CHAPTER 174

STRUCTURAL BEHAVIOUR OF TEN TON DOLOS ARMOUR UNITS

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ABSTRACT

This paper summarizes the results of a research program conducted to examine the structural behaviour of nine full scale ten ton Dolos armour units subjected to a well defined loading regime. Three unreinforced and six reinforced units were tested. The effects of three different types of reinforcement (rebars, hollow steel tubes, and prestressing bars) on the behaviour of the units was determined. Different design approaches for armour units are discussed and one possible new approach is presented.

1. INTRODUCTION

Rubble-mound breakwaters have been used extensively in Canada and throughout the world for harbour protection. The seaward faces of such breakwaters can be subjected to extremely destructive wave actions and thus require some form of protection. This protection is achieved by placing a cover, called the 'armour layer', over the breakwater to help dissipate wave energy and thus protect the breakwater core from direct wave attack. In environmentally demanding locations the armour layer usually consists of concrete armour units which have some interlocking capability. One of the most common is the 'DOLOS' armour unit developed by Eric M. Merrifield and first used in South Africa (Merrifield, 1968). These units dissipate energy very efficiently and can be manufactured with standard construction contractors' equipment.

During the 1970's a series of failures occurred in breakwaters utilizing Dolosse. One likely cause for these failures was the fracture of individual armour units which lessened their interlocking capability and thus lowered their hydraulic efficiency.

As a result of the situation described it was decided to examine the strength and behaviour of Dolosse from a structural engineering perspective. This paper summarizes the results of a research program (Uzumeri et. al. 1985) conducted to examine the structural behaviour of nine full-scale Dolos armour units subjected to well defined loading regimes. The major variable considered in this project was the effect of different types of reinforcement on the structural behaviour of the armour units.

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2.   EXPERIMENTAL PROGRAM

2.1   Specimens

A unit weighing ten tons (proportions shown in Figure 1) was selected
for the test program so as to eliminate any scale effects. A total of
nine units (designated specimens 0 through 8) were tested with specimen
0 being used as a pilot test to gain familiarity with the handling and
testing of the units. Four different types of units were studied in the
test program as follows:

          Specimens 1,2,3   Unreinforced
          Specimens 0,4,5,6 Reinforced with eight rebars
          Specimen 7   Reinforced with a steel tube
          Specimen 8   Prestressed, Post-tensioned
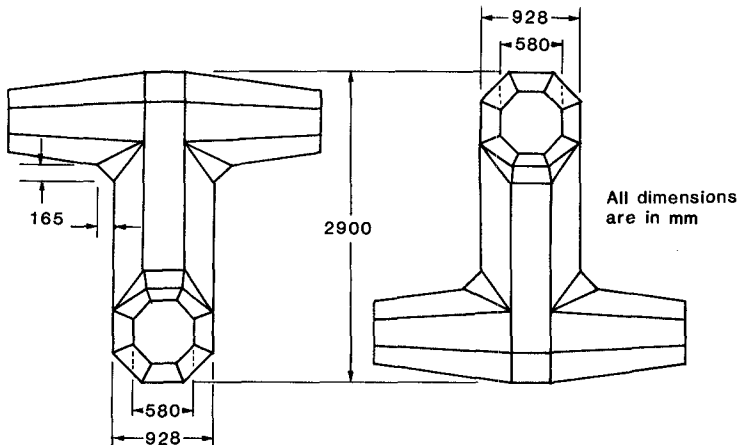
Figure 1: Proportions of Test Unit

All of the reinforcement had a minimum clear cover of 100 mm.   The
layout of the reinforcement was chosen so as to provide maximum struc-
tural benefit combined with ease of fabrication.   Table I gives the
reinforcement details for the test units.

2.2   Materials

2.2.1 Concrete

The concrete used in this test series was obtained from a ready-mix
supplier. The strength was specified to be 25 to 30 Mpa at 28 days with
no air entrainment used as only the structural behaviour of the units
was being investigated. Table II gives the average observed concrete
properties for each of the specimens.

TABLE I

REINFORCEMENT DETAILS

Specimen	Shank Reinforcement		Fluke Reinforcement	
	Number and Type	Total Area (mm^2)	Number and Type	Total area (mm^2)
0,4,5,6	8 - 25 mm dia. rebars	4000	8 - 25 mm dia. rebars	4000
7	1 - Hollow tube 114.3 mm OD 88.9 mm ID	4054	1 - Hollow tube 63.5 mm OD 38.1 mm ID	2027
8	1 - 36 mm dia. Dywidag bar	1018	1 - 26 mm dia. Dywidag bar	548

TABLE II

AVERAGE CONCRETE PROPERTIES

Specimen	f'_c (MPa)	ε_o (mm/mm)
0	33.4	0.0022
1	50.3	0.0024
2	42.1	0.0025
3	58.7	0.0021
4	30.6	0.0017
5	25.9	0.0016
6	31.3	0.0022
7	30.9	0.0018
8	28.2	0.0022

2.2.2 Steel

Three different types of longitudinal steel (rebars, hollow steel tubes and prestressing bars) were used in this investigation. The average properties for each of these types of steel are given in Table III. Values for the rebars were obtained from a minimum of three tensile coupon tests. Since only one each of the hollow tube and prestressed units were tested. it was possible to determine the strength characteristics of the actual bar (or tube) used in the specimen. The results for the prestressing bars were obtained from tensile tests while the tube results were obtained using a compression (stub column) test.

2.3   Test Procedure

The tests were conducted in the Sandford Fleming Structural Laboratory of the Department of Civil Engineering at the University of Toronto. The laboratory contains a 5 metre by 5 metre reaction wall and an 18

TABLE III

AVERAGE LONGITUDINAL STEEL PROPERTIES

Specimen	Reinforcement Type	Area (mm^2)	f_y (MPa)	f_u (MPa)	ε_{sh} (mm/mm)
0	25 mm dia. rebars[a]	500	516	860	0.005
4,5,6	25 mm dia. rebars[a]	500	432	656	0.011
7	Hollow Tubes: Shank : 114.3 mm O.D. 88.9 mm I.D. Flukes : 63.5 mm O.D. 38.1 mm I.D.	 4054 2027	 380[b] 620[b]	 710[c] 840[c]	 --- ---
8	Dywidag prestressing bars: Shank : 36 mm dia. bar Flukes : 26 mm dia. bar	 1018 548	 899 976	 1031 1150	 0.012 0.013

Notes: a) 8 evenly distributed bars placed on a circle of 760 mm dia.
　　　　b) 0.002 offset strain method.
　　　　c) Maximum test load.
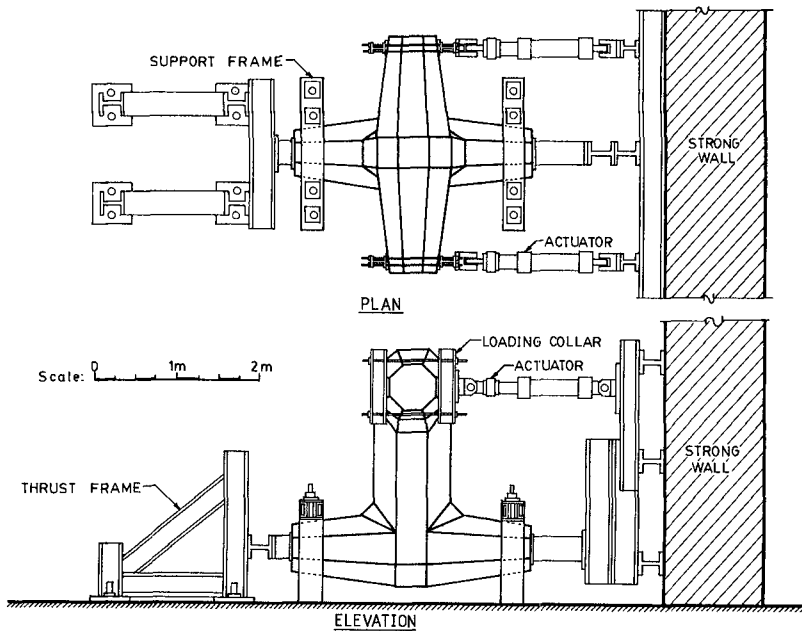
Figure 2: Test set-up

metre by 12 metre strong floor with two-way patterned anchor points on
the floor.   The test units were placed on the strong floor with the
shank in a vertical position.   The bottom fluke was supported by con-
crete pedestals attached to the strong floor.   The top fluke was loaded
by actuators reacting off the strong wall.   The details of the test set-
up are shown in Figure 2 while Figure 3 shows a typical test in prog-
ress.
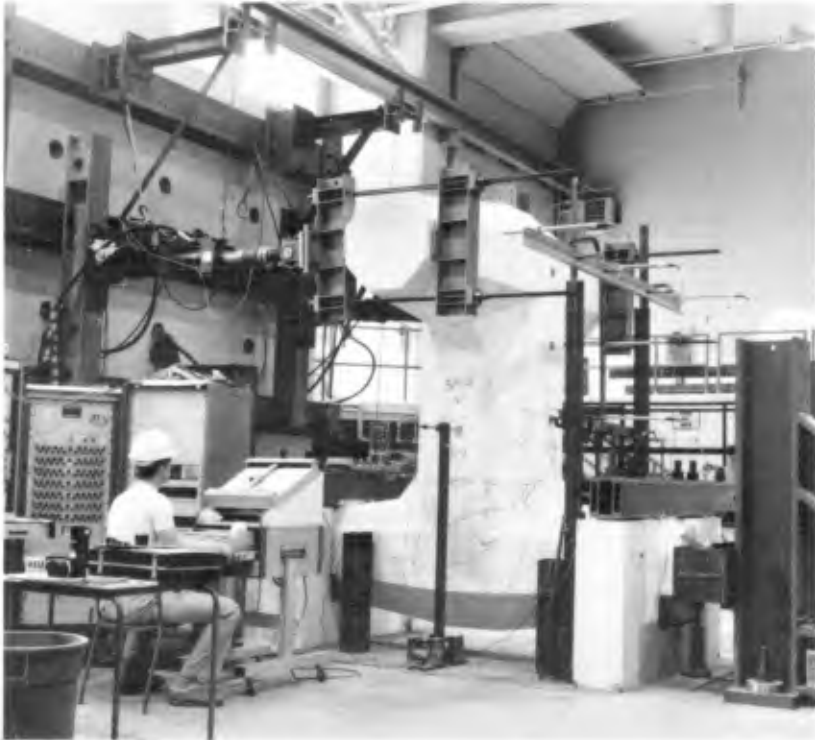
Figure 3: Test in Progress

Three different load combinations were utilized in this investigation as
follows:

      TYPE I   Both ends of top fluke loaded.   Loads equal in magnitude
                and direction.   (Bending moment and shear forces
                generated in the shank).

      TYPE II   Both ends of top fluke loaded.   Loads equal in magnitude
                but opposite in direction.(Pure torsion generated in the
                shank).

      TYPE III One end of top fluke loaded.   (Bending moment, shear and
                torsion forces generated in the shank).

A schematic representation of the loading types is given in Figure 4.

Type I: Moment and Shear   **Type II: Pure Torsion**   **Type III: Moment, Shear and Torsion**
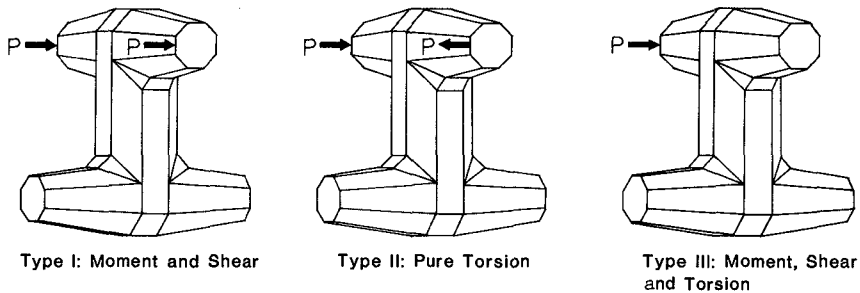
Figure 4: Load Types Considered

For each of the three load combinations the same six stage loading
sequence was used as follows:

> STAGE 1   Monotonic to cracking of specimen in the
>   initial direction.
>
> STAGE 2   Monotonic to cracking in the direction
>   opposite to that in Stage 1.
>
> STAGE 3   Cycle between the two cracking displace-
>   ments (+/-) for 100,000 cycles.
>
> STAGE 4   Monotonic to overall yielding of speci-
>   men in the initial direction.
>
> STAGE 5   Monotonic to yielding of specimen in the
>   direction opposite to that in Stage 4.
>
> STAGE 6   Cycle between the two yield loads until
>   major stiffness deterioration is noted.

The total time required to test each specimen varied from two hours for
the unreinforced units to an average of thirty hours for the reinforced
specimens.

3.   EXPERIMENTAL OBSERVATIONS

3.1   General

Table IV lists the observed cracking and ultimate load capacities for
each of the specimens. Figures 5 through 13 show the appearance of the
specimens at the end of the tests and the observed response for each of
the nine specimens. To give an indication of behaviour, a short summary
of the experimental observations for each type of reinforcement will be
presented in turn.

TABLE IV

CRACKING AND ULTIMATE STRENGTH SUMMARY

| Spec. No. | Force Applied by Actuators (kN) | | | |
| | At Cracking | | At Ultimate | |
	Initial Direction	Opposite Direction	Initial Direction	Opposite Direction
0	241	168	418	417
1	185	---	185	---
2	255	---	255	---
3	130	---	130	---
4	199	190	464	466
5	263	260	263	261
6	153	138	236	228
7	150	149	293	264
8	260	239	332	334

3.2   Unreinforced Specimens

Since specimens 1,2 and 3 were unreinforced, the first crack coincided with failure as expected. The specimens had each separated into two pieces by the end of the test. No ductility was exhibited by any of the unreinforced specimens.

3.3   8-Bar Reinforced Specimens

The four 8-bar reinforced specimens (specimens 0,4,5 and 6) exhibited similar behaviour. They were all very stiff (slightly stiffer than the unreinforced units) up to the appearance of the first crack in the initial ·direction. During the third stage of loading no stiffness degradation was observed.

Subsequent loading to yield in each direction caused extensive cracking in the shank and a rapid deterioration in stiffness. Maximum crack widths ranged from 30 mm to 40 mm by the end of the test.

3.4   Tube Reinforced Specimen

The first crack for specimen 7 appeared at the base of the shank as expected. Subsequent testing indicated a slight loss in stiffness with continued cycling but difficulties with the control equipment caused the first portion of the test regime to be shortened to 3100 cycles. During stages 4,5 and 6 of the load regime the stiffness deteriorated rapidly. Maximum crack widths were approximately 80 mm.

3.5   Post-Tensioned Specimen

Specimen 8 was very stiff until the first crack developed and remained
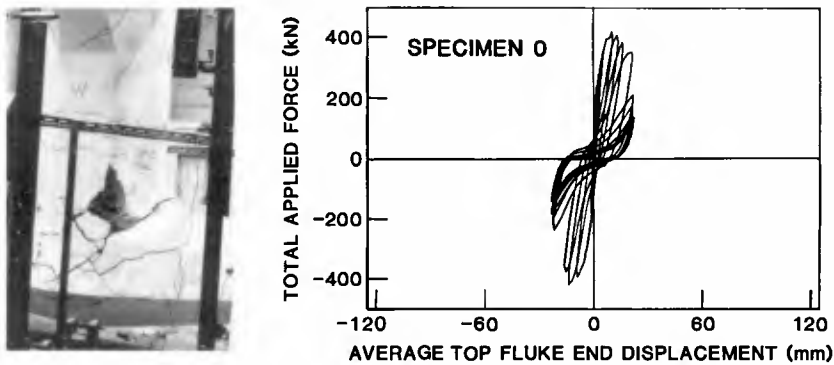
Figure 5: Final Appearance and Observed Response of Specimen 0
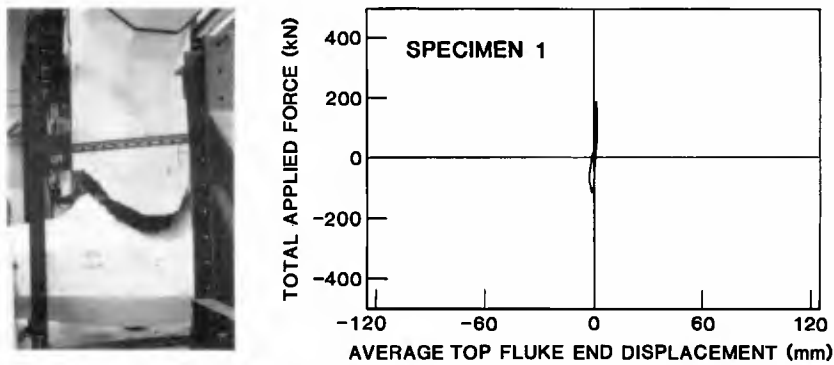
Figure 6: Final Appearance and Observed Response of Specimen 1
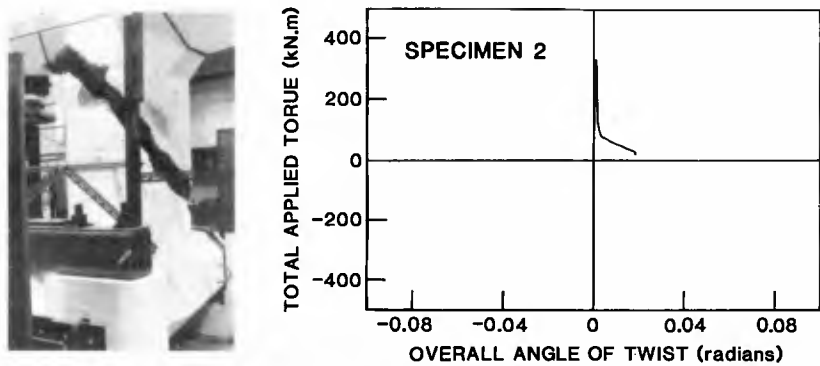
Figure 7: Final Appearance and Observed Response of Specimen 2
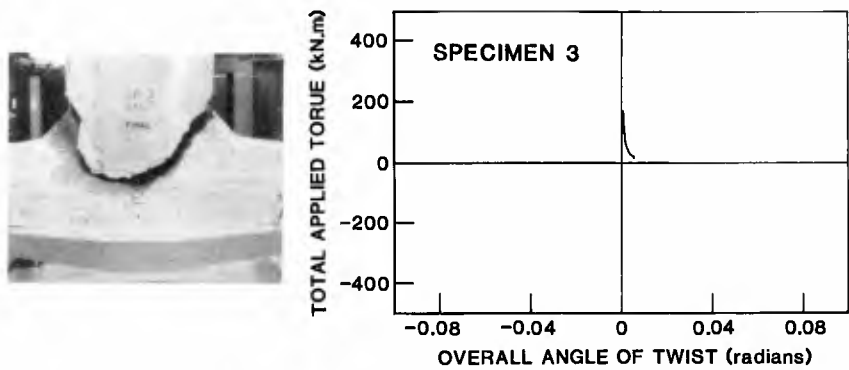
Figure 8: Final Appearance and Observed Response of Specimen 3
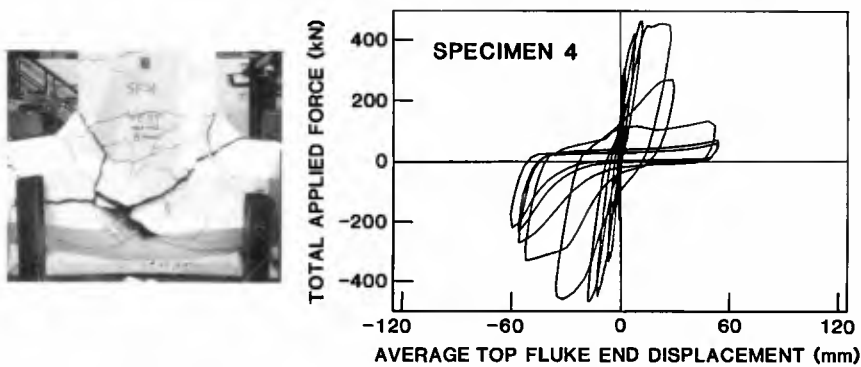
Figure 9: Final Appearance and Observed Response of Specimen 4
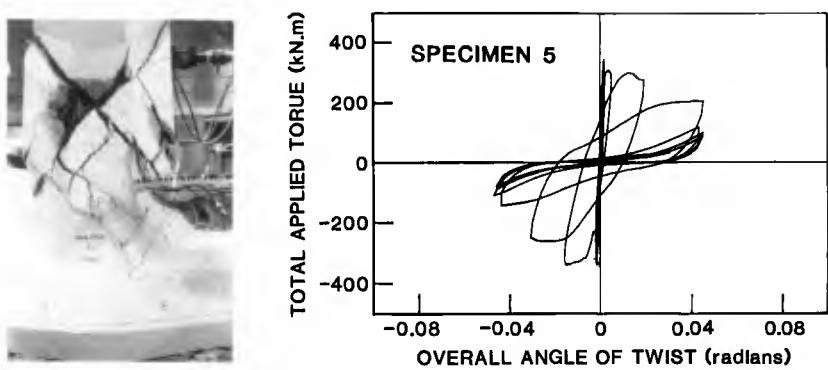
Figure 10: Final Appearance and Observed Response of Specimen 5
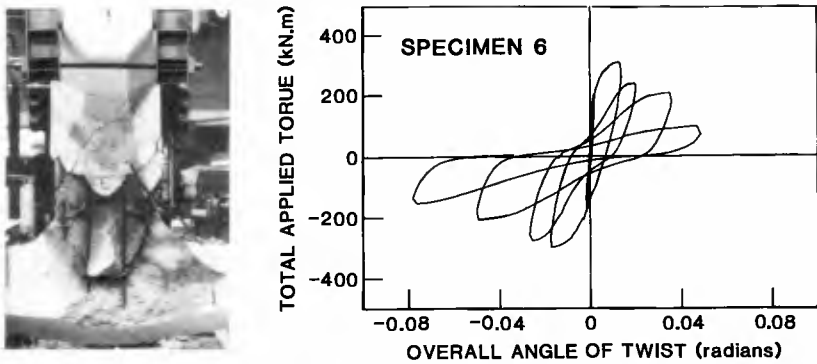
Figure 11: Final Appearance and Observed Response of Specimen 6
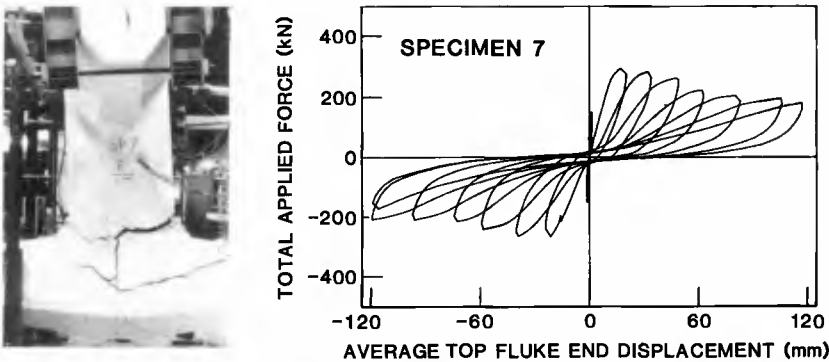
Figure 12: Final Appearance and Observed Response of Specimen 7
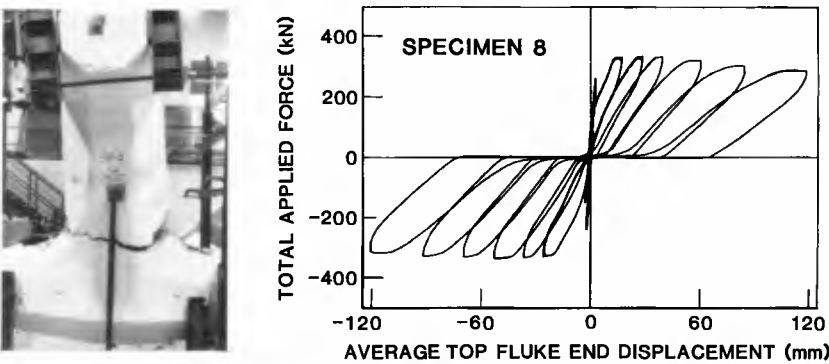
Figure 13: Final Appearance and Observed Response of Specimen 8

stiff with little deterioration during stage 3 of the loading regime.
During the final three loading stages the existing crack became wider
but no new cracks were formed. Maximum crack widths were of the order
of 70 mm.

4.   DISCUSSION

4.1   Specimen Comparisons

When one considers the three different load cases applied to both the
unreinforced and the 8-bar reinforced specimens it seems apparent that
loading type III (combined bending, shear and moment) was the most
severe with lower initial cracking loads and ultimate loads. This
generalized type of loading is the most likely to occur in the prototype
due to the random placing of armour units in a breakwater.

The unreinforced specimens did not behave satisfactorily in a structural
sense since they failed as expected at the first crack. No cycling was
possible. This brittle behaviour could contribute to breakwater
failures.

The reinforced specimens behaved in a satisfactory manner, withstanding
100,000 cycles of low level load reversals and several cycles of high
level load reversals. The behaviour of the reinforced specimens was
quite similar for the first 100,000 cycles with the units being initi-
ally quite stiff and exhibiting little stiffness loss during low level
cycling. During the high level load reversals, the stiffness of the
reinforced specimens dropped quite rapidly and the cracks became very
large. By the conclusion of testing the reinforced specimens had
sustained a high degree of damage but were still intact.

Comparing the three different types of reinforcement used in this study
it was evident that the 8-bar reinforced units behaved in the most
satisfactory manner with the highest resisted loads and the smallest
initial crack widths (desirable for corrosion control). This behaviour
occurred as a result of the even distribution of the reinforcement
located nearer the perimeter of the cross-section as compared to the
tube reinforced and prestressed specimens. In all cases the crack
widths could have been further reduced by the introduction of rein-
forcing steel at the shank-fluke intersection.

Considering the effort required to fabricate the test specimens it is
evident that the unreinforced units were the simplest to construct. Of
the reinforced units, the 8-bar reinforced specimen was the simplest to
produce followed by the tube and finally the post-tensioned specimen.
All of the specimens were quite simple to cast and strip.

4.2   Alternative Design Approaches For Armour Units

4.2.1   Current design approach

Historically, the design of armour units has been performed by hydraulic
and/or coastal engineers. Breakwater design is based partially on
results obtained in hydraulic laboratories where the common practice has

been to construct scale models of the actual breakwater and armour
units. Unfortunately, although the armour unit can be scaled for size
and weight it is very difficult to accurately scale the strength of the
unit. Thus, scale armour units used in model breakwaters usually have
significantly higher strength than the corresponding prototype units.

The higher strength of the scale armour units results in model tests in
which the armour unit rarely fails. Thus, the design of a breakwater is
usually based on the assumption that the armour units will not frac-
ture. This assumption is not consistent with prototype experience in
which failures of armour units and breakwaters have been observed
(Magoon et. al., 1974, and Anonymous, 1982). The effect of armour unit
breakage on the performance of a breakwater is not fully understood but
it clearly has an effect on performance.

If one were to design an unreinforced concrete armour unit with the
criterion that no breakage should occur then the unit will necessarily
be larger than optimum since the uncertainties in the determination of
the possible loads and the expected concrete strengths must be estimated
conservatively to allow a reasonable safety factor. If some of the
units were allowed to break then the effects on the stability of the
breakwater as a whole must also be examined.

4.2.2 Design based on determination of expected loads

One approach to the design of an armour unit is the determination of the
expected loads that the unit will be subjected to. The unit could then
be designed to resist these loads.

The determination of the expected loads on the prototype unit is a
complex and expensive process which is of questionable value as the
loads obtained may only be applicable to the specific site measured.
Different wave heights, wave regimes, and breakwater geometries could
significantly affect the magnitude and nature of the loads in a manner
which is not understood. Thus the loads may not be transferable to
another site.

The determination of the loads on a model unit is somewhat easier than
for the prototype since one is working under laboratory conditions.
Using a model breakwater has the advantage of being able to use differ-
ent wave heights and regimes and being able to alter the breakwater
design. This would allow the determination of the loads for different
sites. Unfortunately, the scaling of the loads from the model to the
prototype and the determination of a safety factor based on the strength
of the units introduces many uncertainties.

4.2.3 Design based on determination of desired response

It may be advantageous to approach the design of concrete armour units
from the viewpoint of the response desired from the unit. Thus, if the
desired response for the prototype unit is that it emulate the model
unit and maintain it's integrity then one must examine the steps
required to meet this objective.

In order to maintain it's integrity the unreinforced concrete armour unit must resist the load effect that causes cracking since cracking effectively causes failure of the unit. The load effect which causes cracking for a particular size of unit can be easily calculated and thus the amount of reinforcement required to sustain this load level can be determined. This would be the minimum amount of reinforcement required for ductile behaviour. An additional requirement for reinforcement may be necessary in order to control crack widths since crack sizes could be large, leading to possible corrosion problems. Thus, some level of reinforcement greater than the minimum required for ductile behaviour would seem to be desirable. Placement of additional steel will lead to enhanced ductility, improved crack control, and an increase in load carrying capacity. It is important to note here that the increase in ductility is the fundamental reason for adding reinforcement.

In summary, rather than design unreinforced units for the maximum expected loads, with uncertainties in quantification of both the loads and the resistance of the unit, one could <u>ensure</u> that the armour unit will not fail after cracking and be ductile enough to endure further deformation by the addition of reinforcement. In this manner a ductile unit would spread the load to adjacent units but still remain in one piece thus satisfying the performance objective.

5. CONCLUSIONS

Based on the experiments described in this paper the following conclusions can be drawn:

1) The best approach to the design of Dolosse is likely to be the definition of a desired response and the determination of the amount of reinforcement required to achieve this response.

2) The use of steel reinforcement leads to an increase in both the ultimate strength and ductility of a Dolos concrete armour unit as compared to an unreinforced unit.

3) The best results are obtained when steel is well distributed throughout the unit as close to the perimeter as possible consistent with corrosion control.

4) The cost of a reinforced unit should not be substantially higher than an unreinforced unit since they are simple to construct. The relative cost of reinforcement represents a very small proportion of the cost of a breakwater.

ACKNOWLEDGEMENTS

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NOTATIONS

ε_o Average longitudinal strain corresponding to the maximum stress in the concrete.

ε_{sh} Strain in steel corresponding to the start of strain hardening.

f_c' Strength of plain concrete as determined from a standard (152 mm diameter x 305 mm long) cylinder test.

f_u Ultimate stress in steel.

f_y Yield stress of steel.