STRUCTURAL INTEGRITY OF XBLOC® BREAKWATER ARMOUR UNITS PROTOTYPE AND NUMERICAL DROP TESTS

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The structural integrity of the single layer armour unit Xbloc® has been investigated by means of an extensive program comprising dynamic prototype tests and dynamic and static numerical tests. The prototype test series comprised overturning and free fall tests with in total over 150 individual drops. The numerical test series comprised 9 cases. Comparing the prototype and numerical results of Xbloc® with Accropode and Core-Loc® it can be concluded that the Xbloc® has a better structural performance than the Core-Loc® and that Xbloc® has a strength that is comparable to Accropode.

1. INTRODUCTION

The breakwater armour unit Xbloc® has been launched by Delta Marine Consultants bv (DMC) in September 2003 after the successful completion of an extensive development program that lasted over two years. The armour unit has a simple, bulky shape and is made of unreinforced concrete. Due to its good interlocking quality it is randomly placed in a single layer, which makes the unit comparable to other single layer armour units such as the Accropode and Core-Loc®. The Xbloc® development comprised review of existing breakwater armour concepts, consulting marine contractors and designers, hydraulic model tests, structural tests, fabrication and placement studies and economic studies. The results from these studies are presented in Muttray et al. (2003) and Reedijk et al. (2003).

There are several examples of breakwater failure that were attributed by breakage of armour units, e.g. Sines, Arzew, San Cyprian, Tripoli. It was therefore considered essential to investigate the structural integrity of Xbloc®. The dynamic and static structural response of Xbloc® has been investigated by means of prototype and numerical overturning and (quasi-) free fall tests. The purpose of these studies was to optimise the Xbloc® shape by simulating loads that may be generated during manufacturing, handling and placement and loads in-service due to rocking of the units. The paper describes these tests and compares the results with the performance Accropode and Core-loc®.

2. PROTOTYPE DROP TESTS

2.1 Configuration

The Xbloc® unit consists of an X-shaped base with four spiky legs and two cubical legs that are attached to the centre of the X- shaped base, see Figure 1. To conduct the test series four 4m^3 prototype Xbloc® units have been casted with a mass of approximately 9.4 metric ton each. For the test unit D equals 2.29m, a equals 0.54m and b equals 0.33m The prototype units have a fillet with a radius of 30mm at the edge between the cubical leg and the X-shaped base.

Each test unit was casted using a standard concrete mix with the Dutch designation B35 Mk5b Cg3 CEM III/B 42.5 LH HS. This mix design is comparable to an international concrete type C30/37 with a maximum water/cement factor of 0.5. Maximum aggregate size in the concrete mix was 32mm.

The compressive and splitting tensile strength of the concrete have been determined within 5 to 8 days after prototype testing from three cores that were taken from each unit. The average density ranged between 2,345kg/m^3 and 2,383kg/m^3. The average compressive strength ranged between 27.5N/mm^2 and 41.3N/mm^2. The splitting tensile strength ranged between 4.0N/mm^2 and 5.2N/mm^2. The Young's Modulus has been estimated with the formula $E = 22{,}250 + (250 \times \text{compressive strength})$ yielding an overall average value of 30.6kN/mm^2.

The test units were dropped on a reinforced concrete floor with a mass of nearly 90t and dimensions 7.5m wide, 10m long, 0.5m thickness and concrete quality C20/25. Note that the mass of the test unit was approximately 10% of the test floor mass. This floor was embedded in compacted sandy subsoil and covered with 30mm thick steel plates to prevent plastic deformation of its surface during impact. This has maximized the impact load for the Xbloc® test units.

The drop test program consisted of four different test series, from which the particulars are described hereafter. A large loader (Volvo L150) was used for positioning the test units and for conducting all tests. For the overturning tests, the fall height was set at the desired level by keeping the unit with the forks in a predefined position. An unrestricted drop movement was subsequently induced by quickly retracting the loader forks.

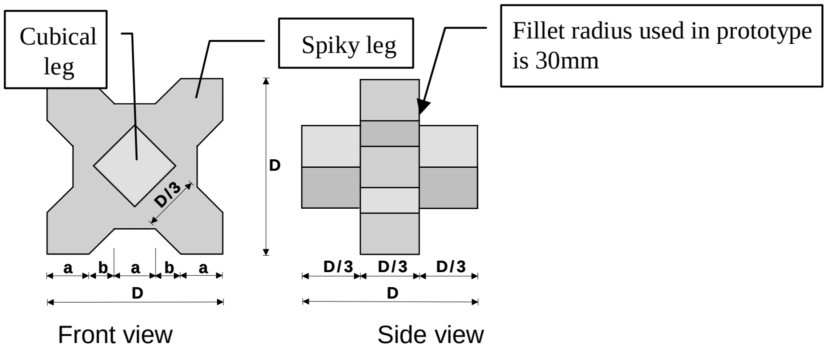

Figure 1: Xbloc® armour unit.

For test series 3 the forks were used to rotate one half of the test unit, hereby lifting one spiky leg from the test floor. For free fall tests the units were entirely lifted from the test floor and subsequently dropped; more details are given further on. Note that test series is defined as repeated testing of a test unit for one drop type at different fall heights. Drop test is defined as an individual drop whereby the armour unit is tested for a particular drop type at a particular fall height.

Test series 1 Overturning – Cubical Leg tests

The strength of the cubical leg is tested by overturning the test unit in such a way that the cubical leg hits the test floor, see Figure 2. The fall height was incrementally increased with steps of typically a few centimeters, up to the maximum geometrical fall height. Fall height is defined as the distance between the floor and the lowest part of the cubical leg. The fall height is limited because of the geometrical shape of the Xbloc®. After reaching the maximum fall height, the tests were repeated 51 times to test the fatigue behavior at maximum load conditions. Test series 1 comprised 69 drops; of which 51 have been conducted at the maximum fall height of 334 mm. Since the damage after Test series 1 was minimal, the test unit has also been used for free fall drop tests.

Figure 2: Photograph of Overturning – Cubical Leg test set-up.

Test series 2 Overturning – Spiky Leg tests

The strength of the spiky legs that are attached to the X-shaped base is tested, see Figure 3. The test procedure was similar to the one used for test series 1. Test series 2 comprised 60 individual drops, of which 50 have been conducted at the maximum fall height of 370 mm. The damage after this test series was minimal; therefore this test unit has also been used for free fall drop tests.

Figure 3: Photograph of Spiky Leg test set-up.

Test series 3 Hammer drop test

During the hammer drop test series the X-shaped base was kept in a vertical position, see Figure 4. One spiky leg functioned as a rotation point, while the tested leg was lifted to the desired height and subsequently released to generate an impact load on this leg. The fall height between the tested leg and the test floor was increased with small increments, typically a few centimeters, up to breakage of the tested leg. This point was reached after 9 drops and for a fall height of 305 mm.

Figure 4: Hammer drop test set-up.

Test series 4 Free fall drop tests

Three test units have been used for this test series: two had also been used for test series 1 and 2, respectively, the third had not been used for overturning tests. The fall height was increased from approximately 0.5m to 2.5m, see Figure 5. The unit was held by the forks of the loader and the impact force was induced by either rapidly lowering the forks (Method 1) or by tilting the forks (Method 2); both methods have been applied with the loader standing still. During a few tests the loader was driving and then suddenly hit the brakes and tilted the forks downwards, which caused the unit to depart the forks with an angular momentum (Method 3). Only with Method 1 it was possible to ensure that the impact location and unit orientation was predictable, because the orientation of the test unit was not changed upon reaching the floor. However, due to the functioning of the hydraulic system of the loader forks it was not possible to generate an unrestricted free fall with this method, resulting in quasi free fall conditions. From video images it has been derived that the vertical acceleration was 0.8g, which was considered in the transformation of the measured fall height into an equivalent free fall height. Methods 2 and 3 caused a rotational movement of the unit resulting in a varying impact locations.

Figure 5: Free fall test set-up.

2.3 Results Xbloc® test series

Test series 1 and 2 Overturning tests – Cubical Leg and Spiky Leg
Throughout both test series the damage and weight loss was minimal, even after repeated testing at the maximum fall height. The leg tip was slightly flattened at the impact location and small pieces broke from the rotation legs. It can be concluded that the impact energy was absorbed by marginal concrete crushing since no cracks were visible. Due to the marginal weight loss with both overturning test series, these units were further used in the free fall test series.

Test series 2 Hammer drop test
While increasing the fall height, small pieces broke off from the rotation leg; this weight loss accounted for less than 1% of the total weight loss after completion of the test series. At a fall height of 162mm, i.e. at the fifth drop, a small crack appeared in the tested leg at the intersection with the central part of the X-shaped base. While further increasing the fall height, the crack width also increased, which ultimately lead to breakage of the leg at a fall height of 305mm (ninth drop). The total weight loss at this point was 1.3t (14% of the test unit mass).

Test series 4 Free fall tests
The damage pattern and weight loss depend highly on the unit orientation, the fall height and the number of individual drops that the unit had experienced. For test unit 1, the weight loss was 40% for 2 individual drops with a maximum equivalent fall height of 1.5m. For test unit 2, the weight loss was 40% in a free fall series of five individual drops with a maximum equivalent fall height of

2.6m. For test unit 4, the weight loss was 20% in a free fall series of 9 individual drops, reaching an equivalent free fall height of 2.2m. With each drop small pieces broke off from the unit, and for increasing fall heights cracks occurred at the intersection with the central part of the X-shaped base.

A summary of the prototype test results is given in Table 1.

Table 1: Summary of results.

	Cubical Leg	Spiky Leg	Hammer drop	Free fall
Nr. of drops	69 (51)	60 (50)	9	16
Maximum fall height [mm]	334	370	305	approx. 2.6m
Total weight loss [%]	0.2	0.3	14	Varied

2.4 Prototype drop tests for other types of single layer armour units

A fall test program has been conducted with two 6.3 m^3 Accropodes (mass each 15t), Sogreah (1984). The concrete particulars are unknown. Because the test arrangement with a crawler type crane did not allow a fully unrestrained free fall, an equivalent free fall height is presented based on the relationship between the drop height and the dropping time. The test units were dropped onto consolidated breakwater core material (quarry run, degree of consolidation is unknown) and on a parallelepiped concrete block of dimensions 2.25m x 2.25m x 1.4m (concrete particulars unknown). In both cases the impact location was the edge of one of the Accropode’s anvils.

No damage occurred to test unit 1 when it was dropped onto the breakwater core due to absorption of kinetic energy of the fall by deforming of core material. The equivalent fall heights were 1.5m, 2.8m, 4.2m and 5.1m. Test unit 1 was subsequently dropped onto the concrete block, whereby the equivalent fall height was increased from 0.5m to 5.5m. In total 15 drops where carried out, resulting in a total weight loss of 35%. At a fall height of 1m fissures appeared, but no weight loss is reported. The top part of the central protuberance broke off at a fall height of 5.1m. Test unit 2 was dropped on the concrete cube with 1.0m to 7.3m equivalent fall height. Fissures appeared in the protuberance of the Accropode atr a fall height of 2.2m. At a fall height of 3.2m the fissured part broke off. At a fall height of 3.7m the test unit broke into pieces at the base of the anvil. The accumulated weight loss after the test series of 9 drops was 16%, because half of the upper anvil broke off.

Prototype drop tests with the Core-loc® have been conducted with three 4m^3 units of mass 9.2t, (Turk, 1998). The test series conducted with Core-loc® units are comparable to the overturning (Cubical Leg) tests and the hammer drop tests of the Xbloc® test program. Furthermore, one free fall test configuration was used, whereby the test unit was dropped onto one of its anvils. The test units were dropped onto a concrete base (1m thickness, total mass and foundation unknown) and during the test series the strain was recorded by strain gauges that were placed at five critical high-stress locations. The concrete compressive strength of the test units was 43 N/mm^2 and the splitting tensile strength was 3.2 N/mm^2. No information is presented about weight loss throughout the test program.

The overturning test series comprised 46 individual drops, whereby the first 12 drops were carried out with a 20mm thick plywood layer on top of the base. Results from overturning test series indicate that the unit showed no cracking up to a fall height of 300 mm. The test unit failed because one vertical member broke off due to a semi-circumferential crack at the underside of one of the central horizontal members. The weight loss is estimated at approximately 25%. The hammer drop test series comprised in total 18 drops. At a fall height of 0.1m the vertical member that was subjected to the impact load broke off. The free fall test series comprised four series of each 9 drops at different fall heights, with a maximum fall height of 0.23m. Damage occurred when a tip of the anvil broke off.

2.5 Conclusions

For the overturning (Cubical Leg) Xbloc® had less than 0.5% weight loss, whereas Core-Loc® had 25% weight loss. For the hammer drop test series the critical fall height for Core-Loc® is approximately 30% of the critical fall height for Xbloc®. For the free fall test series the critical fall height of Core-Loc® is 10% of the critical fall height for Xbloc®. The fall heights to which the Accropode test units were subjected were higher than for Xbloc®, but the test configurations are not comparable. Accropodes were tested on consolidated rock material and on a concrete base that was only slightly larger than the test unit. Xbloc® test units on the other hand were dropped onto a rigid concrete base with a mass that was nearly 10 times larger than the test unit mass. The Xbloc® units showed damage (accumulated weight loss more than 15% - 40%) for drop heights of more than 2 m.

From the Xbloc® drop test results and the comparison with other single layer armour units it can be concluded that the Xbloc® shape yields a large structural strength. Xbloc® has a significantly better structural performance than the Core-loc®. The Accropode has only been tested with one block orientation (Sogreah, 1984), which is not regarded to be critical for its structural integrity.

3. NUMERICAL STUDY

3.1 Configuration

The static and dynamic structural response of the Xbloc® unit has been investigated with a three-dimensional (3D) Finite Element (FE) model using the computer program ANSYS 6.1. The objective of this study was to optimize the fillet sizing at the Xbloc® unit to diffuse the tensile stresses and to compare the tensile stresses of Xbloc®, Accropode and Core-loc®. The 3D FE models of Accropode and Core-loc® have the same properties as the Xbloc® FE model: unit volume 4m^3, solid density 2,350 kg/m^3, Young's Modulus 30 kN/mm^2, Poisson ratio 0.20 and 2,000 elements. These particulars are comparable to those used by Melby (1997) and Sogreah (publishing year unknown). A fillet radius of 120mm yielded the optimum spreading of internal tensile stresses. It should be noted that the fillet radius depends on the volume of the chosen Xbloc® unit. Moreover, the prototype units had a fillet with a radius of 30mm at the edge between the cubical leg and the X-shaped base.

The static load cases to which the FE models have been subjected, involved exposure due to flexure, torsion and combined flexure and torsion. The FE model properties and load cases for this study are comparable to those found in literature, i.e. Melby (1997) and Sogreah (publishing year unknown, ca. 1984), to allow comparison of the results. One additional flexure case and two quasi-dynamic free fall cases have been considered that have not been published before. Furthermore, a dynamic Xbloc® model has been developed for numerical hammer drop and free fall tests. The results of the (quasi-) dynamic load cases are not presented in this paper.

The numerical study focused on the assessment of the tensile tresses in the FE model, because these stresses are the governing factor for initial damage. The stresses and strains that are computed in each of the elements are linearly related to the displacement of the corresponding nodes of the elements. A graphical presentation of the FE models used in this study is given in Figure 6.

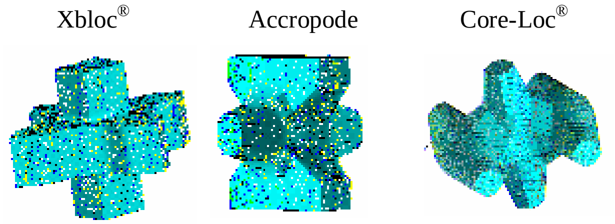
Xbloc® Accropode Core-Loc®

Figure 6: FE models used in the numerical study.

Static load case Flexure

A 9t point load, hence almost the same load as the unit weight, was imposed on the outer edge of the spiky leg tip. The opposing side of the unit was restrained. This case is denoted Flexure 1. One alternative flexure load case has been considered, which cannot be found in literature. In this case a 9t point load is applied to the upper edge of one of the cubical noses. This case is denoted Flexure 2. See Figure 7 for both flexure load cases.

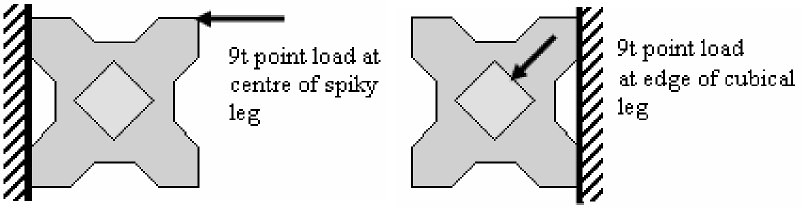

Figure 7: Schematic of Flexure 1 and Flexure 2 load case.

Static load case Torsion

Torsion was generated by imposing four 4.5t concentrated loads to the tips of the four spiky legs. Two of these loads are pushing and two loads are pulling. These loads were oriented normal to the surface of the X-shaped base. This operation generated the maximum torsion. For this load case the units were fixed on the centre line. See Figure 8.

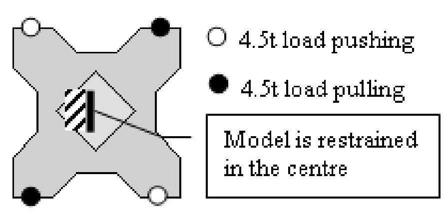

Figure 8: Schematic of torsion load case.

Static load case Combination of flexure and torsion

A combination of both flexure and torsion was considered by applying a 4.5t point load on the ends of two spiky legs and imposing a 9t point load on one end of a spiky leg, see Figure 9. The opposing spiky legs were fixed rigidly along the outside surface.

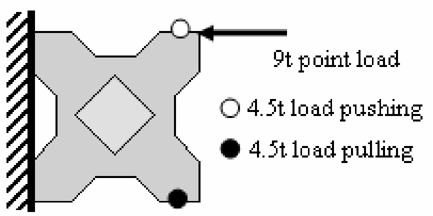

Figure 9: Schematic of combined flexure and torsion load case.

3.2 Results and conclusions

Figure 10 gives the maximum tensile stress results found from the various static load cases. The focus shall not be drawn to the absolute value of the tensile stress but to the relation between the tensile stresses of the three units considered. The highest tensile stresses occur for the Flexure 2 load case and the combined Flexure and Torsion load case. The critical tensile stresses are found near the connections between the base of the unit and the legs. The Xbloc® has the lowest tensile stresses, whereas the Core-loc® has the highest tensile stresses for all four load cases (Figure 10). For the combined flexure and torsion load case and the alternative flexure load case the tensile stresses for the Xbloc® and Accropode are comparable.

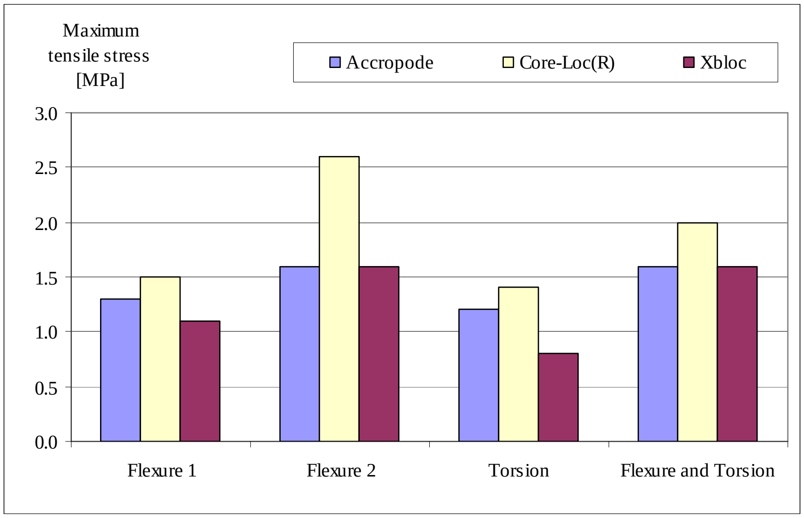

Figure 10: Results FE study.

4. SUMMARY AND CONCLUSIONS

The Xbloc® armour unit has been subjected to an extensive structural strength test program, including prototype and numerical tests.

Prototype drop tests: Four Xbloc® prototype test units have been subjected to over 150 individual drops, whereby the Xbloc® has been tested at various orientations and fall heights. From the recorded damage patterns and the comparison with other single layer armour units it can be concluded that the shape of the Xbloc® yields an inherent structural strength. Xbloc® has a significantly better structural strength than the Core-loc®. The Accropode has only been tested for one drop position, which is not critical for its structural integrity.

Numerical study: The numerical analyses of standard load cases proves that the structural response of the Xbloc® unit is comparable to or even better than the response of the Accropode unit and significantly better than the response of the Core-loc®.

It can be concluded that the Xbloc® is a robust armour unit, which has a high internal strength, not only in the central part of the unit but also in the legs and at the intersections between the legs and the central part of the unit.

5. RECOMMENDATIONS FOR FUTURE RESEARCH

The following subjects are suggested for future research:

- Determination of the actual loads during construction and in-service in order to derive realistic test scenarios
- Preparation of a general applicable (standard) procedure for prototype drop tests to allow comparison of results
- Conducting a comparative study with prototypes of different types of armour units, with same test unit volume and mass, test floor particulars, load cases, etc.

6. REFERENCES

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