will not be damaged and thus the chance on loss of oil is reduced considerably compared to a collision with a rigid wall.

The depth of the wall must be some 25 metres. To ensure that the tanker will not punch through the wall and to bring the collision forces to the caisson of the structure, a rigid wall is necessary within the "soft" ring.

On the outside of the protection ring, an outer skin of normal concrete prevents the foamed concrete of being affected by wave attack. This outer skin is to be dimensioned in such a way that it can withstand high local stresses, spreading them over a large area of foamed concrete. This way a small collision, for example by a supply boat, will not cause any significant damage. Without such an outer skin, small boats with strong, stiff bows could easily penetrate the foamed concrete, causing unproportioned large damage to the protection structure.

Another function of the outer skin is the support of a boat landing, navigational warning devices and other items to be installed on the outside of the ring.



OUTER WALL



The strength per unit of area of the crash cushion must be the same as the strength per unit of area of the tanker bow, delivering a collision force of 250 MN. This condition determines the strength of the cushion at 0.4 MN/m\*\*2. The container carrier induces a smaller collision force, but has a strength per unit of area of 1.2 MN/m\*\*2. When a container carrier hits the "soft" ring, with a strength of 0.4 MN/m\*\*2, it will crush the ring and cause little damage to itself.

The force exerted by the crash cushion on the container carrier depends on the area of the ship perpendicular to its direction of propagation. In turn, this area depends on the penetration depth of the ship in the crash cushion. The resulting force versus penetration in the wall is given in fig 22.



fig. 22 penetration load on container carrier

The energy dissipated by the crash cushion, E dis =  $1.3 \times 10^{**9}$  Nm.

The kinetic energy of the container carrier before collision, E kin = 3.0 \* 10\*\*9 Nm., so the container carrier is not stopped by the crash cushion. The inner wall must therefore be dimensioned to resist this locally higher force of the container carrier. The maximum total force is always smaller than that of the tanker.

In the previous energy contemplation several energy absorption mechanisms were not taken into consideration. The total amount of energy absorbed by these mechanisms however can become more than 25 % of the initial kinetic energy of the vessel.

The figures of deformation given above are therefore conservative, but because no further research has been done here to the effect of the various phenomena, these figures are supposed to be representative.

## 6 CRASH CUSHION OF FOAMED CONCRETE

The idea to use lightweight concrete for crash cushions is not new. In the United States the use of cellular concrete in vehicle crash cushions was tested on prototype installations in the early 70's (Highway Research Record nr 386).

The crash cushion proofed to be an effective system to protect motorists from collisions with rigid obstacles. The vermiculite concrete used in the various tests had an average compressive strength of 0.4 N/mm\*\*2 and an average unit weight of 330 kg/m\*\*3



Mod III concrete crash cushion.



fig. 23 vehicle crash cushions



Test F sequential photographs (overhead view).



t = 0.031 sec

t = 0.064 sec



t = 0.130 sec



t = 0.199 sec



t = 0.380 sec



t = 1.480 sec

fig. 24 vehicle test

One of the properties of foamed concrete is that its compressive strength, and other mechanical properties, can be varied by varying the density of the concrete. A lower density, a higher percentage of air, leads to a lower strength. Fig 25 gives an impression of the relation between density and compressive strength, based on commonly used types of foamed concrete.



# fig. 25 compressive strength vs. density

It must be remarked that there is a spread in values for compressive strength of a given density. This spread is a result of variation in the following parameters:

- water-cement ratio
- amount of cement per m\*\*3 concrete
- sort and quality of cement
- amount of water per m\*\*3 concrete
- sort and amount of aggregates and additives
- type of foaming agent
- foaming technique

A crash cushion of foamed concrete to stop a tanker must have a crushing strength of 0.4 N/mm\*\*2. Fig 25 learns that foamed concrete with a density of 300 kg/m\*\*3 has a compressive strength of 0.4 N/mm\*\*2. Normally the crushing strength of solid concrete will be larger than the compressive strength because the crushed concrete will pile up. The high volume percentage of air in foamed concrete, especially in foamed concrete with a density as low as 300 kg/m\*\*3, will prevent this piling up effect totally or at least for a large part. Here is assumed for foamed concrete with a low density that the crushing strength equals the compressive strength.

The ship crash cushion of foamed concrete must have an average density of 300 kg/m\*\*3. This low average density can be achieved at two ways:

- using "solid" foamed concrete with a density of 300 kg/m\*\*3
- using foamed concrete with a larger density in combination with polystyrene

Produced in large quantities, the density and strength variations of foamed concrete can be kept within small margins once the production line is fully adjusted. A density of 300 kg/m\*\*3 is then feasible. Special attention has to be paid to the stability of the air bubbles in the foamed concrete mortar because of the large volume of air per cubic metre. To ensure stability the use of proteine foam is preferred above the use of synthetic foam. Proteine foam has smaller bubbles and is more stable than synthetic foam. The density of proteine based foam, 50-75 kg/m\*\*3, is larger than that of synthetic based foam, 35-50 kg/m\*\*3.

Casting of the concrete in thin layers will be costly in case of stagnation. It is more economical to pour the concrete in several layers with a thickness of 2 to 3 metres. To prevent difficulties by hydration heat, the concrete slab has to be cooled during hardening. The hydration heat can also be reduced by application of a large amount of fly ash. Fly ash has the same behaviour in mortar as cement.

In order to give an indication of the composition of the basic mortar, the following quantities per cubic metre concrete are feasible:

80 kg cement 150 kg fly ash 50 l water The amount of air in the concrete is 0.85 m\*\*3. To realize this, 0.90 m\*\*3 foam per cubic metre concrete is needed.

The water absorption of Cellcrete, a foamed concrete fabricated by Mebin in Holland, under water has been researched using test cubes of 100\*100\*100 mm. This yielded the results of fig 26





The figure shows a large water absorption, especially when the density is low.

Water absorption is a proces that starts at the outside of the structure. The values of these cubes are therefore not representable for thick structures as is the crash cushion ring.

Nevertheless, the concrete will be permanent under water over a long period of time and a coating to prevent waterabsorption might be necessary. The resistance of foamed concrete against low temperatures has proven to be good. Polystyrene has a density that is negligible. The strength is high enough to resist the forces by freshly poured concrete, so it is easily applicable in concrete.

The foamed concrete surrounding the polystyrene elements may have a larger density than 300 kg/m\*\*3, depending on the ratio concrete - polystyrene. A cost optimalisation will produce the most economic ratio.



fig. 28 combination foamed concrete (600 kg/m\*\*3)
 and polystyrene

The fluidity of foamed concrete mortar and the fact that the concrete does not have to be densified, makes almost every configuration of polystyrene possible. When the dimensions of the polystyrene elements become very large however the question arises whether the system of polystyrene and foamed concrete can still be regarded as solid foamed concrete with an equivalent density.

## 7 DESIGN OF CRASH CUSHION RING

Based on the previous results, a rough design of the crash cushion ring can be made. The ring must have an inner free diameter of 40 metres to house the deck support and ventilation shafts. A wall with a depth of 7 metres is needed to transfer collision forces to the caisson and to stop vessels which are not stopped by the crash cushion. The total inner diameter of the crash cushion is then 54 metres. The required depth is 25 metres, which makes the outer diameter 104 metres.

The height above mean sea level must be such that at high water even tankers in ballast will hit the cushion over their full height. This condition leads to a height of 15 metres above mean sea level.

The depth below mean sea level to which the cushion has to be extended in order to stop a loaded tanker has to be 25 metres. The mean waterdepth is 47 metres, so the cushion will be 22 metres above the seabed. The caisson of the structure has a height of about 20 metres, leading to a gap of 2 metres between crash cushion and caisson. For reasons of installation, connection and transfer of forces, the cushion is extended to the roof of the caisson. The total height of the crash cushion becomes 42 metres.

The outer skin of the crash cushion ring has to protect the foamed concrete against impact of small vessels. The minimum wall thickness of this outer skin is therefore determined by punching shear forces.

The outer skin is constructed of normal concrete, B 37.5, which has a minimum shear strength of 0.9 N/mm\*\*2. The ratio in stiffness of the outer skin and the foamed concrete is such that the outer skin can be schematized as a rigid plate. The consequence is that forces exerted on the outer skin are spread over its full area of 27.9 \* 10.5 metre.

Bow strengths of small vessels vary, but 2 N/mm\*\*2, 5 times the bow strength of a tanker per unit of area, is a conservative value. An outer skin with a wall thickness of 1 metre can resist this stress over an area of 5.5 m\*\*2, taken into account the wedged shape of the ship's hull.



fig. 29 small vessel load on outer skin

The bow strength of 2 N/mm\*\*2 will only be reached at a head on collision, which is highly unlikely. In order to reach an area of  $5.5 \text{ m}^{*}2$ , the bow of the ship has to deform considerably, depending on the form of the vessel. At a sideward collision the vessel will always loose from the wall.

The total impact force of a small vessel is too small to cause any damage to the foamed concrete. The 2 N/mm\*\*2 over an area of 5.5 m\*\*2 will induce a compression stress of 0.04 N/mm\*\*2 in the foamed concrete, only 1/10 of its compressive strength.

In the head on collision of a large vessel, the function of the outer skin is to deform the bow of the ship in order to enlarge the contact area of the ship when it penetrates the foamed concrete crash cushion. This way the crash cushion is more effective.



fig. 30 side view protective ring

- 42 -



fig. 31 section A-A of fig. 30

When a major collision has taken place, the crash cushion will be damaged. Repair of a solid ring, for a large part under water, will take a long time, during which the structure is, partially, unprotected. The feasibility of such a repair can also be questioned.

It is better to divide the ring in elements. After collision, the damaged elements are replaced by new elements.

The elements can be made in advance and be transported immediately when required. The amount of time during which the ring is under repair is reduced as is the amount of repair work offshore, which reduces the cost of repair.

When the ventilation structure is constructed, the elements are installed on the structure on or near shore. The low density of the elements is favourable, because the dimensions of the caisson can be limited. The total amount of ballast to install the structure however will increase as result of the low density.

When elements are replaced, the new elements are towed to location or transported on a barge, from which they are lowered into the water on location. In either case, the element will be afloat for more or less time. During this period of time, the element has to be stable. According to D.N.V., a metacentric height of 0.30 metre is required to ensure stability. When elements with a height of 10.5 metres and a width of 12.5 metres are applied, the metacentric height will be 0.46 metre. An increase in height or a decrease in width reduces the metacentric height.

The length of the elements depends on the location in the ring and on the total number of elements. Here, the plan of figures 30 and 31 is chosen. There are two types of elements needed, see figures 32 and 33.











### fig. 33 inner element

Of both types 48 elements are needed. The large element has a weight of 970 ton, the small element weighs 700 ton. The total volume of the crash cushion ring is 267,120 m\*\*3.

The connection of the elements to each other and .to the caisson demands special attention. Not only must the connection be strong enough to keep the elements together, it must also be possible to connect and disconnect the elements offshore in case of repair. This last requirement eliminates grouted connections.

More feasible are connections by steel bars or cables. In vertical direction tubes can be cast in the element through which cables are drawn, connected to the roof of the caisson and brought under tension. This way the elements are preesed upon each other and friction will prevent lateral displacement.

The cables can also be used when elements are installed on location to guide the elements and get them into position. Special equipment then has to be developed which can be

- 46 -

placed on top of the element. With this equipment the cables are tensioned, thus lowering the element into position. The cables are securely fixed to the element after tensioning and covered with a protectional layer of concrete. The top elements can be lifted directly on top of the lower elements.

The removal of elements can be done with the same procedure the other way round. Tension on the cables is lessened and the element becomes afloat. It is necessary that each element is secured separately, so the elements can be replaced individually.

The above described method is only a rough idea. Further research to connections and replacement schemes of the elements will have to be carried out.



\_\_\_\_\_

8 COSTS

The costs of construction of the elements can be estimated, based on the costs of raw materials, wages and forms. The foamed concrete consists of:

80 kg cement 150 kg fly ash 0.90 m\*\*3 foam

The following prices for the raw materials can be taken:

cement fl 130.- per ton fly ash fl 35.- per ton foam fl 15.- per m\*\*3

The price of fly ash depends on the quality. A reduction in price because of the large order is not likely, for fly ash producers rather prefer a constant demand over a long term than a peak demand.

The costs of materials per cubic metre of foamed concrete is:

The production costs of 1  $\,$  m\*\*3 of foamed concrete consists of:

- man hours
- equipment costs

On the building site several production units will be used. It is reasonable to assume that one unit will produce an average of 20 m\*\*3 foamed concrete per hour and that 4 men are needed to reach this production. The price of 1 man hour is fl 40.-. Per m\*\*3 of foamed concrete 4/20 = 0.2 man hour is needed, costing fl 8.-.

With the costs of equipment as mixers, foam generators and pumps, estimated at fl 3.- per m\*\*3, the price of 1 m\*\*3 of foamed concrete ready to be cast becomes:

```
materials fl 29.-
wages fl 8.-
equipment fl 3.-
total fl 40.-
```

- 49 -

For casting of the concrete 1 man hour per m\*\*3 is needed, setting the price of 1 m\*\*3 of foamed concrete cast at fl 80.-. The price of 1 m\*\*3 of normal concrete is f1 275.-. Forms cost fl 70,- pr m\*\*3. With the above mentioned data the construction costs per element can be calculated. costs large element: - foamed concrete 2950 m\*\*3 a fl 80.- = fl 236,000.-- normal concrete 300 m\*\*3 a fl 275.- = fl 82,500.-- forms 1400 m\*\*2 a fl 70.- = fl 98,000.-----fl 416,500.total costs small element: - foamed concrete 2350 m\*\*3 a fl 80.- = fl 188,000.-- forms 900 m\*\*2 a fl 70.- = fl 63,000.-----total fl 251,000.-Of both types 48 elements are needed: 48 \* fl 416,500.- = fl 20 million = fl 12 48 \* fl 251,000.-\*\* ----fl 32 million total The 32 million guilders mentioned above are the construction costs of the elements. Not included are costs of: - rigid inner wall - adjustments of caisson - cables to connect the elements to the structure

- transport and installation, initially or in case of repair

## 9 CONCLUSION

The property of foamed concrete that its compressive strength can be varied by varying the density, makes this material suitable to be used in a vessel crash cushion. The strength of such a cushion can be adjusted to the bow strength of the ship, e.g. an oil tanker. In this manner, the damage to the ship can be limited and thus the detrimental effects of a major collision. In the case of a 318,000 dwt tanker, which sail through the Channel, the density of the foamed concrete must be 300 kg/m\*\*3.

A crash cushion ring with a width of 25 metres and a height of 42 metres is required to protect the ventilation structure in a shipping friendly way.

#### BIBLIOGRAPHY

- [1] Betoniek no.5/26, june 1982, Vereniging Nederlandse Cementindustrie, 's Hertogenbosch.
- [2] Betoniek no.6/23, march 1985, Vereniging Nederlandse Cementindustrie, 's Hertogenbosch.
- [3] Bijl, ing. P.S. van der and Soen, H.H.M., "Schuimmortel met asfalt in RAI", Land en Water-nu, page 28-30, august 1984.
- [4] Boer, ir. J.F. den and Siemes, ir. A.J.M., "Literatuurstudie schuimbeton", CUR, Rijswijk, 1986.
- [5] "Cellcrete", Mebin product information.
- [6] CUR/VB, Aanbeveling no.7, "Schuimbeton", Zoetermeer, 1985.
- [7] Ivey, Don L. et al.,
   "Evaluation of crash cushions constructed of lightweight cellular concrete",
   Transportation Research Record no.386,
   Washington, 1972.
- [8] Ohnishi, T. et al., "Ultimate strength of bow construction", IABSE-colloquium, page 227-233, Copenhagen, 1983

