RESEARCH CORPORATION OF THAILAND

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MATERIALS FOR CONCRETE

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ROOFING ELEMENT IN FERROCEMENT

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FERROCEMENT ROOFING ELEMENT

By Jens Overgaard* and Narong Sukapaddhanadhi*

SUMMARY

An investigation of ferrocement application for self-supporting roofing elements of long spans, and its suitability for prefabrication in mould.

A prototype element was made in a wooden mould. The design was a folded plate type with a W-shape section. It's span was 7.00 m and it's width was 1.20 m. Thickness was 20-25 mm with 6 layers of gauge 25 galvanized "chicken mesh" and 6 mm bars centre reinforcement.

The reinforcement was bent and tied primary to being placed for plastering in the mould. Plastering proved very difficult, although a pneumatic vibrating trowel was used. Ultimate bending strength was very high equivalent to a load of 600 kg/m^2 roofing area. The deflexion at the critical load was about 1/130 of the span.

INTRODUCTION

ASRCT's earliest investigations on ferrocement were focused on its marine application. Later research aimed at establishing general knowledge on its physical properties with respect to distribution of reinforcement.

Recently attention has been given to its eventual terrestrial applications, among which a grain silo intended for storage of rice should be mentioned as a successful result. A large construction company in Bangkok has had good results in it's efforts to produce fresh-water storage tanks in ferrocement.

Common for all these applications is that they all make use of ferrocement as a material with high strength and impermeable to water. The same two properties indicate that ferrocement should be a suitable roofing material.

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Economic roofing in Thailand is usually made of either asbestos-cement or galvanized steel, both carried on a wooden structure, and therefore subject to deterioration by rot, termites or fire. In addition to this, Thailand is facing a shortage of wood and any effort to moderate the use of this material is in the interest of the nation. On short spans (i.e. less than 5 m) the amount of wood in an asbestos-cement or corrugated iron roof is still not excessive, but above 5 m span, the wooden structure begins to contribute considerably to the cost of the roof.

It appears that in the range between 5-15 m span, above which reinforced concrete or steel usually dominate, there would be an advantage in utilizing ferrocement in a design that eliminate the use of trusses.

The types of constructions that make use of roofs with free spans of that length are many. They include sheds, industrial buildings, and office buildings, but also residential housing may benefit from using roofs which can span from one external wall to the other, as it gives greater freedom in design and better flexibility in placing partition walls, which then need not be loadbearing. As a matter of fact, the design chosen for this investigation was part of a low-cost housing project designed by the National Building Research and Development Centre (see Figure 1).

The Italian architect Pier Luigi Nervi, who gave this material its name, has constructed several buildings with ferrocement roofs, some as thin shells with single or double curvature and others in various shapes of folded plates.

MATERIALS AND METHODS

The materials used for ferrocement construction are cement, sand, and steel, with small amounts of additives. The cement-sand mortar is very rich on cement and should have a low water/cement ratio. The reinforcement is composed of thin wire mesh tied to a 10-15 cm skeletal grid of mild steel bars. It is important that the reinforcement is uniformly distributed in the mortar matrix.

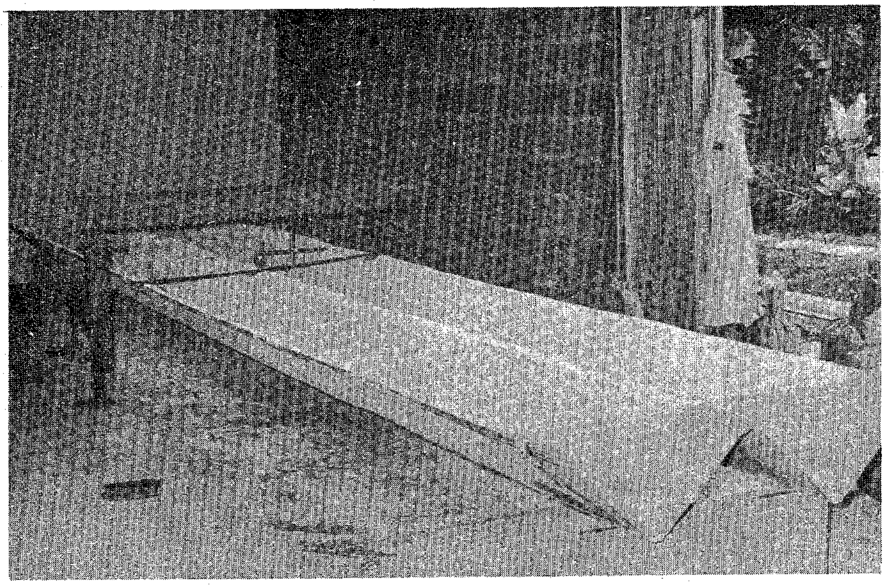

Figure 1. Ferrocement roofing element prepared for load test.

Sand

To obtain a suitable grain size distribution two types of sand were mixed in the proportion 1 part fine sand to 4 parts coarse, see Table 1.

TABLE 1. GRAIN SIZE DISTRIBUTION OF SANDS

Sieve opening (mm)	.125	.2	.5	1	2	4	8	Fineness-modulus
Fine sand, passing (%)	3	12	95	99	100	100	100	1.90
Coarse sand, passing (%)	1	2	28	63	83	94	99	3.29
Combination: passing (%)	2	4	42	70	86	95	99	3.02

Cement

An ordinary Portland cement (Type I) was used.

Additives

To the mortar a plasticizer was added and an agent was used to prevent the development of hydrogen bubbles along the reinforcing rods due to galvanic action.

Reinforcement

Two kinds of reinforcing steel rods were incorporated in the element. Nominal 6 mm rods for the skeletal grid and nominal 9 mm rods as stringers in the extreme compressive and tensile zones. To each side of the skeletal grid was tied three layers of Japanese-made hexagonal zinc coated wire mesh, gauge 25 wire with $\frac{1}{2}''$ openings. The rods were rerolled material, this explains the difference in yield point and ultimate tensile strength between the 6 mm and the 9 mm rods. Data for the two kinds of reinforcement are in Tables 2 and 3.

TABLE 2. DATA FOR WIRE MESH

Weight per m^2 wire mesh	:	350 g/m^2
Zinc content	:	310 g/kg mesh
Steel content	:	690 g/kg mesh
Diameter of naked wire	:	0.41 mm
Diameter of galvanized wire	:	0.5 mm
Yield stress of wire	:	42.7 kg/mm^2
Tensile strength of wire	:	60.8 kg/mm^2

TABLE 3. DATA FOR REINFORCING RODS

Description	Diameter (mm)	Yield stress (kg/cm^2)	Tensile strength (kg/cm^2)
6 mm grid	5.80	3,800	4,700
9 mm stringers	8.60	-	9,400

Note. The 9 mm bars had no pronounced yield point and showed only about 18% elongation before breaking.

Mortar

Previous investigations have proved that a cement/sand ratio of 1:1.75 is suitable for ferrocement. The water/cement ratio was set to 0.40 after a mortar with a w/c = 0.35 had proven too hard to work. Additives were used in a total quantity of 3.1 ml per kg cement.

The mortar was worked into the reinforcement from one side only. It was a very difficult task that lasted 5 working days. However, only two men and a supervisor were available for mixing of mortar and plastering.

The mortar was mixed in a small "freefall" concrete mixer (capacity 35 l). Due to the low w/c-ratio it was necessary to pre-mix the dry materials, and then with only the water in the mixer, add the dry materials little by little. It became clear that this kind of mixer was unsuitable for low water mortars. It was also learned that a vibrating trowel was essential for working the mortar into the reinforcement. The cold joints were treated with a pure cement slurry before continuing the plastering.

When the element was demoulded it was discovered that the mortar penetration had not been completed all over, but no attempts were made to repair the voids, see Figure 2.

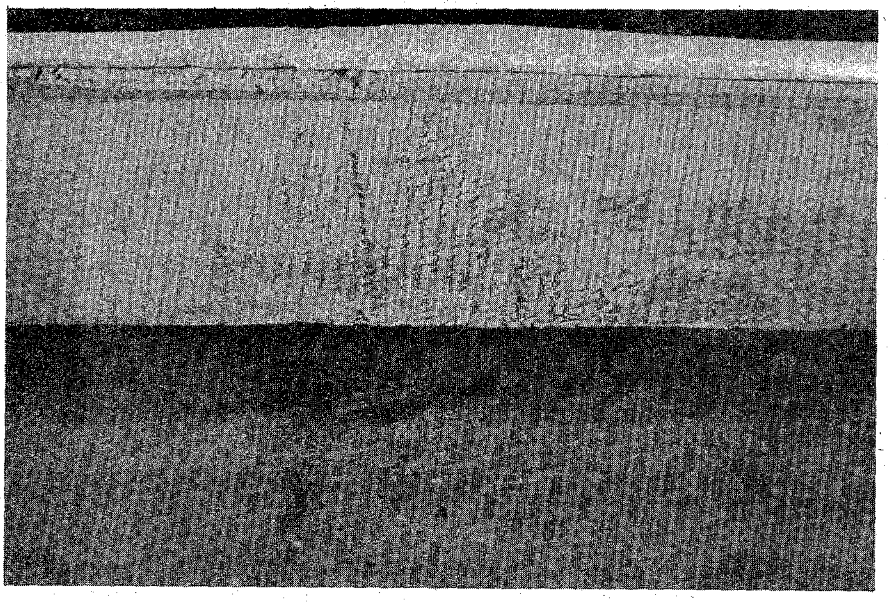

Figure 2. Voids due to incomplete penetration of mortar.

Design of element

The element was designed as a folded plate with an effective width of 12 M (M = modular unit = 10 cm) and an overall length of 732 cm. Above the supports, i.e. 16 cm from each end was made a diaphragm of ferrocement to serve as a stiffener and also as a place to hook lifting gear when handling the element. Figure 3 shows a section of the element with location of reinforcement. The sides were designed to form an overlapping joint, that would be able to transfer horizontal compressive forces. One of the design criteria was to make it possible to cast elements of various length in the same mould, and elements that would still be able to fit together. It is the small tolerances dictated by the joints along the sides that necessitate the use of a mould. The W-shape allows for negative as well as positive bending moments. When the roof is desired to cantilever over for example a porch, the extra rods may then be placed in the top of the section.

Materials cost

Table 4 gives a breakdown of quantities of materials per metre element, note that the element is 1.20 m wide.

Effective area covered: 1.20 m^2
Volume: 34 dm^3
Weight: 90 kg

TABLE 4. QUANTITIES AND COST* OF MATERIALS PER METRE

6 layers of mesh:	10 m^2	3.5 kg	47 ฿	39%
ø 6 mm rods:	26 m	5.8 kg	25 ฿	21%
ø 9 mm rods:	7 m	3.5 kg	15 ฿	12%
Subtotal:		12.8 kg	87 ฿	72%
Cement		24 kg	12 ฿	10%
Sand		41 kg	3 ฿	3%
Water, additives etc.		10 kg	1 ฿	1%
Subtotal:		75 kg	16 ฿	14%
Formwork, formoil etc.			17 ฿	14%
Grand total			120 ฿	100%

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*Note. Prices refer to early 1973. The rising trend in steel prices prevailing at the time of writing will not change the general picture showing reinforcement as the most costly material input.

From the materials breakdown it is obvious that the reinforcement constitutes by far the largest share of the cost, and the wire mesh is the most expensive single item. The amount of wire mesh used in this element is already less than what is usually recommended for marine structures, but still, considering the results of the load test, it may be possible to reduce the amount of wire mesh further, in order to make the element more economical.

Labour

On the basis of laboratory experiences it is very difficult to evaluate the labour input necessary for a production of such elements. It appears, however, that it is rather high for this type of heavily reinforced element. Considering the labour needed for binding reinforcement, plastering, curing and demoulding only, once a team is familiar with the work, an educated guess should roughly be:

Supervisor:	½	man-hour/m
Trained labour:	10	man-hour/m
Unskilled:	10	man-hour/m

Muck work goes into binding the reinforcement, and also the plastering stage takes time, as it is difficult to work the stiff mortar into the dense wire mesh. The use of less layers of wire mesh would also give substantial savings in labour.

Load test procedure

After one month of wet curing the element was transferred to two supports placed 7.00 m apart for the load test. During this operation, one end of the element was accidentally dropped on the concrete floor from a free height of about 40 cm. However the impact only caused minor local damage at the very end of the element where it hit the floor.

Before the load test, the element was given a limewash to facilitate the detection of crack patterns during the test, and a device was set up to measure deflexion and horizontal movements of the midspan section. Load was applied by symmetrically placed sand bags, each weighing 25 kg. At the point of failure the element carried a total of 3,100 kg of sand.

RESULTS AND DISCUSSION

During **plastering** samples were taken from the mortar and three 5-cm cubes were made from each sample. The cubes were cured for 28 days and their compressive strength was determined. Probably due to the difficulties encountered with the mixing, the results were not very uniform, but varied from 400 kg/cm^2 to 600 kg/cm^2. As the lowest was considerably higher than the compressive stress expected at failure, the mortar was considered strong enough.

During the load test, the deflexion had, as seen in Figure 4, a linear relation to the bending moment up to about 3,700 kg.m, at this point cracking was heard when new load was applied and several branched crack patterns could be observed around the mid span. It was evident from the steady movement of the dilatometer's arm, that the yield point of the reinforcement had been reached, and the cracks opened from being hairline to open cracks. All cracks were perpendicular to the axis of the element. The longitudinal cracks seen in Figure 5 appeared only at failure due to the impact with the concrete floor.

A moment curve for the load at around the yield point and at the point of failure is given in Figure 6.

At the elastic limit the mortar has carried a stress of about 165 kg/cm^2 and the steel about 4,400 kg/cm^2 and the deflexion was about 1/200 of the span.

From the close up of the fractured element it can be seen that at the critical load the upper part of the ridge has no longer been able to withstand the compressive forces. The mortar has crushed and the 9 mm reinforcement rod placed here has buckled up.

During the load test, the horizontal movement of the two sides were measured at mid-span to determine if failure was due to lacking stability. This proved not to be the case, as the profile had opened only 0.88 mm at the critical load. It shows that an additional diaphragm in the middle will not improve the elements loadbearing capacity, and that joints along the sides should be designed to prevent differential deflexions rather than giving horizontal support to neighbouring elements.

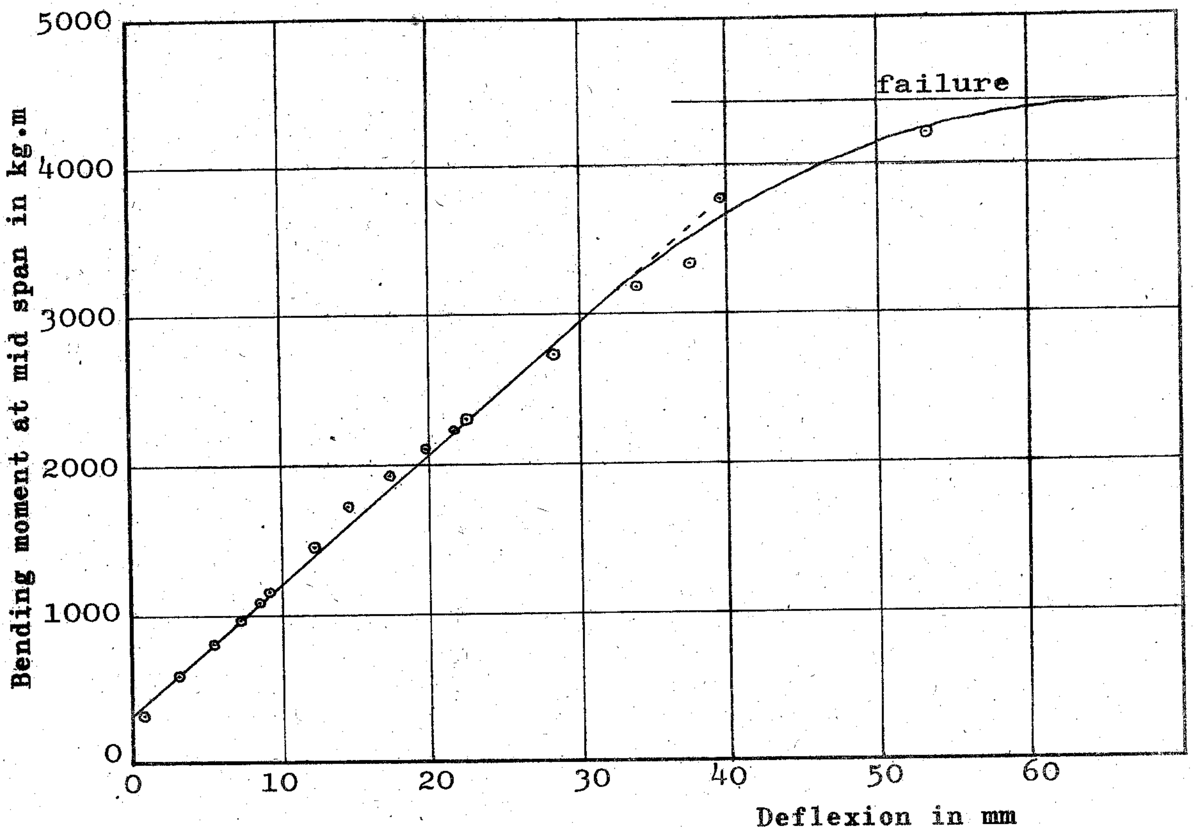

Figure 4. Deflexion in relation to bending moment from live load. (Dead load adds 500 kg.m to the bending moment.)

Figure 5. Tensile reinforcement is yielding and mortar is crushed in the compressive zone. A Ø9 mm bar under compression is seen buckled up.

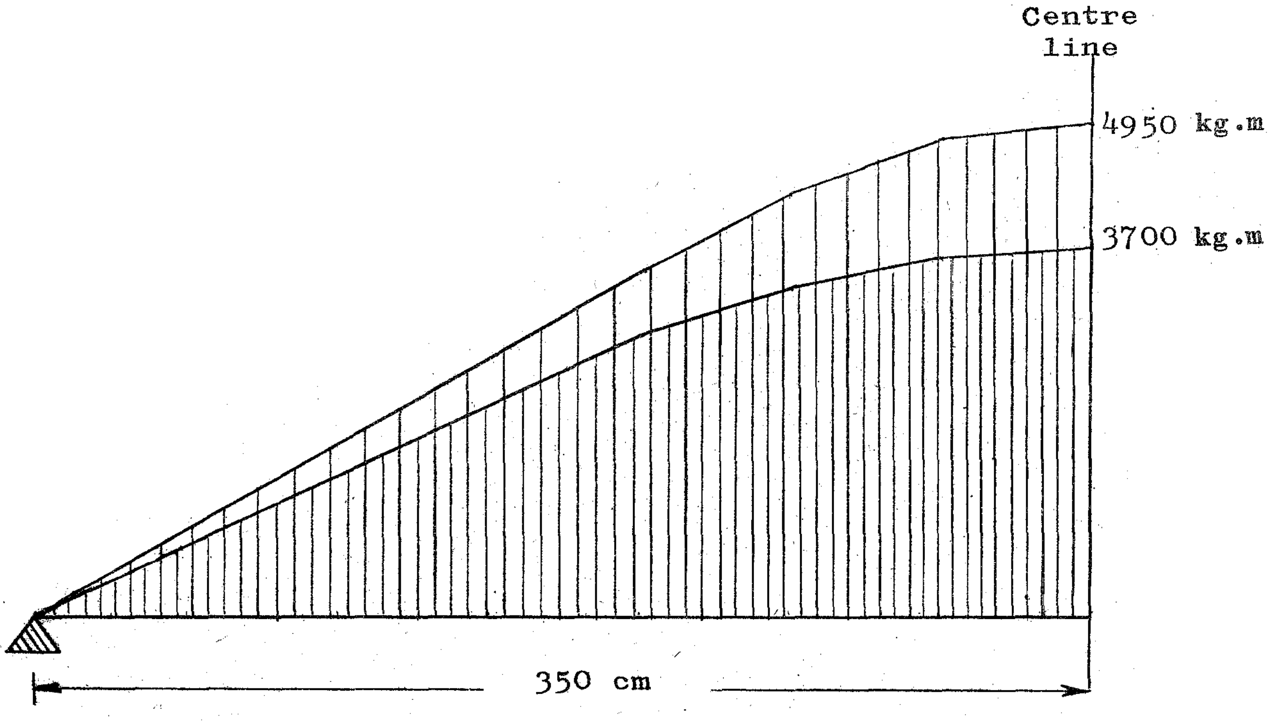

Figure 6. Distribution of bending moment over the span at the elastic limit, and at the critical load in kg.m.

Considering two third of the elastic limit as a reasonable design stress, and a safety coefficient of 1.0 for dead load and 1.5 for live load, we can calculate the span at which this type of roofing element would carry 50 kg/m^2, which is the live load roof structures in Thailand must be designed for.

Width of element:			1.20	m
Dead load of element:	90 x 1	=	90	kg/m
Live load:	50 x 1.2 x 1.5	=	90	kg/m
Allowed bending moment:	$\frac{2}{3}$ x 3,700	=	2,460	kg.m

With analogy to a simple supported beam we then have:

$$\text{Span} = \sqrt{\frac{2{,}460 \times 8}{90 + 90}} = 10.50 \text{ m}$$

At this span however, the deflexion for full load will be about 5.15 cm or 1/200 of the span. A deflexion of this measure requires special attention to joints between individual roofing elements, and also to joints with interior non-loadbearing walls. However the deflexion from live load alone will only be 1.85 cm or 1/570 of the span.

CONCLUSION

The design chosen proved to be suitable for spans up to about 10 m. For spans above 10 m a similar shaped element with a depth of about 40-50 cm should be chosen.

Both the binding of reinforcement and plastering were more time-consuming than what is suitable for an industrial production, but as the strength of the element was very high, use of more simple reinforcement is expected to alleviate this problem without impairing the strength drastically.

Materials cost are about 100 baht/m^2 of which 70% goes into reinforcing materials. The wire mesh is the most expensive single component. It constitutes about 40% of the total materials cost, and is therefore a post which offers possibilities for substantial savings.

Experiments designed to study the loadbearing characteristics of a similar element, but with only longitudinal rods and three layers of mesh, are in progress. Results will be found in a later report.

ACKNOWLEDGEMENT

The authors wish to thank staff members of the National Building Research and Development Centre for their constructive criticism at the time when the element was still on the drawing table.

APPENDIX I

DISTRIBUTION OF BENDING MOMENT AT VARIOUS LOADS

Load at support (kg)	Bending moment in kg.m at x cm from centre line (from live load only)							Deflexion in mm at centre line
	x= 300	x= 250	x= 200	x= 150	x= 100	x= 50	centre line	
600	300	565	780	945	1060	1125	1140	9.3
1200	600	1130	1560	1890	2120	2250	2280	22.3
1200	600	1165	1680	2145	2490	2685	2730	28.3
1200	600	1200	1800	2400	2860	3120	3180	33.8
1200	600	1200	1800	2400	2930	3255	3330	37.2
1340	670	1340	2010	2680	3280	3675	3771	39.5
1480	740	1480	2220	2960	3630	4095	4212	53.1
1550	775	1550	2325	3100	3805	4280	4398	fail

<ins>Note</ins>: Below the line cutting through the table the moment distribution is linear.

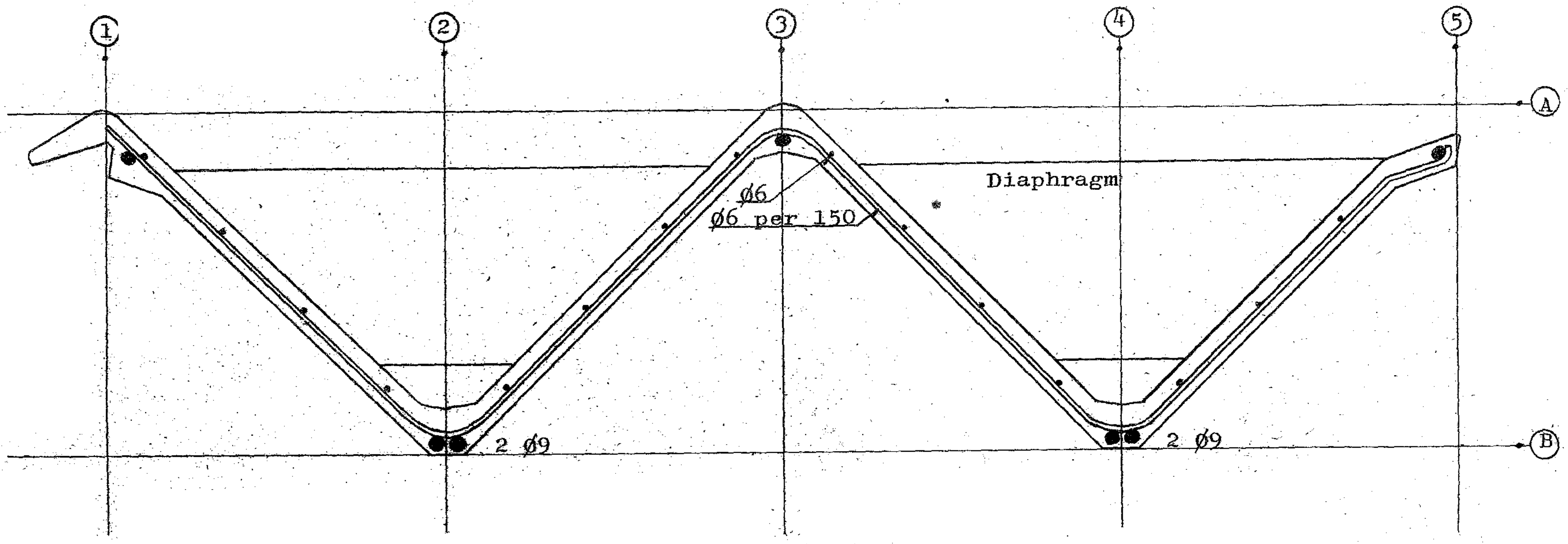

Figure 3. Section, scale 1:5. All measures are in mm.