IMPACT STRUCTURAL RESPONSE OF CORE-LOC®

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ABSTRACT

In 1996, the U.S. Army Corps of Engineers, Waterways Experiment Station, Coastal and Hydraulics Laboratory in conjuction with Oregon State University and Concrete Technology Corporation, Tacoma WA, conducted the first structural response experiments of the new concrete armor unit, CORE-LOC®. Large scale 32-kg and prototype 9.2-tonne core-loc units, were molded, cast, and fitted with surface-mounted strain gages. The units were subjected to repeated impact loads generated during drop tests. In addition to the CORE-LOC® drop test, similiar tests were conducted on 26-kg and 10.9-tonne dolosse. The structural response to these loads were recorded and analyzed. Measured maximum tensile stresses in CORE-LOC® were approximately half those in similiar size dolosse.

INTRODUCTION

The CORE-LOC® (heretofore referred to as Core-Loc), invented and developed at the U.S. Army Engineer Waterways Experiment Station, is a new-generation optimized breakwater concrete armor unit for protecting shoreline and navigation structures (Figure 1). The versatile unit can be used for a wide range of coastal armoring applications including the repair and rehabilitation of dolos armor layers. Until recently the majority of experiments on Core-Loc focussed on hydraulic stability. Because of the very difficult construction, in-service, and repair conditions associated with high energy wave environments, a need was identified to characterize the dynamic impact structural response of Core-Loc. The most common method of accomplishing this is the drop test. In the past

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two decades, these types of tests have been conducted on other types of concrete armor units. Nishigori et al (1989), Zwamborn and Phelp (1989), Burcharth (1981), and others have tested both dolosse and tetrapod to destruction using drop tests.

Figure 1. The first 9.2-tonne prototype CORE-LOC™ units

DEVELOPING CORE-LOC® DROP TESTS

Drop tests are used to evaluate the structural performance of an armor unit when exposed to impact loads. In 1996, the U.S. Army Corps of Engineers, Waterways Experiment Station, Coastal and Hydraulics Laboratory in conjuction with Oregon State University and Concrete Technology Corporation, Tacoma WA, conducted the first structural response experiments of the new concrete armor unit, Core-Loc. In the experiment described herein, two sizes of Core-Loc were tested, 32-kg and the 9.2-tonne. Also, 26-kg and 10.9-tonne dolosse were tested for comparison. The test configurations were essentially the same except for scale. The experiment involved measuring impact strains with surface-mounted strain gages, as the armor units were dropped from incrementally increasing heights onto a rigid concrete base. The units were tested to failure where the unit completely broke apart. For the smaller units, shims of various thicknesses were pulled from under the unit allowing it to freely drop to the concrete base pad. For the prototype, a crane was used to lift the unit to the pre-determined drop height. A quick-release mechanism attached to slings was used to release the unit, dropping it onto the one meter thick concrete base. The drop height was then increased and the unit dropped again.

The Core-Loc units cast at CTC were the first prototypes ever built. A rational decision had to be made as to standard drop test configurations. One aim of the experiment was to compare results with past drop test experiments of other popular types of concrete armor units. In order to best accomplish this, several types of drops were performed. To best compare Core-Loc to dolos, the "hammer drop" was chosen. These two drops are shown in Figure 2. Tetrapods are typically dropped by lifting the unit completely off the concrete base. The Core-Loc drop configuration, dubbed "anvil drop" is similiar to the tetrapod drop in that it also is completely lifted off the base. These are shown in Figure 3. A third Core-Loc drop configuration (Figure 4), unlike any other armor unit drop test, was needed to emulate the typical manner by which a non-interlocked Core-Loc rocks on slope or how a Core-Loc can fall over due to handling mishaps. This drop is called a "tipping drop." Each of these three drop configurations were performed during the experiment at CTC.

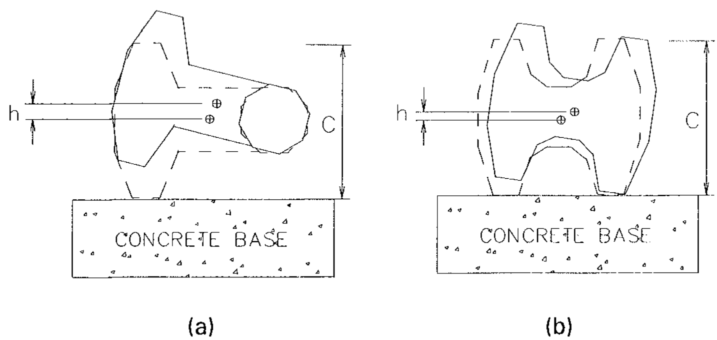

Figure 2. Drop Tests, (a) standard dolosse, (b) hammer drop

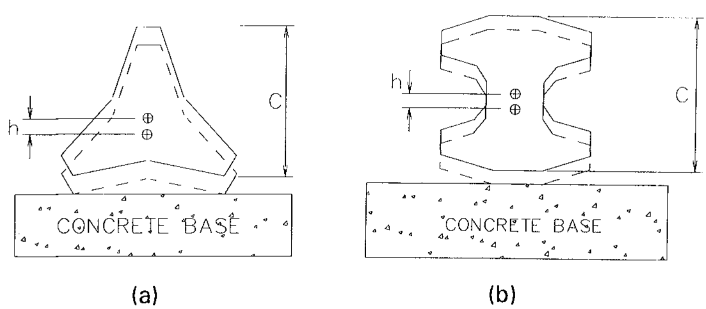

Figure 3. Drop Tests, (a) standard tetrapod, (b) anvil drop

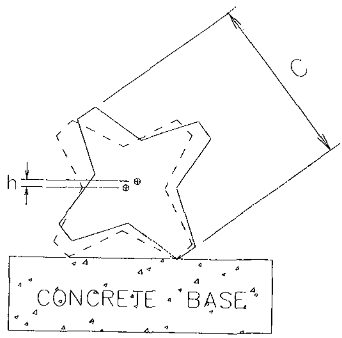

Figure 4. CORE-LOC® tipping drop test

PREPARATION FOR EXPERIMENT

The preparation for the experiment consisted of making molds, fabricating, and instrumenting a single 32-kg Core-Loc and four 9.2-tonne Core-Loc. In addition, three two-year old surplus 10.9-tonne dolosse were fitted with strain gages for measurement of strain in the unit's shank section. The drop tests of 26-kg dolosse, referred to in this report, were conducted in 1994 during the Large Scale Dolos Flume Study (Melby and Turk, 1994).

The first major task in preparing for the experiment was to build molds for both the 32-kg and 9.2-tonne Core-Loc units. For the smaller units, a two-piece fiberglass mold was fabricated. A sophisticated four-part steel "clamshell" mold (Figure 5) was constructed and used to cast four 9.2-tonne units. This unique mold design simplified the difficult casting and mold stripping process usually associated with concrete armor units.

The 32-kg model Core-Loc unit and the 26-kg dolos were cast using concrete with prototype properties. The properties of the large scale model units were as follows:

Property	Core-Loc	Dolos
Concrete Type	Type I Portland Cement	Type I Portland Cement
Aggregate	Coarse Sand	Coarse Sand
Specific Weight, γ	2170 kgf/m^3	2180 kgf/m^3
Modulus of Elasticity, E	21 Gpa	26 GPa
Poisson Ratio, υ	0.43	0.46
Compressive Strength, f_c	45 Mpa	54 MPa
Appox. Tensile Strength, f_t	≈ 4.5 Mpa	≈ 4.5 MPa
Armor Unit Mass, M_a	32-kg	26-kg
Characteristic Length, C	40.6 cm	43.2 cm

The mix design used to cast the 9.2-tonne Core-Loc units, was the same mix designed used two years prior to cast the 10.9-tonne dolos, as follows:

a) Concrete Type	Type III Portland Cement
b) Coarse Aggregate	16 mm Gravel
c) Fine Aggregate	Paving Sand
d) Water-to-Cement Ratio, W/C	39% (max)
e) Cement Content, C_C	390 kg/m^3
f) Water-Reducing Admixture	Conforming to ASTM-C494
g) Superplasticizing Admixture	Meets the requirement for Type F, W-R admixture
h) Air-entraining Admixture	Complies with ASTM C-260.

Figure 5. Four-piece "clamshell" mold

After the concrete was poured in the mold, it was cured for 24 hours. It had been CTC'c experience that accelerated curing is not required to achieve high release strength for this type of concrete product. Insulated "curing houses" were placed over the forms to control heat loss during curing. This system effectively forms a heated envelope with a uniform, controlled temperature gain of 4-7^0 C/hr. This curing method has a long history of successfully attaining transfer strength requirements within a daily production cycle.

The high strength concrete mix allowed the molds to be stripped after 24 hours and the drop tests to be performed after seven days. During each casting, test cylinders and beams were made so the compressive and modulus of rupture strength, along with the modulus of elasticity, could be determined. The concrete used for the Core-Loc units cured for one week before the drop tests were conducted. The 10.9-tonne dolosse tested were two years old. Core samples were taken from the concrete used in the three dolosse and tested immediately prior to the drop tests. Like the Core-Loc, the dolos concrete compressive and tensile strength, and modulus of elasticity were determined. The specimens for a given Core-Loc or dolos were tested on the day of its drop test. The mean properties of the concrete and prototype units were as follows:

Property	9.2-tonne Core-Loc	10.9-tonne dolosse
Specific Weight, γ	2400 kgf/m^3	2400 kgf/m^3
Compressive Strength, f_c	43 Mpa	81.2 Mpa
Splitting tensile strength, f_{st}	3.2 Mpa	4.2 Mpa
Modulus of Rupture, f_{MR}	5.1 Mpa	N/A
Modulus of Elasticity, E	33.4 Kpa	35.9 Kpa
Armor Unit Mass, M_a	9.2-t	10.9-t
Characteristic Length, C	259 cm	293 cm

INSTRUMENTATION AND DATA ACQUISTION

For most drop tests in the past, failure was characterized by some arbitrary crack width. Thus results were subject to interpretation. Melby and Turk (1994) first collected drop test data with a sophisticated Data Acquistion System (DAS) attached to 26-kg dolosse. Sensitive surface-mounted strain gages were applied directly to the concrete surface. With this technique, direct precise measurements of strain and rate of strain were obtained. This same system and strain gaging technique was used on the 32-kg and 9.2-tonne Core-Loc, and the 10.9-tonne dolosse.

The new strain gaging technique and data acquisition technologies increased signal-to-noise ratio and range such that accurate impact measurements could be made. The waterproofed 350 Ω polyester-backed gages were capable of detecting minute strains on the surface of the concrete Core-Loc with a variable range of around 1000 $\mu\epsilon$, depending on the gain and sampling rate. The strain gages were sensitive enough to respond to small changes in strain with a resolution of $\pm$ 2 $\mu\epsilon$ (a change in length of 2E10^{-6} cm per cm). The gages proved extremely sensitive yet robust enough to survive repeated impacts. They were repeatedly checked for integrity, and except for the anvil drop performed flawlessly throughout the experiment.

The strain gaging for the dolosse was different than that used on the Core-Loc. With the principle stress direction well defined for the dolosse drop test, single gages were placed longitudinally along the axis of dolosse shank, near the intersection of the vertical fluke (Figure 6a). This is the primary gage location used for both the 26-kg and 10.9-tonne dolosse. The 26-kg dolos had additional gages placed on the fluke For the dolosse, strain was converted to stress by application of Hooke's Law, $\sigma_T = E\epsilon_T$, where σ_T is tensile stress, E is modulus of elasticity, and ϵ_T is tensile strain.

The stress state for the Core-Loc is more complex, and principal stress direction ill-defined. Thus for the 32-kg and the 9.2-tonne Core-Loc, five critical stress locations on the surface of the units (Figure 6b) were selected from finite element analyses of computer simulated drop tests. Instead of the single gage quarter bridge configuration used on the dolosse, strain gage rosettes (three gages per rosette) were used for the Core-Loc. Each time an instrumented Core-Loc impacted against the hard concrete base surface with enough force to trigger any one of the 15 individual gages in the five rosettes, strain data were recorded. The individual strains measured by the three gages in the rectangular rosette were converted to principal tensile stress by:

$$\sigma_T = E\left[\frac{\epsilon_A+\epsilon_C}{2(1-\nu)} + \frac{1}{2(1+\nu)}\sqrt{(\epsilon_A-\epsilon_C)^2+(2\epsilon_B-\epsilon_A-\epsilon_C)^2}\right] \qquad (1)$$

where

ν = Poisson's Ratio
$\epsilon_A, \epsilon_B, \epsilon_C$ = strains from three gage rosette

The 15 channels of raw data were decimated and reduced by selecting the peak or maximum impact stress for each individual triggered impact. Therefore, for example, if a single impact duration lasted one second, the 150,000 data points collected (10 kHZ x 15 channels) would be reduced to five data points representing the maximum principal tensile stress at the five locations on the Core-Loc for a single impact.

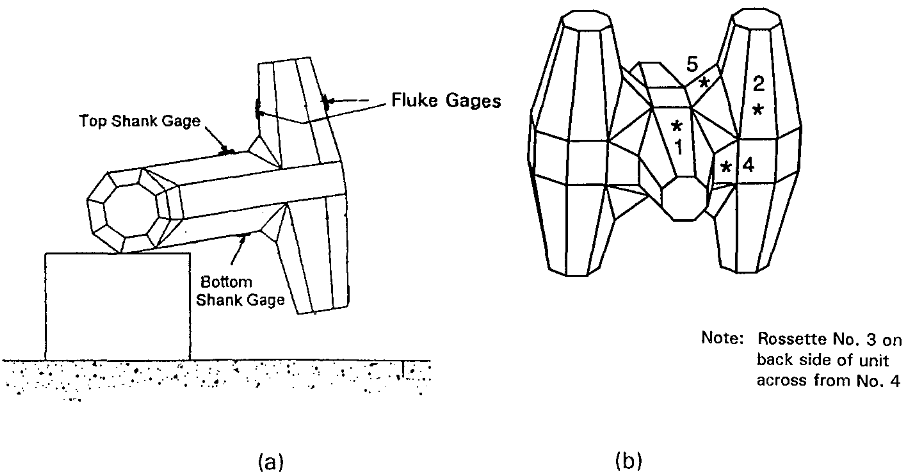

Figure 6. (a) Dolos gage locations, (b) CORE-LOC® gage locations

LARGE SCALE AND PROTOTYPE DROP TEST RESULTS

For all the results presented herein, the maximum tensile stress or the mean of the maximum tensile stresses (for multiple drops at the same height), σ_T, was expressed as a non-dimensional tensile stress, $\sigma_T/(E\gamma C)^{1/2}$. These stress values are plotted as a function of the centroidal drop height, expressed as the non-dimensional parameter $(h/C)^{1/2}$, where h is the drop distance between the centroid of the armor unit at rest and lifted off the concrete base the predetermined drop height distance. By expressing results in these terms, it becomes simpler to compare results between different types and different sizes of units.

The drop tests for Core-Loc and dolos are similar but not directly comparable. When dropping the dolos, almost 1/3 to 1/2 of the total weight of the dolos is supported on a pedestal, whereas the full weight of the Core-Loc is unsupported at impact. The first set of drop test results compares the 32-kg Core-Loc to the 26-kg dolos. Figure 7 shows the stresses generated in the similar size Core-Loc and dolos units. For the dolos, the plot shows stresses in both the shank and fluke sections (Figure 6a). For the Core-Loc, the maximum tensile stresses produced during the hammer and tipping drops are compared to the dolos stresses. The highest stresses in the dolos are in the shank where dolosse typically fail. Fluke stresses are approximately 75% of the shank stresses. The hammer drop and tipping drop stresses are 48% and 31%, respectively, of the dolos shank stresses. And the hammer drop and tipping drop stresses are 68% and 41%, respectively, of the dolos fluke stresses.

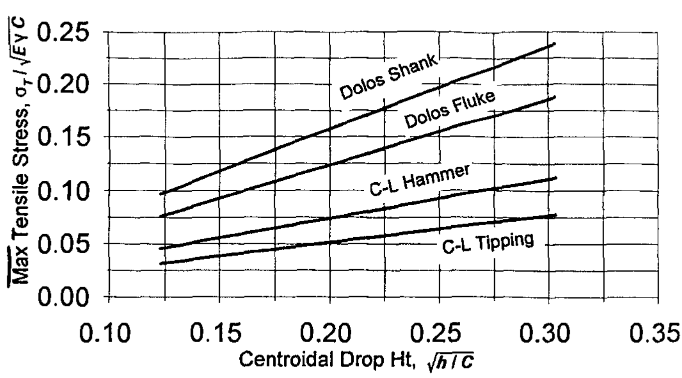

Figure 7. Drop test results from 26-kg dolos and 32-kg CORE-LOC®

A complimentary data set to the 32-kg Core-Loc and dolos drop test compares the prototype 10.9-tonne dolosse to the 9.2-tonne Core-Loc. It is to be noted that the prototype dolosse were only instrumented in the shank section. Figure 8 shows the same divergent trends between the prototype dolosse and Core-Loc as found for the smaller units. In this case, the Core-Loc hammer drop test is compared to the standard dolos drop. As in Figure 7, the same trends emerge for the prototype tests. In this case, the Core-Loc stresses are 55% that of the dolosse. Figure 9 shows the results of the prototype tipping drop test for the 9.2-tonne Core-Loc. In comparing these results to the dolosse, the mean stresses are 52% of the dolos stresses. The anvil drop test was also conducted. In this test the Core-Loc was lifted completely off the concrete base before being dropped. Figure 10 shows the results. Only a single Core-Loc was used for the anvil drop, and the test was conducted in stormy weather. The data show lower stresses than either the tipping or hammer drop, which appears suspect. Some problems were encountered with collecting data as some of the strain gages started to malfunction during inclement weather.

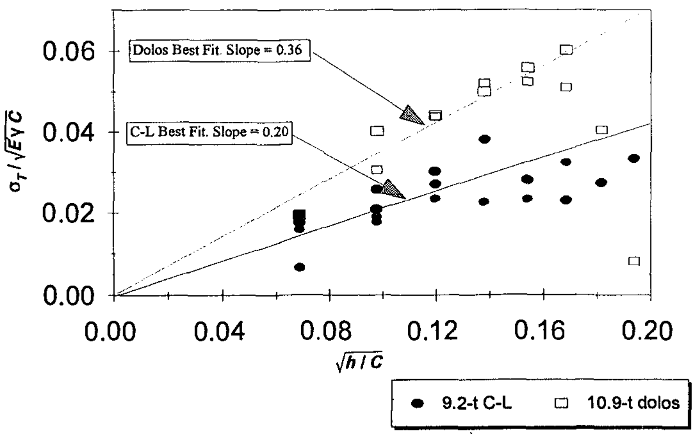

Figure 8. Drop test results for 10.9-t dolos and 9.2-t CORE-LOC®

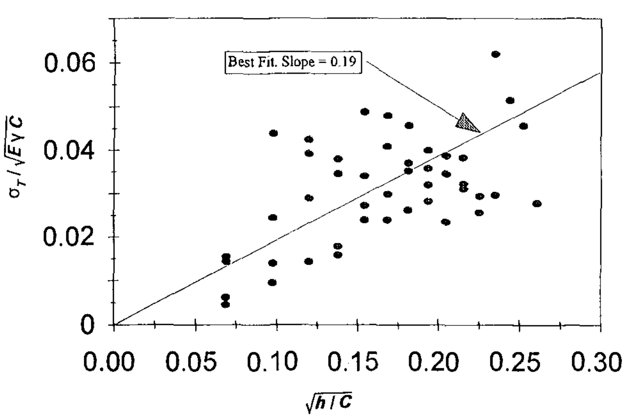

Figure 9. 9.2-t CORE-LOC® tipping drop test

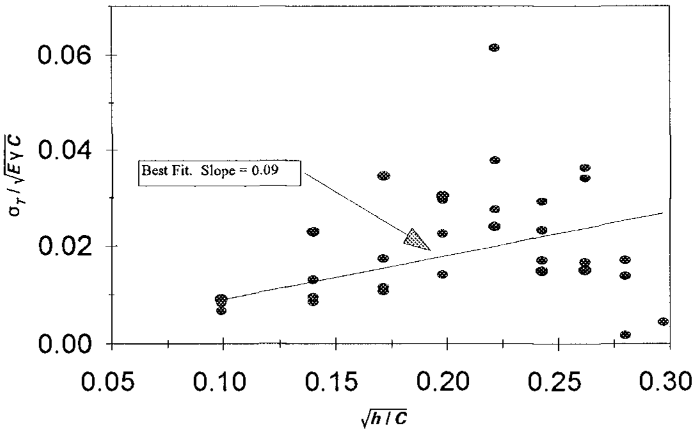

Figure 10. 9.2-t CORE-LOC® anvil drop test

DISCUSSION OF DROP TEST RESULTS

All the drop tests conducted at CTC used a very stiff base over a meter in thickness. Dropping units on this type of base creates one of the most severe impacts that can occur. Defining impact strength in itself is very difficult. There is no definite or unique relationship between the static strength of concrete and impact strength; but Neville and Brooks (1987) reported that, in general, the higher the compressive strength of the concrete the lower the energy absorbed per blow before cracking. Thus the impact strength and total energy absorbed by the concrete increases with compressive strength and age. It can be surmised that older units would have more impact resistance. However, in comparing drop test results, the two-week old Core-Loc consistently showed more impact resistance than the two-year old dolosse. Also, when dropping dolosse in the "standard" configuration, 1/3 to 1/2 of the weight of the dolos is supported on a pedestal, whereas the full weight of the Core-Loc is unsupported at impact.

For the prototype armor units tested, the mean flexural tensile strength of the dolosse was 140% of the Core-Loc and the mean compressive strength of the dolos was 188% the Core-Loc. The modulus of rupture for the Core-Loc was approximately 12% of the compressive strength and it is expected that it would be similiar for the dolos since the mix design was the same for the two types of units. Thus the dolos concrete was nearly twice as strong as that of the Core-Loc. The modulus of elasticity was minimumly higher for the dolosse (107% of the Core-Loc). But repeatly, the Core-Loc significantly outperformed the dolosse either in drop height and/or number of repeated blows to failure.

The data sets collected during the drop test experiment were relatively limited and warrant significant expansion. The prototype drop tests were conducted with four Core-Loc units of one size and the same type concrete. As with all experiments concerning tensile strength of unreinforced concrete, there is fair amount of scatter in the data. Definitive trends are difficult to ascertain.

CONCLUSIONS

For the prototype drop tests conducted at CTC, the Core-Loc proved more robust than the dolosse tested. In the dolosse armor units tested, the tensile strength of the concrete was 140% of the Core-Loc and the compressive strength of the dolos concrete 188% of the Core-Loc. Young's Modulus was minimumly higher for the dolos (107% of the Core-Loc). In comparing drop test results, the two-week old Core-Loc consistently showed more impact resistance than the two-year old dolosse. Stresses generated in the Core-Loc are approximately half of those generated in similiar size dolos. Repeatly, the Core-Loc outperformed the dolos either in drop height and/or number of repeated blows to failure.

ACKNOWLEDGEMENT

The work described herein was conducted as part of the Repair, Evaluation, Maintenance, and Rehabilitation Research Program of the US Army Waterways Experiment Station, Vicksburg, MS. Permission to publish this paper was granted by the Chief of Engineers.

REFERENCES

Burcharth, H.F., (1981). "Full-scale dynamic testing of dolosse to destruction." Coastal Engr. Vol. 4

Melby, J.A. and G.F Turk, (1994). "Scale and modeling effects in concrete armor experiments," *ASCE Proc. 1st Int. Conf. on Role of L.S. Exp in Coas. Res.*, ASCE, New York, NY. pp. 686-700

Neville, A.M. and J.J. Brooks, (1987). Concrete Technology. John Wiley & Sons, Inc. New York, NY.

Nishigori, W., Endo, T., Nemoto, K., Noguchi, Y., Yamamoto, M., 1989. "Similarity law of impact between model and prototype tetrapods." *ASCE Proc. Seminar on stresses in concrete armor units*, ASCE, New York, NY pp 107-122

Zwamborn, J.A. and Phelp, D.T., (1989). "Structural tests on dolosse." *ASCE Proc. Seminar on stresses in concrete armor units*, ASCE, New York, NY. pp. 40-60